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The emerging global crisis of land use

How rising competition for land threatens international and environmental stability, and how the risks can be mitigated

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Report summary

Humanity faces a deepening 'land crunch' in the coming decades, as on current trends the demand for land for farming, climate change mitigation and other essential uses will increasingly exceed the availability of appropriate land. Intensifying competition for land will make international cooperation on solutions more important, but also more elusive.

Pressures around land use are emerging as one of the defining environmental challenges of modern times. Competition for productive and ecologically valuable land, and for the resources and services it provides, is set to intensify over the coming decades. Ever more land will be used to produce food and renewable energy; at the same time, more land will be required to sequester carbon to mitigate climate change, while fulfilling other essential needs such as supporting biodiversity. As land use in any given domain – for example, climate action – will potentially tie up land critically needed in others, humanity faces the prospect of an acute 'land crunch' in which land, despite its apparent abundance, will increasingly be defined by its scarcity. In one scenario, for example, by the middle of this century the world could face an agricultural land deficit – the gap between the amount of farmland needed and that available – of 573 million hectares, almost twice India's land area (see Chapter 6).

This report explores the drivers of the land crunch, models how the pressures associated with it could play out between now and 2050, and presents ideas for promoting more sustainable land use and cooperative land stewardship. While the crunch is, in some respects, already a contemporary phenomenon – reflecting relentless growth in resource consumption, stagnating land productivity and accelerating biodiversity loss – the pressures will continue to mount in the future. So what can and should humanity do now to prevent existing pressures on land from becoming unmanageable within decades?

The emerging policy dilemmas are unprecedented. Although land has been a strategic asset and the object of territorial ambitions and conflict throughout history, choices over land use are now more entwined with globally consequential environmental outcomes than ever before. In particular, the climate crisis is changing

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the picture. Global heating and extreme weather events are degrading lands globally. Meanwhile, the land footprints of some of the energy and carbon-capture solutions currently being proposed for achieving net zero can only, at the scale required, impinge on other land uses such as farming – itself often a grossly inefficient land user. At a time when the planet is already being pushed beyond what it can sustainably support, the reality is that land will very soon be expected to provide yet more resources and services from an essentially finite area.

International cooperation is essential, we argue, for tackling a challenge of this scale, but prospects for effective action are complicated by the political impulses and resource security agendas of individual countries. There is a real risk that governments and corporations will respond to prospective and actual increases in the pressures on land with aggressive efforts to control or appropriate land resources in their own self-interest. This trajectory would both make conflict more likely and further exacerbate the very supply constraints liable to motivate such behaviour.

Rising demands, finite supply

In this report, we examine the main sources of demand for land, and consider how changes in key sectors might translate into different levels – and new patterns – of land use in the future. We survey contemporary land-use trends, from urbanization to deforestation, setting out the environmental problems many of these continue to create. Drawing on assumptions in the academic and policy literature, we also examine in detail the potential land requirements for energy sector decarbonization and food production, expected to be two of the most significant drivers of land-use change between now and 2050. We consider variables such as whether consumers continue with current dietary patterns or shift to more sustainable alternatives. We also quantify the prospective land use specifically associated with deploying bioenergy at scale, an increasingly topical question in the context of policymakers' bullish proposals for the use of bioenergy with carbon capture and storage (BECCS).

The results of our analysis are, in the main, profoundly sobering. First, even though BECCS, a much-hyped technology to capture carbon dioxide emissions while producing energy, is now widely considered as a mainstream option for climate change mitigation, it is high-risk. It is unproven at the scale needed, has questionable benefits in terms of reducing net emissions, and is extremely land-hungry (see Chapter 5, Box 11). Biomass-based energy, of which BECCS is one type, requires upwards of 1,000 times as much land as fossil alternatives per unit of power generated, and approximately 40–50 times more than solar photovoltaics. By 2050, we estimate, the area of agricultural land needed for cultivation of bioenergy crops, if policymakers rely substantially on bioenergy and BECCS to limit global heating,[1] could be equivalent to over 20 per cent of current global cropland.

1 Our analysis draws on a joint International Energy Agency and International Renewable Energy Agency scenario for energy demand in the low-carbon transition, positioned as being 'compatible with limiting the rise in global mean temperature to 2°C by 2100 with a probability of 66 per cent, as a way of contributing to the "well below 2°C" target of the Paris Agreement' (see Chapter 5).

Second, and at the same time, the changing consumption patterns and preferences of a global population that now stands at around 8 billion threaten to make food systems ever more unsustainable. While the overall rate of population growth is now slower than at any time since the 1950s, the number of people on the planet is not expected to peak until the 2080s. As affluence increases in some countries, lifestyles – including diets – become more resource-intensive.

To quantify the anticipated pressures, the report envisages six scenarios for land use by 2050 (see Chapter 6). All six scenarios assume a common increase in the deployment of renewable energy, to keep global heating to below 2°C, but with varying food system trajectories from 'business as usual' to profoundly reformed. In one scenario, farmers adopt sustainable techniques for improving agricultural productivity, food waste is cut by 50 per cent, and healthy diets are adopted globally. In another, half of all meat, dairy and related animal-product consumption is replaced by consumption of plant-based 'imitation' meat.

Overall, we find significant reductions in the land footprint are achievable through the most reform-oriented options – even eliminating the global agricultural land deficit in some cases and freeing up more land for conservation. But we also confirm the very poor outlook for land-use sustainability under business-as-usual conditions. By 2050, without significant changes in agriculture and diets, the amount of land used for farming could grow by over a fifth (see Chapter 6).

With biodiversity protection and ecosystem restoration also needing to be included in the land-use mix – not least to increase resilience to a changing climate – it is clear that, in the absence of international cooperation on progressive policy action, the world simply will not have enough land to meet all of humanity's currently desired and envisioned uses by mid-century. (It should be noted that land reclamation is a virtual non-starter for relieving supply constraints, as even at an extremely ambitious scale it would barely make a dent in the problem and would create resource use issues of its own.)

Difficult trade-offs and policy decisions await. To put it bluntly, without significant reforms governments will be forced into a series of untenable choices: between feeding people, meeting climate targets and preserving nature; between economic prosperity today and safeguarding populations' well-being tomorrow; and between asserting national resource security agendas and managing foreign relations to avoid conflict. Existing inequalities and tensions will increase if competition between land uses, and users, is not addressed by policies that acknowledge national constraints without surrendering the ambition to reduce global resource use.

However, these are not irresolvable dilemmas or inevitable outcomes. Many of the measures needed to mitigate the land crunch are well understood – indeed, some of the most important proposed solutions are not even new – although implementing them is no less challenging. There is an intrinsically political dimension to asking governments to re-engineer their economies, or people to change their consumption habits, for the sake of a common goal that depends on solutions being coordinated across geographical and political divides. The best approach in any given country will also vary according to the specific land resources and economic resources at that country's disposal.

A new Land Wealth Index – quality as well as quantity

To better understand the factors that might determine national land-use choices in the future, we have created the Chatham House Land Wealth Index (LWI). Developed specifically for this report (and presented in Chapter 7), the LWI offers a country-by-country picture of 'land wealth' worldwide, reflecting the extent and essential characteristics of the productive and environment-supporting lands of 163 countries. (Very small countries such as Singapore are omitted from the index, although where relevant some are specifically referred to in the analysis; a few other countries or territories, such as Greenland, are excluded on grounds of insufficient comparable data despite meeting the threshold for land area.)

The index is a composite of 16 quantitative indicators covering variables such as cropland quantity, land degradation (for example, trends in tree cover loss), governance, economic capacity, environmental risks such as water scarcity, and direct and indirect population pressures. These measures are not exhaustive, but they have the utility of capturing values not typically included in economic assessments: for example, the holistic conception of 'wealth' used in the LWI recognizes the ecological and societal value of land as well as its market potential.

Having a lot of land is not, on its own, a guarantee of land wealth – especially if that land is degraded, poorly governed or both.

The LWI is not intended as a definitive 'league table' of land wealth. Rather, in presenting the index, we aim to provide an intuitive sense of how globally important resources are distributed between nations, along with a data-driven indication of countries' susceptibility or resilience to land-related pressures in the widest sense. As such, perhaps the key aspect of the LWI is the light it sheds on the *qualitative* dimensions of land wealth. What this means, in simple terms, is that although absolute land area is a significant determinant of a country's land wealth, it is far from the only factor. Huge countries such as the US, Russia, Australia, China, Brazil and Canada all, unsurprisingly, feature in the top 10 places in the LWI. But a smaller country can also rank highly if it has high-quality land or manages its land well, among other variables. A good example is Germany, which ranks fifth in the index despite being the 64th largest country by area.

At the same time, the LWI confirms the essential truth that having a lot of land is not, on its own, a guarantee of land wealth – especially if that land is degraded, poorly governed or both. Algeria and the Democratic Republic of the Congo (DRC), in their own different ways, illustrate the point. These two countries rank 95th and 56th in the index respectively, despite being the 10th and 11th largest countries in the world. Both suffer from weak governance, with Algeria's position in the index also reflecting the inherent challenges associated with a predominantly desert landscape. The DRC, in contrast, is one of the most carbon- and biodiversity-rich countries, possessing high-quality lands that are important beyond its borders for mitigating and providing resilience to global environmental change. However, the country's very low institutional capacity, rapid projected population growth and high vulnerability to land exploitation bring down its overall ranking. India also ranks far lower, at 45th, than it would in a table reflecting size alone (i.e. seventh), with poor soil quality a factor across much of the country.

More than just providing a snapshot of relative status, the LWI is intended to give an idea of how countries might be motivated, or best placed, to act in the future on the basis of their land wealth, and what this could mean for international relations and land-use pressures. As such, the index loosely informs a set of five geopolitical typologies – **'land superpowers'**, **'potential land elites'**, **'threatened land-wealthy countries'**, **'land-poor geopolitical elites'** and **'land-poor developing countries'**. These typologies are intended to reflect some of the more noteworthy intersections between land wealth and geopolitical and economic power, and to indicate the likely impacts of such power on a country's future land wealth and vice-versa.

All other factors being equal, a large and prosperous country is more likely to have substantial geopolitical and economic power, and thus to qualify as either a land superpower or potential land elite. Many of the top 20 countries in the LWI are land superpowers. Conversely, a small but rich country might have the ability to acquire or access land-derived resources overseas to compensate for a lack of native resources. Qatar – near the very bottom of our index – scores lowest of all 163 countries featured in the LWI for amount and quality of land, yet on a per capita basis is one of the world's richest countries. In our framework, it is categorized as a 'land-poor geopolitical elite'. This leaves it far better placed to avoid or manage resource constraints than the 'land-poor developing countries' that occupy most of the lowest positions around it in the index. More generally, there is a troubling risk of a new scramble for resources, in which countries with significant geopolitical heft will wield their soft power and economic influence to exploit other countries' lands.

To be clear, no rigid correlation exists between a country's LWI ranking and its typology, and a simple sorting exercise is not our objective. This is partly because the index measures one half of the equation (land wealth), not the other (geopolitical and economic power). Some countries, for instance, have features associated with more than one typology. One such example is China, which we classify primarily as a land superpower; however, the country's high risk of water scarcity means that in some respects it also falls into the 'threatened land-wealthy' category. Other countries featured in the index fall outside the five typologies discussed in the report; this is particularly the case for countries with middling land wealth or geopolitical/economic power profiles. In other words, the typologies are designed to highlight interesting patterns and commonalities rather than provide a comprehensive system of categorization covering every country.

Geopolitics: a tragedy of the commons in the making?

Countries across different typologies have very uneven susceptibilities to the land-use pressures and resource scarcity we anticipate between now and 2050. Their responses, quite naturally, are likely to prioritize protecting national interests such as food security and critical resource supplies. As mentioned, however, this could conflict with efforts to optimize land use at a global level. Although it is tempting to treat the problem as a technocratic one – identifying or imagining the optimum global mix of land uses for aggregate sustainability – the task of getting countries to reform their land use for the sake of a common interest is inherently political.

To explore this problem in more depth, the report sets out four hypothetical scenarios, or 'futures', describing the geopolitics of land use to 2050 (see Chapter 8). Under business-as-usual dynamics – which we call **'tipping over the edge together'** – land use continues along its current unsustainable path. Multilateralism remains important as an organizing principle in international relations, but it is insufficient to prevent severe land degradation and intensifying resource scarcity. No one wins in this scenario, although land superpowers fare better relative to other country typologies.

The second future sees an unwelcome shift towards unilateralism. We call this scenario **'plunder thy foreigner'** – an intentional nod to the term 'beggar thy neighbour' familiar in economic theory. In this future, in response to rising competition for land and to feared or actual resource shortages, more powerful countries seek to appropriate or exploit the natural resources of less powerful ones. Commitments to upholding multilateral agreements are subordinated to the pursuit of short-term resource security, and a breakdown in international cooperation undermines efforts to tackle global problems. Some categories of country – for instance, land superpowers and land-poor geopolitical elites – may fare relatively better than others, but this is the worst of the four scenarios for planetary health and sustainable land use. The risk of conflict over land is especially high in this future.

In the third future, which we label **'self-sufficiency for national security'**, unilateralism also dominates international relations, but the emphasis of land policies is different. In response to trade disruptions, food shortages and geopolitical tensions, governments focus on domestic resource self-sufficiency. Some countries grow more of their own produce. This has limited, localized benefits for sustainability in some cases, but it makes global land use less efficient in aggregate. The temptation of protectionism also undermines prospects for coordinated action on global land uses that are best for people and the planet. Land-poor developing countries reliant on foreign aid and imported food are especially vulnerable in this future.

A **'land-wealthy world'** is the most optimistic and sustainable of our four futures. High levels of multilateral cooperation enable land use to become optimized for global benefit, creating a world in which the negative impacts of climate change, land degradation and biodiversity loss are reduced, and competing land uses are balanced more effectively. Sustainability becomes the defining principle of land resource management for most countries through to 2050. This is achieved through multilateral cooperation. Geopolitical relationships become more progressive and constructive than in other potential futures, and land use is less destructive.

These four scenarios are not exhaustive – any number of other futures can be imagined – nor are they mutually exclusive. One future may overlap with or lead to another. For example, there may be elements of business-as-usual multilateralism in a 'plunder thy foreigner' future. Nor will all countries conform to type in any given future: in a 'land-wealthy world', for example, some countries may still attempt isolationist or predatory approaches; others will still need international support in addressing their vulnerabilities. The world could move from one set of dynamics to another as more impacts of the land crunch are felt and the effectiveness of responses is assessed. 'Plunder thy foreigner' would be a disturbing but natural progression from the failure of status quo multilateralism, whereas a 'self-sufficiency for national security' future, while unwelcome in itself, could conceivably morph into more cooperative dynamics as countries start to see the impacts and limitations of isolation.

Recommendations: getting to a 'land-wealthy world'

In the context of these challenges, what can and should decision-makers do now to avert the worst impacts of the land crunch, and to improve the chances of achieving the 'land-wealthy world' scenario described above? One thing, for sure, is that success will require a whole-of-society effort, so our recommendations are aimed at a wide variety of stakeholders – including governments, regulators, international organizations, scientists and businesses.

Our recommendations (summarized here and set out in full in Chapter 9) are divided into three categories of action: 1) reduce humanity's land-use footprint and related pressures; 2) govern global land resources systemically and cooperatively; and 3) value land differently and finance its stewardship.

1. Reduce humanity's land-use footprint and related pressures

This is the big one. More than any other action, humanity needs to bring its consumption of resources down to collectively sustainable levels. If this does not happen, other solutions for addressing land-use pressures simply cannot succeed. And if pressures on land intensify to the point of unmanageability, the risks of conflict will increase.

Key tasks:

Transform food systems

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Agriculture is by far the largest human land use, and food systems are central to rising pressures on land, so efforts to transform food systems need to be redoubled. This will include shifting from animal- to more plant-based diets, and reducing supply-chain food losses and consumer waste. Ideas on this topic have been around for a long time, but have so far failed to gain sufficient political traction to overcome incentive structures perpetuating the status quo. However, the potential of food system reform to reduce, and improve the sustainability of, land use is such that these ideas cannot be ignored. What has been missing is political momentum. Just as biodiversity protection had its galvanizing political moment, akin to the Paris climate conference, at the COP15 summit of the Convention on Biological Diversity (CBD) in 2022, food systems now need their own 'Paris moment' if genuinely systemic and transformative approaches, with global buy-in, are to be unlocked. The extensive diplomatic groundwork around food systems undertaken in the run-up to the COP28 climate summit in late 2023 confirms that the urgency to act is widely understood internationally. However, this must be backed by concerted, ongoing and holistic action to match the rhetoric.

Don't bank on BECCS

Reliance on high-risk climate change mitigation technologies such as bioenergy with carbon capture and storage (BECCS) needs to be minimized. BECCS is prohibitively land-intensive, and unrealistic expectations for it are causing other necessary climate change mitigation actions to be deferred or overlooked. BECCS may have some future role as part of a diverse portfolio of climate solutions, but it should be used very sparingly. Instead, other technological and nature-based carbon dioxide removal solutions – from forest and grassland protection to 'blue carbon' sequestration options like mangrove and seagrass restoration – need to be explored more fully. Scientists and civil society must urgently deliver systematic, country-by-country analysis of the practical applications of such solutions, their limitations, their net carbon, biodiversity and livelihood impacts, and their suitability for different geographies and economies.

Use marginal lands better

'Marginal lands' of little current productive value, particularly extensive areas of degraded or barren lands such as deserts, must be harnessed for sustainable use or returned to their full ecological potential. This could include using them for nature restoration, carbon capture and storage, solar energy generation, or – in environments that can sustain them – land-sparing food production facilities such as vertical hydroponic/aquaponic farms or cultured-meat laboratories. To facilitate such changes, development donors could use foreign aid and other financial flows to build local resilience through appropriate land restoration and investment in sustainable economic activities in marginal areas.

Build the circular economy

Inclusive 'circular' economies, if widely adopted, will help to decouple economic prosperity from growth in material consumption and its reliance on land. This will be especially important as demand increases for biomaterials as substitutes for extractive resources like critical minerals and fossil fuels. Existing bio-based economic practices such as land-intensive agriculture and forestry will also need to be replaced with alternatives that have smaller land footprints and are associated with fewer environmental and societal harms. Private sector innovation has a key role to play in facilitating this transition, by innovating to extend product lifespans, reduce resource use per product, and maximize opportunities for recycling and reuse. But governments will also need to be involved, so that technical barriers to trade – for example in second-hand and remanufactured goods and recycled raw materials – can be lowered or removed. Regulatory and trade requirements will need to be unified between jurisdictions, while new trade agreements must embed principles of circularity and inclusivity.

2. Govern global land resources systemically and cooperatively

International cooperation will be critical to reducing land-use pressures, as all countries will suffer if the geopolitics around land use degenerate towards zero-sum approaches. Yet the outlook for multilateralism is deteriorating. This suggests the prospects for forging new binding agreements or creating brand new global institutions to tackle environmental problems are remote. Instead, we argue, countries should persevere with multilateralism under the current architecture, doing what they can with existing institutions and mechanisms, while also exploring new ways of working together. Minilateral or ad hoc arrangements will be needed at times, although these must not supplant broad-based multilateral action.

Key tasks:

Coordinate between the 'Rio conventions'
Progress on land-use cooperation remains more likely via established treaties and UN conventions than through fundamental reform of the international architecture for environmental governance. An immediate priority should be greater alignment between the bodies and workplans of the three 'Rio conventions': the United Nations Framework Convention on Climate Change (UNFCCC), the United Nations Convention to Combat Desertification (UNCCD), and the CBD. Mechanisms should be developed that incentivize and legislate for sustained increases in policy ambition, and that are coherent across all three conventions (so that, for instance, the design of climate change mitigation takes biodiversity implications into account). At the national level, greater effort is required in many countries to ensure that domestic policymaking advances progress towards meeting the objectives and targets enshrined in all three conventions. For each country, this approach should reflect an overarching, coherent strategy, coordinated across government offices and agencies, instead of the piecemeal and often discordant policymaking currently observed.

International forums such as the UN Food Systems Summit offer cooperation mechanisms that could be recruited to support the efforts above. One approach would be to integrate national strategies on food system transformation into countries' nationally determined contributions (NDCs) on emissions reductions within the UNFCCC, as well as into their national biodiversity strategies and action plans under the CBD's new Global Biodiversity Framework (GBF).

Measure, report and verify land use consistently
Policymakers need better information to assess the risks of land degradation, weigh up the relative merits of different land-use policies, and drive change accordingly. A consistent measurement, reporting and verification (MRV) framework covering all land uses needs to be developed, perhaps drawing on lessons from the forestry-specific experiences of MRV in relation to the UNFCCC's REDD+ framework. An expanded framework of this kind would need to cover all countries (not just developing countries, as under REDD+) and a wider range of ecological and social metrics (such as biodiversity, farmer incomes, etc.).

Another option could be to use the voluntary reporting metrics of the UN's Land Degradation Neutrality Target Setting Programme to increase accountability on sustainable land use. However, for greater effectiveness, the adoption of the programme's land degradation neutrality targets needs to be extended beyond the current 129 participating countries. Target-setting could also be bolstered by widespread adoption of the UN's new 'SEEA Ecosystem Accounting' framework, which recognizes natural capital in economic reporting.

In the private sector, fuller transparency on land use and related risks is needed, and disclosures may increasingly be demanded by governments that have adopted the GBF's new biodiversity targets, announced in late 2022. Existing corporate disclosure frameworks, coupled with regulation and policy galvanized by the GBF, could be used to make land- and nature-related disclosures a core part of every company and financial institution's annual reporting. For example, the Financial Stability Board's Taskforce on Climate-related Financial Disclosures (TCFD) and the new international Taskforce on Nature-related Financial Disclosures (TNFD) could prompt increased corporate disclosures, using the land-use headings in their reporting systems.

Anticipate and communicate land-use risks

Improved monitoring and modelling of the quality and condition of land are needed so that the risks to land sustainability associated with environmental change – as well as the risks associated with different policy options – can be more accurately and convincingly communicated and acted on. As a first step, the scientific community needs to provide analysis of contemporary and future land, climate and biodiversity interactions in more policy-actionable formats. This should include scenarios highlighting the potential sectoral and temporal trade-offs associated with different land-use, trade, development and climate strategies. (For instance, does an energy decarbonization policy have unintended consequences for food security; or does an agricultural policy to boost food security today undermine food security tomorrow by irreversibly degrading productive lands?)

Such work would enable policymakers to develop clearly articulated global pathways and guidelines for responsible investment, dietary change, and technological and nature-based climate change mitigation. These are needed in turn to inform national-level action plans on the collective transformation of land use. Work could be overseen, at least initially, by the United Nations Environment Programme.

'Horizon scanning' of potential sources of pressure arising from global land demand is also needed to provide decision-makers with better visibility of land-related risks and early warnings of future problems. One way to address this would be to set up an inter-agency global risk-scanning institution, specifically devoted to land use, modelled on the G20's Agricultural Market Information System (AMIS). AMIS essentially exists to prevent market failure. It aims to enhance food market transparency and boost policy coordination in times of market uncertainty. The new agency could identify and audit risks from land-use changes and land degradation, and scan for cascading risks from biodiversity loss and climate change.

Increase enforcement of land rights and protections
Countries, landowners and land-using communities need legally enforceable preventive measures that they can use when their land resources are at risk of expropriation or degradation (for example, by private profit-making entities). They will also require mechanisms for legal redress when abuses occur. Environmental and rights-based litigation – already being used by affected communities and non-governmental organizations – could serve to plug regulatory gaps, and to hold companies responsible for acts and omissions in their value chains.

Concerted efforts will be needed to ensure that the protection of high-value lands is not at the expense of local, indigenous or vulnerable stakeholders. Decisions around land protection should involve the participation of communities most affected by land-use change, complemented by financial compensation mechanisms, investment in local livelihoods, and robust land rights legislation.

3. Value land differently and finance its stewardship

To incentivize the protection of land, its value in providing long-term public goods needs to be systemically recognized and accounted for. Accelerated mobilization of financial resources, particularly in and for lower-income countries, will also be needed to incentivize and enable sound environmental stewardship. This ambitious endeavour is politically challenging in the current economic context, but supporting poorer countries with these efforts will have global benefits.

Key tasks:

Formalize the value of protected and ecologically rich land
The long-term value that protected and other ecologically rich lands provide – both for the countries in which they are situated and for planetary health – needs more formal, institutional recognition. Ad hoc, intrinsic valuations need to be replaced with regulations or payment schemes and other market-based instruments that explicitly assign financial values to social and environmental goods, including biodiversity.

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Reductionist carbon accounting that fails to reflect the importance of broader ecosystem integrity and functionality needs to be avoided. Instead, widespread adoption of 'natural capital accounting' could help jurisdictions to ascribe economic value to land in a manner commensurate with the value of its biodiversity, ecosystem functions and utility as a carbon sink. (Natural capital accounting measures changes in the extent and condition of ecosystems at a variety of scales in a standardized format; its wider use could enable the flow and value of ecosystem services to be integrated more readily into economic accounting and reporting systems.)

Develop regulatory and market measures to incentivize change
New measures will be required to ensure that the environmental and social costs and benefits of land-based products and services are better reflected in economic valuations and trade. As a starting point, this will require nations and trading jurisdictions to institute economy-wide carbon pricing for emissions and sequestration. Mandating measures to verify emissions sequestration may also be required.

Applying pricing mechanisms to the valuation of *non-carbon* elements of land wealth, such as embodied biodiversity costs or land footprints, is more complicated.

However, such issues, and their alignment with global trade rules, could usefully be explored through the Trade and Environmental Sustainability Structured Discussions (TESSD) at the World Trade Organization.

Redirect public funds towards sustainable land use
Public money should be redirected to supporting practices that reduce, rather than increase, pressures on land. This will entail reallocation of publicly funded subsidies, removal of perverse incentives, and correction of market failures to enable better use of private and public goods. Agricultural subsidy reforms are an urgent priority. Reforms in this area may be accelerated if policymakers successfully meet the 2025 deadline, as set in the GBF, to identify how they will phase out subsidies deemed harmful for biodiversity. This could encourage the replacement of such subsidies with what the framework describes as 'incentives for the conservation and sustainable use of biodiversity'.

Invest in nature-based solutions and create a 'Rio convention fund'
More public and private sector financing for nature-based solutions (NBS) is urgently needed to reduce land pressures. NBS consist of a wide variety of activities involving the conservation, management and restoration of ecosystems. Beyond their carbon sequestration and emissions mitigation roles, NBS offer myriad climate change adaptation and biodiversity benefits if sensitively and appropriately deployed in each landscape.

One means of financing NBS would be through 'payments for ecosystem services' (PES), which can involve payments by governments or private beneficiaries of the services in question. While PES activity is increasing, especially in domestic contexts, such initiatives need to go further, faster. There is an expanding role for governments to provide domestic finance and policy oversight in this area, though more international public finance and private capital are also required.

In the longer term, the creation of an additional 'Rio convention fund' using public or blended finance may offer the best chance of mobilizing money to address the land crunch. Funding could be made available to integrate action spanning all three Rio conventions, for example aligning (a) NDCs on greenhouse gas emissions (under the UNFCCC); (b) national biodiversity strategies and action plans (under the CBD); and (c) national plans for achieving land degradation neutrality targets (under the UNCCD).

An urgent imperative

All of the above are vital actions, which need to be taken by a multitude of stakeholders if humanity is to avert the worst outcomes from the deepening land crunch. But perhaps most fundamentally, governments in particular have to make land an urgent priority. They need to start recognizing and acting on the land crunch as one of the existential issues of our time. Governments need to acknowledge the magnitude of the challenge, take responsibility for addressing it, and effect institutional changes that embed land crunch planning at the centre of domestic, foreign and economic policy.

01 Introduction

Land has always been a strategic resource, but the imperatives of combating climate change underline the criticality of sustainable stewardship as competition between different land uses – including for food production, carbon sequestration and bioenergy – increases.

Land is unlike other resources. While modern societies depend on energy and materials and we cannot exist without food and fresh water, these resources – commonly described as 'strategic' or 'critical' – are all provided by, or require access to, land. No less vitally, land performs many wider roles. It regulates the environment at local and global scales, shaping weather patterns and moderating the carbon and nitrogen cycles; it provides habitats for millions of species, space for human settlement, and natural infrastructure such as flood plains that protect against natural disasters. Less tangibly, land is a source of significant cultural value, while access to land is critical to human well-being.

While some resources, such as fossil fuels and minerals, are obviously exhaustible, and others, such as timber and fresh water, are renewable, land is more complex. Land can clearly be put to different uses, but there are limits to its abundance. The quantity of land is, broadly speaking, finite. A certain tract of land can only yield so much food, sequester so much carbon or support so much biodiversity. Moreover, a tract of land's potential or capacity is not constant – it can be exhausted or renewed. Human use and environmental change may degrade land, diminishing its productivity and limiting the extent and range of resources and services it can supply. In some cases, land can be restored, but because processes of restoration typically take much longer than processes of degradation, land cannot be considered a renewable resource.

The multifunctionality of land gives it a strategic importance beyond its direct provisioning role. It has an economic value derived from the resources produced on or extracted from it; these resources can be traded or accumulated. And possession of land can be used to exert power and influence over others. Landowners can control access to critical transport corridors and infrastructure. Accordingly, dominance of topographical features such as natural harbours, mountain passes and fertile plains has preoccupied governments and their militaries for centuries.

These characteristics make land critical to economic development and geopolitics. Landlocked countries with low agricultural potential and limited resources have typically struggled to develop at the same rates as better-endowed countries.[2] Conversely, the US's historical rise to power had much to do with its abundance of productive and resource-rich land, overlaid with extensive navigable waterways and connected to an accessible coastline. China owes its prosperity to the North China Plain – a vast, fertile riverine area on the country's northeastern coast between Beijing and Shanghai. This was the birthplace of Chinese civilization: the region's ability to sustain two rice and soybean harvests each year supported rapid population growth, and the North China Plain is now one of the most densely populated places on the planet. Today, its accessible coastline and natural harbours support China's role as manufacturer to the world. Russia's prominent position in international affairs, despite its current diplomatic isolation as a result of its war on Ukraine, is in part a function of its vastness – though Russia's geography presents challenges as well as natural advantages. The country possesses extensive mineral, oil and gas wealth, but much of this is located in Siberia, where a harsh climate and poor soils make living conditions difficult. As a consequence, over 75 per cent of the population lives in the more fertile quarter of Russia's land mass in Europe, to the west of the Ural mountains.[3]

Present-day land resources are often influenced by past and present inequalities, including inequities stemming from colonial rule and imperialism.

Land is frequently a contested resource. In addition to the strategic dimensions noted above, land's importance to cultural identities, political relations and livelihoods has put it at the centre of disputes throughout history. Present-day land resources are often influenced by past and present inequalities, including inequities stemming from colonial rule and imperialism. When unresolved, scarcity of land or insecurity of land tenure can contribute to or be an aggravating factor in large-scale violent conflicts either internationally or intra-nationally (as seen in Colombia and Rwanda, among many examples).

Yet land is not in and of itself destiny; how a country or society chooses to use the land it has is critical to its long-term prospects. Today, many of the same processes of deforestation, soil depletion, species loss and overexploitation of resources thought to have undermined past civilizations are global phenomena driving planetary risks at unprecedented scales.

This report examines the future of global land resources and their use in the context of rising demand for land and increasing environmental degradation, and considers the implications of what we term a 'land crunch' for geopolitics, security and international cooperation. The fragility of the world's land resources has perhaps never been so starkly apparent. Crises in 2022 and 2023 have included, among many: wildfires that ravaged much of Europe, Canada and Hawaii; severe floods that submerged a tenth of Pakistan and inundated much of the rest of South Asia;

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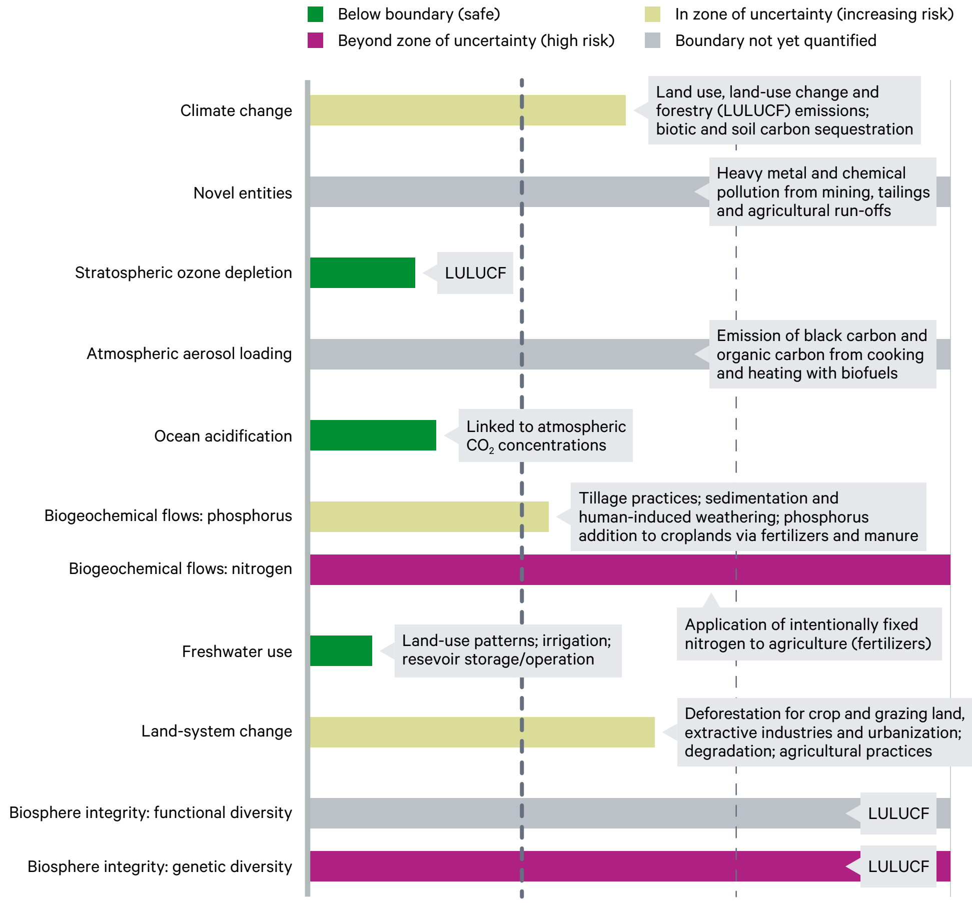
2 See, for example, Gallup, J. L., Sachs, J. and Mellinger, A. (1998), 'Geography and Economic Development', National Bureau of Economic Research, NBER Working Paper 6849, https://doi.org/10.3386/w6849.
3 Marshall, T. (2015), *Prisoners of Geography: Ten maps that tell you everything you need to know about global politics*, London: Elliot and Thompson.

the worst drought in 40 years in the Horn of Africa; the hottest month on record in July 2023;[4] and widespread pressures on food security arising from Russia's war on Ukraine. Couple all this with the fraying of the liberal international order, the rise of nationalism, and stuttering progress in international forums to agree urgently needed environmental targets – and to finance the means to adhere to them – and the challenges are even more palpable.

In the report, we study in detail some of the more significant pressures on global land use, consider how countries' differing land assets may shape their future economic and geopolitical prospects, and ask how these resource and governance challenges can best be met to sustain land resources that are supportive of humanity and biodiversity.

1.1 Unsustainable land use

Figure 1. Planetary boundaries and how they are affected by land use



Source: Steffen, W. et al. (2015), 'Planetary boundaries: Guiding human development on a changing planet', *Science*, 347(6223), https://doi.org/10.1126/science.1259855.

4 NASA (2023), 'NASA Clocks July 2023 as Hottest Month on Record Ever Since 1880', press release, 14 August 2023, https://www.nasa.gov/press-release/nasa-clocks-july-2023-as-hottest-month-on-record-ever-since-1880.

Land use is a principal driver of environmental degradation. Of seven planetary boundaries so far delineated by scientists, four are at major risk of being breached as a result of land use (in the categories of climate change, biogeochemical flows, land-system change, and genetic diversity contributing to biosphere integrity – see Figure 1).[5] Agriculture, forestry and other land uses (AFOLU) are together responsible for around a quarter of global greenhouse gas emissions, and are thus major drivers of climate change. Fertilizer use is a principal disruptor of the nitrogen and phosphorous cycles, contributing to the pollution of air and water. Losses of forests, wetlands and grasslands mean the land system risks passing critical thresholds beyond which its ability to provide essential ecosystem services could deteriorate dramatically; these changes in land use are also the main causes of habitat destruction and species loss.

1.2 Unsustainable land demand?

Demand for land and the resources and services it provides is expected to increase significantly over the coming decades. This will be due in part to economic and demographic shifts, but will also reflect demand arising from efforts to tackle climate change itself. Key sources of future demand are likely to include:

— **Carbon sequestration.** Achieving the Paris Agreement's goal of limiting global average temperature increases to well below 2°C (above pre-industrial levels) by the end of this century is likely to require massive carbon dioxide removal (CDR) on a global scale. CDR is a key element of the scenarios, compiled for the Intergovernmental Panel on Climate Change (IPCC)'s Sixth Assessment Report, that limit likely warming to 1.5°C or 2°C by 2100. These scenarios envisage a major role for negative emissions technologies alongside afforestation and reforestation,[6] with a median estimate that over 600 gigatonnes of carbon dioxide ($GtCO_2$) will need to be removed from the atmosphere by the end of this century[7] – an amount roughly equivalent to 11 years of global emissions at current rates.[8] Current opinion is that afforestation and reforestation, along with bioenergy with carbon capture and storage (BECCS), provide the most feasible approaches, but each is land-hungry. One recent estimate concluded that achieving the necessary removals using BECCS would require between

5 The boundaries cover nine major Earth system processes and features. Land use also affects the remaining three quantified categories – stratospheric ozone depletion, ocean acidification and freshwater use – but these are not yet approaching their planetary boundaries. 'Novel entities' and 'atmospheric aerosol loading' remain unquantified. The biogeochemical flows boundary is quantified separately for phosphorous and nitrogen; the biosphere integrity boundary also consists of two components – functional diversity and genetic diversity – of which only the latter is quantified.
6 Afforestation refers to the establishment of trees where they were previously absent, whereas reforestation is the replanting of trees in areas where pre-existing forests or woodlands have been depleted.
7 This estimate consists of cumulative removals of 328 (168–763) $GtCO_2$ from BECCS, 252 (20–418) $GtCO_2$ from managed lands and 29 (0–339) $GtCO_2$ from direct air carbon capture and storage (DACCS) between 2020 and 2100. Median values with 5–95 percentile values in parentheses. IPCC (2022), *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge and New York: Cambridge University Press, https://doi.org/10.1787/72a9e331-en.
8 See, for example, United Nations Environment Programme (UNEP) (2021), *The Heat Is On: The Emissions Gap Report 2021: A UN Environment Synthesis Report*, Nairobi: UNEP, https://www.unep.org/resources/emissions-gap-report-2021.

380 million and 700 million hectares (ha) of land (equivalent to 1.2 to 2.1 times the area of India) for bioenergy trees and crops; afforestation and reforestation could take up even more.[9]

A rapid transition from fossil fuels is vital if the worst effects of climate change are to be avoided. However, renewable energy sources generally require more land.

— **Agriculture and food production.** Over the past six decades, average food consumption per person has increased by 35 per cent. Consumption of animal products has increased by almost 60 per cent per person, and vegetable oil consumption by over 160 per cent.[10] To enable these increases in consumption, global agriculture has intensified, in some cases unsustainably: fertilizer use has increased by 500 per cent; the amount of irrigated land has approximately doubled; and irrigation now accounts for approximately 70 per cent of humanity's total water use, which itself has increased by about 250 per cent since 1960. Assuming business-as-usual trends of rising food consumption and stagnating crop yields, by 2050 farming could require as much as 1 billion ha of new land – a 42 per cent increase on current levels, and equivalent to an area roughly the size of Canada.[11] Although food production is the dominant driver of agricultural expansion, farming of non-food products such as fibres also uses a lot of land (with fibre crops occupying approximately the same land area as Germany[12]).

— **Energy.** With global energy demand increasing, a rapid transition from fossil fuels is vital if the worst effects of climate change are to be avoided. However, renewable energy sources generally require more land. This is particularly true for bioenergy, which requires upwards of 1,000 times as much land as fossil alternatives per megawatt hour (MWh) generated.[13] Estimates of the amount of bioenergy that can be supplied in the future vary considerably, based on differing assumptions about yield growth, food consumption, utilization of waste and residues, and acceptable levels of land-use change. Estimates of between 100 and 600 exajoules (EJ) per year (roughly equivalent to current global primary energy supply) are not unusual, and could equate to a requirement of between 500 million and 2 billion ha of land.[14]

— **Urbanization.** The world's population is increasing, and so is the share of people living in cities. While the overall rate of population growth is now slower than at any time since the 1950s, the number of people on the planet is not expected to peak until the 2080s.[15] By 2050, the global population is expected to be approaching 10 billion, of which around two-thirds will be urban. Cities are also becoming less densely populated, which means they are occupying

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9 Smith, P. et al. (2016), 'Biophysical and economic limits to negative CO_2 emissions', *Nature Climate Change*, 6(1), pp. 42–50, https://doi.org/10.1038/nclimate2870.
10 All based on daily caloric supplies per person from 1961 to 2019. Food and Agriculture Organization of the United Nations (FAO) (2022), 'FAOSTAT > Food Balances (-2013, old methodology and population)', https://www.fao.org/faostat/en/#data/FBSH (accessed 1 Jun. 2022); FAO (2022), 'FAOSTAT > Food Balances (2010)', https://www.fao.org/faostat/en/#data/FBSH (accessed 1 Jun. 2022).
11 Bajželj, B. et al. (2014), 'Importance of food-demand management for climate mitigation', *Nature Climate Change*, 4(10), pp. 924–29, https://doi.org/10.1038/nclimate2353.
12 Calculated from FAO (2023), 'FAOSTAT > Crops and livestock products', https://www.fao.org/faostat/en/#data/QCL (accessed 1 Sep. 2023).
13 Fritsche, U. R. et al. (2017), *Energy and Land Use*, Global Land Outlook Working Paper, Bonn and Abu Dhabi: United Nations Convention to Combat Desertification (UNCCD) and International Renewable Energy Agency (IRENA), https://www.unccd.int/resources/publications/energy-and-land-use.
14 Swilling, M. et al. (2018), *The Weight of Cities: Resource Requirements of Future Urbanization*, Nairobi: UNEP, https://europa.eu/capacity4dev/unep/documents/weight-cities-resource-requirements-future-urbanization.
15 United Nations Department of Economic and Social Affairs, Population Division (2022), *World Population Prospects 2022: Summary of Results*, p. i, https://www.un.org/development/desa/pd/sites/www.un.org.development.desa.pd/files/wpp2022_summary_of_results.pdf.

even more land: in Europe, the urban population changed little between 1975 and 2015, but built-up areas doubled in size over the same period; in Africa, the urban population tripled and the urban land area quadrupled over the same period.[16] Urban expansion often displaces prime agricultural land.[17] This has knock-on effects for agricultural land needs, as urbanization tends to fragment landscapes and consume high-yielding land, pushing farming on to more marginal soils that require greater areas to produce the same quantities of food. Urban expansion is expected to result in the loss of 1.8–2.4 per cent of all croplands – lands that are nearly 80 per cent more productive than the global average – by 2030. Most of these urbanization-related cropland losses (around 80 per cent) will occur in Asia and Africa, and much of the land that will be lost on both continents is more than twice as productive as national averages.[18]

— **The bioeconomy.** There is growing interest in substituting carbon-intensive and polluting materials with plant-derived ones to meet environmental goals and reduce resource dependence. Examples include bioplastics, and the use of novel wood-based materials in place of cement and steel in the construction sector. Yet while the feedstocks for biomaterials are renewable, land will still be needed on which to grow them. Moreover, there is still significant uncertainty concerning, and variability in estimates of, the greenhouse gas emissions generated throughout the life cycles of such products.[19] Estimates of the potential scale of the bioeconomy and its implications for land use are scarce, but it is thought that in Europe in 2005 the cropland used for biomaterials was only slightly less than that devoted to production of biofuels, and that globally in 2008 around 7 per cent (100 million ha) of cropland was given over to biomaterial production.[20] These figures are expected to rise substantially over the coming decades: one study, drawing on historical data for plastic production, suggests that bioplastic use by 2050 could increase by anywhere between 39 and 431 per cent on 2010 levels, with a central estimate of a 186 per cent increase.[21]

Of the multitude of pressures on land, the focus of this report is on the three most significant drivers of future demand: carbon sequestration; agriculture, especially food production; and energy, especially bioenergy.

16 Pesaresi, M., Melchiorri, M., Siragusa, A. and Kemper, T. (eds) (2016), *Atlas of the Human Planet 2016: Mapping Human Presence on Earth with the Global Human Settlement Layer,* EUR 28116 EN, https://doi.org/doi/10.2788/582834.
17 Lambin, E. F. and Meyfroidt, P. (2011), 'Global land use change, economic globalization, and the looming land scarcity', *Proceedings of the National Academy of Sciences*, 108(9), pp. 3465–72, https://doi.org/10.1073/pnas.1100480108.
18 Bren d'Amour, C. et al. (2017), 'Future urban land expansion and implications for global croplands', *Proceedings of the National Academy of Sciences*, 114(34), pp. 8939–44, https://doi.org/10.1073/pnas.1606036114.
19 Climate Change Committee (2018), *Biomass in a low-carbon economy*, London: Climate Change Committee, https://www.theccc.org.uk/publication/biomass-in-a-low-carbon-economy.
20 UNEP (2014), *Assessing Global Land Use: Balancing Consumption with Sustainable Supply – Summary for Policymakers*, https://wedocs.unep.org/20.500.11822/8861.
21 UNEP (2014), *Assessing Global Land Use: Balancing Consumption with Sustainable Supply*, https://wedocs.unep.org/20.500.11822/9546.

Box 1. Other pressures on land

In addition to the primary pressures outlined in this chapter, a number of other activities – although responsible for less expansive cumulative land footprints – pose significant threats to existing land uses, and to the biodiversity and ecosystem services associated with them. Notable among these activities are mining and sand extraction.

Mining[22]
Mining is a particular concern in forests and other fragile ecosystems. Although it is estimated that mining drives only 7 per cent of deforestation, compared with 73 per cent for agriculture,[23] the sector's cumulative and indirect impacts in terms of deforestation and forest degradation can be significant. At least 10 per cent, and as much as a third, of the world's forests may already be affected by mining, with forests in the Amazon, the Congo Basin and Southeast Asia at particular risk.[24] Significant shares of the production and reserves of minerals required for clean-energy technologies and sustainable infrastructure – such as iron ore, copper, nickel, bauxite and cobalt – are found in critical forest landscapes. With rising demand anticipated for many mineral commodities, alongside the depletion of accessible mineral reserves and declining ore grades across the sector, mining activities are likely to push further into forest landscapes, increasing the risk of deforestation and forest degradation. The type of mining, its infrastructure requirements and its effective 'footprint' will vary from commodity to commodity. Low-value, high-volume commodities such as iron ore and bauxite require far more extensive mining infrastructure than do high-value, low-volume commodities such as gold and cobalt.

Mining's direct impacts on forests include land-use change at mine sites, downstream pollution and environmental damage. Indirect impacts include those associated with the development of road, rail and port infrastructure for the transport and export of minerals, and those caused by inflows of workers and related activity such as logging as new infrastructure developments open forests up. A series of studies commissioned by the World Bank identified 3,300 large mines in forests, including 1,500 active mines and a further 1,800 lying idle or under development.[25] The studies found evidence of forest loss and degradation within a radius of 50 km of most of the mines, and in some cases within a radius of up to 100 km. Similarly, research on deforestation in the Amazon has detected evidence of forest impacts within a radius of up to 70 km of mines, and suggests that mining accounted for almost 10 per cent of all Amazon forest loss between 2005 and 2015.[26]

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22 This section is based on, and in part reproduces, material adapted with kind permission from Bradley, S. (2020), *Mining's Impacts on Forests: Aligning Policy and Finance for Climate and Biodiversity Goals*, Research Paper, London: Royal Institute of International Affairs, https://www.chathamhouse.org/2020/10/minings-impacts-forests.
23 Pendrill, F. et al. (2019), 'Agricultural and forestry trade drives large share of tropical deforestation emissions', *Global Environmental Change*, 56, pp. 1–10, https://doi.org/10.1016/j.gloenvcha.2019.03.002.
24 PROFOR (2022), 'Extractive Industries in Forest Landscapes: Balancing the Trade-offs and maximizing the benefits', https://www.profor.info/knowledge/extractive-industries-forest-landscapes-balancing-trade-offs-and-maximizing-benefits.
25 Ibid.
26 Sonter, L. J. et al. (2017), 'Mining drives extensive deforestation in the Brazilian Amazon', *Nature Communications*, 8(1), p. 1013, https://doi.org/10.1038/s41467-017-00557-w.

Sand extraction[27]

Sand and coarser aggregates are the building blocks of the modern world – bound with cement to produce concrete; mixed with bitumen to produce asphalt; and heated to produce glass and components such as silicon chips, on which so many information and communication technologies rely. They are second only to water as the category of raw material most consumed globally. Population growth and urbanization are fuelling an explosion in demand, especially in China, India and Africa.[28] Another major use for sand is in land reclamation and port development. Singapore, the world's largest importer of sand, has increased its land area by 20 per cent since the mid-1960s using large volumes of Indonesian and Malaysian marine sand. Extensive areas of Hong Kong lie on reclaimed land. Globally, population growth, urbanization and development will all boost the need for housing and infrastructure such as roads, bridges, hospitals, schools, airports and dams. Sea-level rise and more intense storm-induced waves associated with climate change are likely to necessitate the construction of many hundreds of kilometres of concrete sea walls to defend critical infrastructure, triggering additional demand for sand.

Although sand is globally abundant, the rate at which it is being used far exceeds the natural rate at which it is replenished by the weathering of rocks by wind and water. There are some suggestions that demand will outstrip supply by mid-century.[29] As the more plentiful forms of fine, wind-blown desert sand are usually too smooth to act as a binder for concrete, demand is concentrated on the more angular and gritty sand dug from rivers, beaches and the sea floor. Rivers account for less than 1 per cent of the world's surface, so extraction of huge quantities of sand from them has major environmental and social impacts. These impacts include: the stirring up of silt, which smothers fisheries and harms local biodiversity and ecosystems; the acceleration of riverine and coastal erosion; changes in river flows, which can increase the risk of flooding and eliminate buffers against storm surges; exploitation of natural resources by criminal gangs; and rises in cross-border or diplomatic tensions. All of this necessitates better resource governance and demand reduction through land-use planning, the use of alternative and recycled materials, and extensions to the lifespans of existing infrastructure. Initiatives are also under way to develop additives that would make desert sand usable at scale.[30]

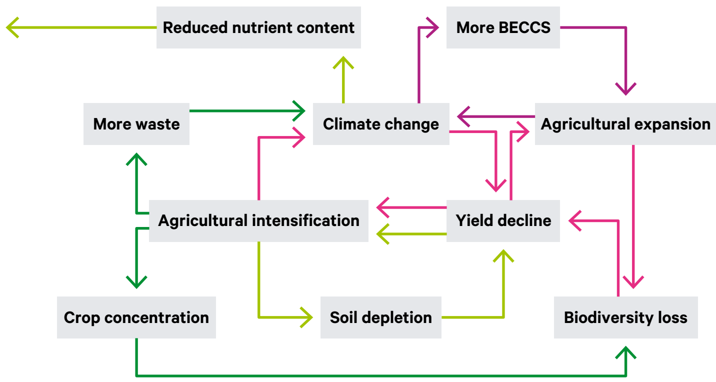
27 This section draws on, and in part reproduces, material adapted with kind permission from Brown, O. and Peduzzi, P. (2019), 'Driven to Extraction: Can Sand Mining be Sustainable?', Chatham House Sustainability Accelerator, 30 May 2019, https://accelerator.chathamhouse.org/article/driven-to-extraction-can-sand-mining-be-sustainable; and Brown, O. and Gallagher, L. (2021), 'Why managing sand sustainably is a gritty problem', Chatham House Explainer, 26 April 2021, https://www.chathamhouse.org/2021/04/why-managing-sand-sustainably-gritty-problem.
28 Bendixen, M., Best, J., Hackney, C. and Iversen, L. L. (2019), 'Time is running out for sand', *Nature*, 571(7763), pp. 29–31, https://doi.org/10.1038/d41586-019-02042-4.
29 Ibid.
30 Diaz, J. (2018), 'The Next Great Building Material? It Could Be Sand From Deserts', *Fast Company*, 18 March 2018, https://www.fastcompany.com/90165549/the-next-great-building-material-it-could-be-sand-from-deserts.

1.3 Vicious circles

Collectively, the areas of land devoted to carbon sequestration, agriculture and energy are immense. Although these functions are not always mutually exclusive – integrated farming systems, for example, may provide opportunities to produce food and energy and sequester carbon on the same parcels of land – it is nonetheless the case that potentially very significant areas of additional land may be needed over the coming decades, and that land use will become increasingly intensive as pressures mount. Returning to the planetary boundaries mentioned above, this implies that land-system change, species loss, greenhouse gas emissions, and disruption of the nitrogen and phosphorous cycles will all accelerate, eroding land's capacity to provide.

The result could be a vicious circle of increasing spread ('extensification') and intensification of human land use, driving declines in provisioning capacity and land-system resilience that, in turn, necessitate further extensification and intensification to cope with declining productivity and increasing demand (Figure 2).

Figure 2. Vicious circles of land-use change



Source: Adapted from Benton, T. G. et al. (2021), *Food system impacts on biodiversity loss: Three levers for food system transformation in support of nature*, Research Paper, London: Royal Institute of International Affairs, https://www.chathamhouse.org/2021/02/food-system-impacts-biodiversity-loss.

In a future in which land has become a primary factor of production not only for food but for energy and materials, productive land will become an increasingly scarce and strategic resource.

1.4 Report outline

In the chapters that follow, we explore the mismatch between land availability and the increasing demand for land from the three major drivers identified above. Chapter 2 explores the current state of the world's land resources. Chapters 3, 4 and 5, respectively, analyse the implications of future demands on land from carbon sequestration and climate resilience measures, food production, and energy –

bioenergy in particular. Then, Chapter 6 considers the interaction of these competing pressures, asks what the implications are for the future of global land use, and explains why a 'land crunch' is likely to deepen in the coming decades.

Next, the focus of the report turns to the strategic status and global distribution of land resources, assessing how these variables shape current geopolitics and international interdependencies and how they are likely to do so in future. Chapter 7 introduces the Chatham House Land Wealth Index (LWI): a global, country-level measure of 'land wealth'. There we explore the relationship between countries' capacity to manage their land resources and their economic and political power. The chapter presents five indicative country typologies, from 'land superpowers' to 'land-poor developing countries'. Chapter 8 elaborates on the LWI framework by considering the concentration and control of land resources among these country groupings. Through a set of indicative scenarios that chart alternative futures between now and 2050, we examine how land wealth, broadly defined, relates to issues of politics, security and protection of the global commons. In conclusion, Chapter 9 sets out an agenda and policy recommendations for averting the worst impacts of the land crunch and improving the prospects for achieving globally sustainable use of the world's land resources.

02 The state of the world's land resources

Rising human land use, alongside climate change, is driving environmental degradation on a global scale. Agricultural expansion, deforestation, urbanization and desertification are diminishing and fragmenting natural or semi-natural landscapes, and threatening biodiversity.

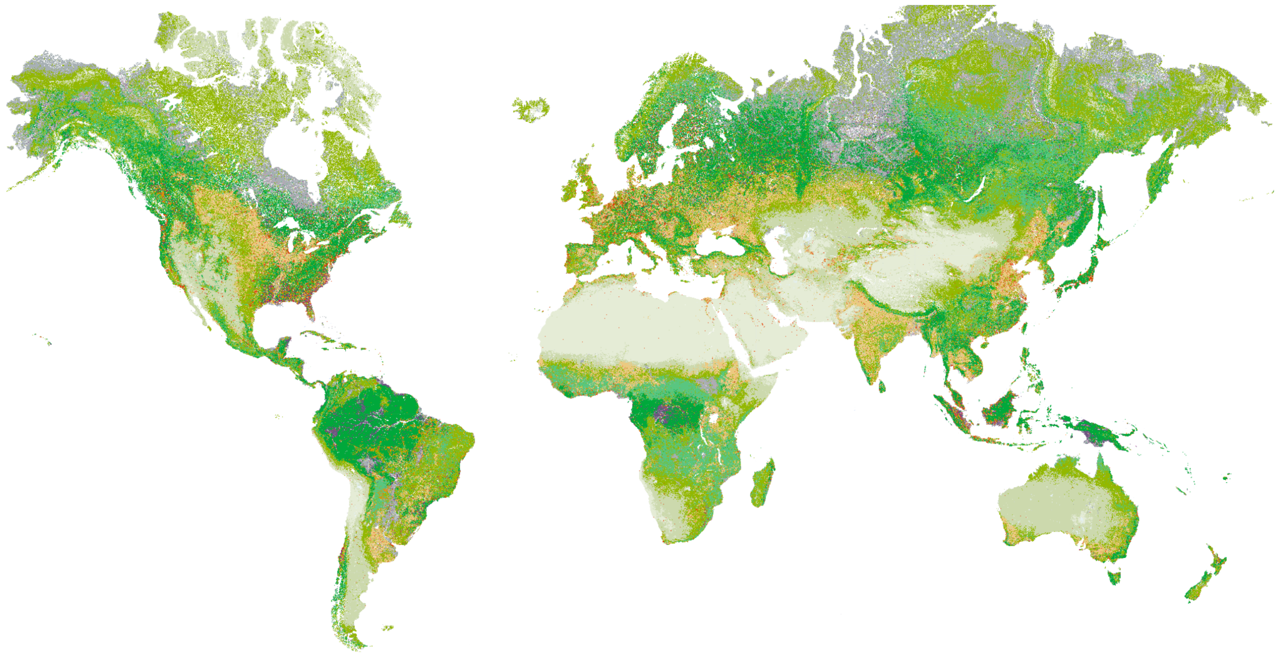
2.1 How much land is there, and how is it used?

Humanity's footprint on the world's land surface is vast and expanding: in the 16 years to 2009, a wilderness land area the size of India was lost to anthropogenic (i.e. human-caused) influence. By that time, less than a quarter (23 per cent) of land outside Antarctica remained ecologically intact and free of direct human pressures; the great majority of this was concentrated in just five countries: Russia, Canada, Australia, Brazil and the US.[31] The geographic distribution of all major natural land cover classes (forms of vegetation, arid cover, wetlands) and land-use categories (croplands, built-up areas, tree cover loss and gain) is shown in Figure 3, together with the major climate domains/ecozones and the aggregate extent of global land use. Pastures, other than on recently deforested land, are not shown as a discrete type of land use; this reflects their highly varied intensities, and the fact that most intensively managed pastures co-exist alongside other intensive land uses.

31 Watson, J. E. M. et al. (2018), 'Protect the last of the wild', *Nature*, 563(7729), pp. 27–30, https://doi.org/10.1038/d41586-018-07183-6; Allan, J. R., Venter, O. and Watson, J. E. M. (2017), 'Temporally inter-comparable maps of terrestrial wilderness and the Last of the Wild', *Scientific Data*, 4(1), p. 170187, https://doi.org/10.1038/sdata.2017.187.

Ecozones with the greatest expanses of human development, such as the low slopes of temperate and subtropical regions, feature the largest proportional areas of land use, with highly fragmented remaining natural land cover. Human land uses in these regions are nearly contiguous. While the vegetated lowlands of Asian humid tropical regions have a land-use intensity similar to that of the US corn belt, the tropics otherwise generally have the greatest theoretical potential for land-use expansion – although such potential is often problematic. South America is a prominent example. As human appropriations drive land-use change, the greater availability of unconverted vegetated lowlands makes the continent especially susceptible to expansion of economic activity in the future.

Figure 3. Global land-use activity and land cover, 2019



Terra firma classes		Wetland classes		Superseding classes
True desert	Dense tree cover	Salt pan	Dense tree cover	Ice/water
Semi-arid	Recent tree cover gain	Semi-arid	Recent tree cover gain	Cropland
Dense short vegetation	Non-fire loss without 2019 trees, cropland or built-up	Dense short vegetation	Non-fire loss without 2019 trees, cropland or built-up	Built-up
Open tree cover		Open tree cover		

Source: Hansen, M. C. et al. (2022), 'Global land use extent and dispersion within natural land cover using Landsat data', *Environmental Research Letters*, 17(3), p. 034050, https://doi.org/10.1088/1748-9326/ac46ec and https://glad.umd.edu/dataset/global-land-cover-land-use-v1.

Such trends are clearly problematic, as preserving the high carbon stocks and biodiversity of natural tropical forests is crucial to reducing global heating and ensuring the continued functioning of Earth system processes. Nearly half of all remaining vegetated land cover is in the tropics; if boreal and Arctic lands are excluded, this includes 74 per cent of remaining lowland tall/dense tree cover and 86 per cent of open/short lowland trees. Until now, climate limitations have generally precluded the development of boreal vegetated lowlands for agriculture, but this could rapidly change as the climate heats. Globally, the vast majority of remaining natural land cover is in close proximity to areas of intensive land use, risking further fragmentation.[32]

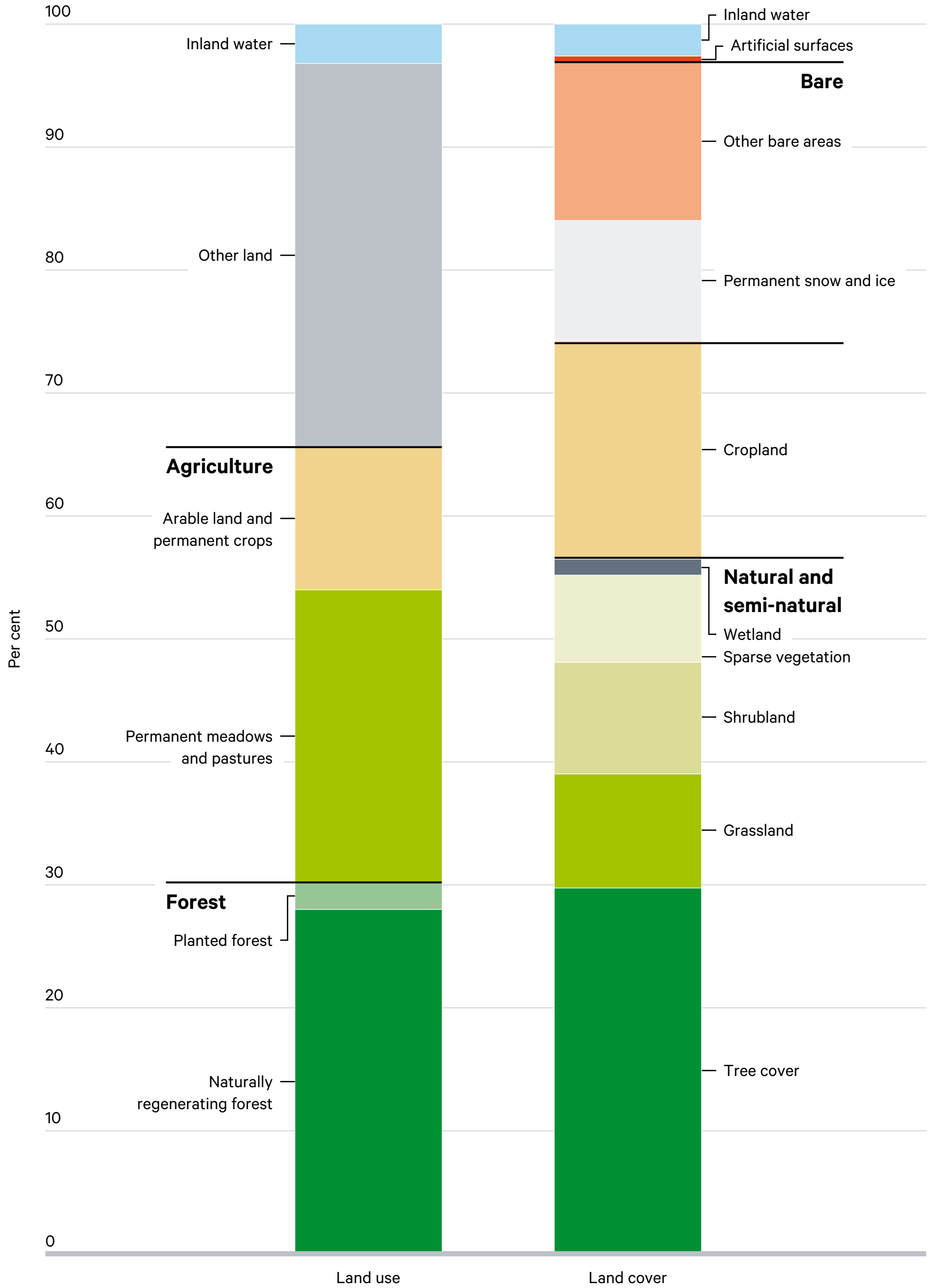
57%
of the world's land area is thought to be naturally or semi-naturally vegetated.

In the map shown in Figure 3, vast latitudinal strata of boreal shrublands and forests, temperate and tropical croplands and grasslands, and equatorial forests and savannahs are clearly visible alongside the barren emptiness of Sahelian Africa and Central Asia.[33] Less clear, however, is the mosaic of smaller parcels of land reflecting myriad fragmented forms of human appropriation. Figure 4 illustrates two relatively simple approaches to aggregating, quantifying and classifying global land types.

According to the land-use classifications of the Food and Agriculture Organization of the United Nations (FAO), the aggregate area of all countries in the world (13.5 billion hectares) is roughly equally divided between agriculture (35 per cent), forests (30 per cent) and other uses (31 per cent), with approximately 3 percentage points of the latter made up of urban areas.[34] The remaining 3 per cent is occupied by inland bodies of water such as lakes, reservoirs, rivers and canals. In terms of land-cover classifications, just over half (57 per cent) of the world's land area is thought to be naturally or semi-naturally vegetated, roughly a fifth (18 per cent) is covered by cropland, and a similar amount (23 per cent) is bare, including permanent snow and ice. There is only a limited anthropogenic footprint on natural and semi-natural land, so these areas are particularly important for maintaining biodiversity and higher-value ecosystem services at the global scale.[35]

32 Hansen, M. C. et al. (2022), 'Global land use extent and dispersion within natural land cover using Landsat data', *Environmental Research Letters*, 17 (3), p. 034050, https://doi.org/10.1088/1748-9326/ac46ec.
33 Of course, many of these desert and arid areas are not truly empty, and they often support remote and fragile ecosystems, but their vast contiguous nature, inaccessibility and limited potential for permanent human activity are nonetheless striking on this global map.
34 Liu, Z., He, C., Zhou, Y. and Wu, J. (2014), 'How much of the world's land has been urbanized, really? A hierarchical framework for avoiding confusion', *Landscape Ecology*, 29 (5), pp. 763–71, https://doi.org/10.1007/s10980-014-0034-y. FAO classifies urban land as 'other' land.
35 Shrubland and sparse vegetation are classified as natural and semi-natural land covers by the OECD, but fall into FAO's 'other' land-use category. See Hascic, I. and Mackie, A. (2018), *Land Cover Change and Conversions: Methodology and Results for OECD and G20 Countries*, OECD Green Growth Papers 2018/04, Paris: OECD Publishing, https://doi.org/10.1787/72a9e331-en.

Figure 4. Land-use and land cover classifications



Note: The land-use areas illustrated, together with coastal waters (0.3 per cent of the total, not shown), constitute the aggregate areas of all countries ('country area'); the global 'land area' is the country area less coastal and inland waters.
Sources: Land-use data from FAO, land cover data from OECD: FAO (2022), 'FAOSTAT > Land Use', https://www.fao.org/faostat/en/#data/RL (accessed 1 Jun. 2022); OECD (2022), 'OECD.Stat > Land cover in countries and regions', https://stats.oecd.org/OECDStat_Metadata/ShowMetadata.ashx?Dataset=LAND_COVER (accessed 1 Jun. 2022).

2.2 Aggregate land cover changes

Despite increasing human pressures, the broad types of land cover have changed relatively slowly in aggregate, with a few dynamic anomalies. Between 1992 and 2019, the largest net increases in land cover were to cropland (which expanded by an area nearly the size of Namibia) and artificial surfaces (i.e. human settlements and infrastructure); almost 60 per cent of the total artificial land surface present in 2019 was added in this 27-year period. The largest net losses were to tree cover (Figure 5).

Figure 5. Global land cover changes, 1992–2019

Source: Calculated from OECD (2022), 'OECD.Stat > Land cover in countries and regions', https://stats.oecd.org/OECDStat_Metadata/ShowMetadata.ashx?Dataset=LAND_COVER (accessed 1 Jun. 2022).

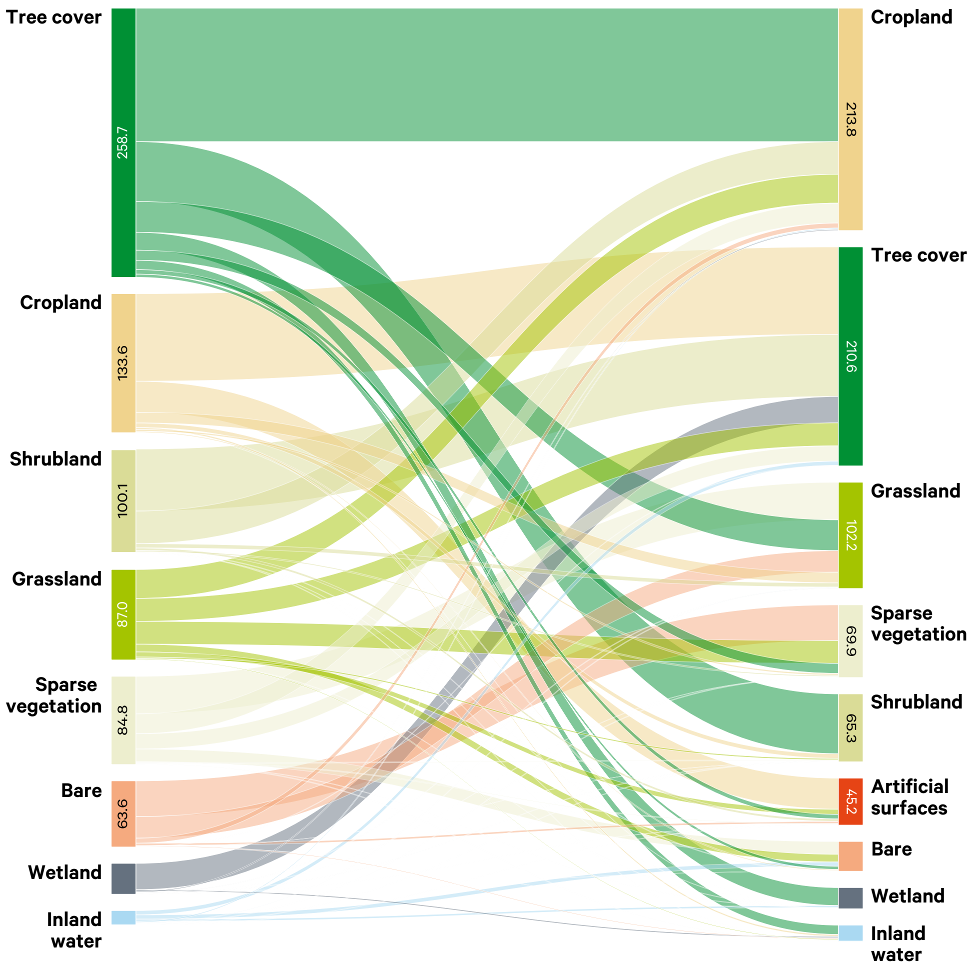
In aggregate, natural and semi-natural types of land cover lost nearly 20 per cent more area than they gained over this period (with only grasslands registering a net increase), although there were significant variations within and across types. Most losses of natural or semi-natural land are the result of its conversion to cropland, but other reasons include desertification and urban expansion. Reasons for gains include afforestation and the abandonment of agricultural lands.[36] Across all categories of natural and semi-natural land, the most dramatic losses and gains have been to tree cover, reflecting massive deforestation (equivalent to the total area of Algeria) and afforestation (equivalent to the area of Saudi Arabia) respectively. The net losses of tree cover between 1992 and 2019, at around 48 million hectares (ha) (equivalent to an area just less than the size of Spain), obscure even more significant impacts on ecosystems: the biodiversity damages from losses are unlikely to have been

36 There is considerable overlap between these factors: afforestation is primarily (although not only) on former agricultural land, and former agricultural land has primarily (but not only) become forest land.

compensated for by equivalent gains, especially as much of the afforestation has been in plantations; homogeneous, immature plantations do not have anything like the biodiversity value of mature natural forests.[37]

In Brazil, more tree-covered area was converted to cropland in the period 1992–2019 than in all OECD countries combined; in Indonesia, such conversion accounted for virtually all tree cover losses. In China, conversions to artificial surfaces from crop and grasslands have been notable. Across OECD countries, despite a complex pattern of land cover changes over the period, tree cover losses and gains have both been more significant than changes in any other form of land cover (Figure 6).

Figure 6. Direct changes in global land cover types 1992–2019 (million ha)



Source: Calculated from OECD (2022), 'OECD.Stat > Land cover in countries and regions', https://stats.oecd.org/OECDStat_Metadata/ShowMetadata.ashx?Dataset=LAND_COVER (accessed 1 Jun. 2022).

37 Hascic and Mackie (2018), *Land Cover Change and Conversions*.

2.3 Land uses and drivers of change

2.3.1 Agriculture

Agriculture, including croplands and pastures, is by far the largest single human land use (Figure 4). Much of the remaining land surface is ill suited to farming, meaning that agriculture usually expands on to more marginal lands that have high biodiversity value and/or lower levels of productivity. The massive expansion of agricultural output in recent decades (a 217 per cent increase in calorie production from 1961 to 2013)[38] has primarily been the result of productivity increases on existing farmland; the area of agricultural land increased by only around 8 per cent during this period.[39]

Over the past 50 years, some 65 per cent of agricultural land-use change has been driven by increased demand for animal products.

Nonetheless, agriculture is also the principal driver of land-use change. The most significant agricultural expansions in recent decades have been in tropical regions, with little change or slight contractions in evidence in temperate zones, resulting in a redistribution of agricultural land towards the tropics.[40] Over the past 50 years, some 65 per cent of agricultural land-use change has been driven by increased demand for animal products.[41] Recent data indicate that the area of global cropland has expanded at an accelerated rate this century, increasing by 9 per cent between 2003 and 2019, largely due to agricultural expansion in Africa and South America. Half of the new crop area replaced natural vegetation and tree cover (especially in these two regions and Southeast Asia), while the other half was due to pasture conversion and the recultivation of abandoned arable land (the major factor in European, Australasian and North Asian expansions).[42]

Despite the expansiveness of global agriculture, the area of cropland directly dominated by food production (as opposed to land used for grazing, or for the cultivation of feedstock crops for livestock and bioenergy) is somewhat smaller. At a continental scale, only about 40 per cent of North American and European arable land is dedicated to food crops, whereas in Africa and Asia about 80 per cent of cropland is used to produce food (Figure 7).[43] Calorie production is dominated by a few staple crops that are geographically concentrated in a few breadbasket regions: maize, rice, wheat and soybean account for nearly two-thirds of all agricultural calories.[44] This focus on calorie production has underpinned agricultural efficiency, but at the expense of food system resilience and biodiversity (discussed in Chapter 4).

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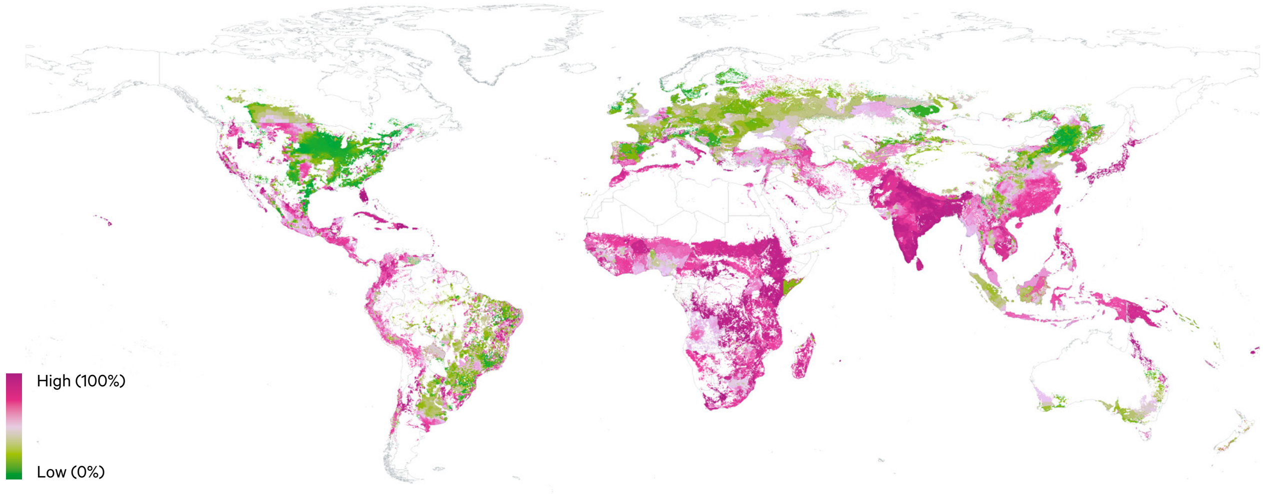
38 Calculated from FAO (2022), 'FAOSTAT > Food Balances (-2013, old methodology and population)', https://www.fao.org/faostat/en/#data/FBSH (accessed 1 Jun. 2022). Note the food balance calculation methodology changed from 2013 onwards, precluding a more recent comparison with 1961.
39 FAO (2022), 'FAOSTAT > Land Use', https://www.fao.org/faostat/en/#data/RL (accessed 1 Jun. 2022).
40 Foley, J. A. et al. (2011), 'Solutions for a cultivated planet', *Nature*, 478(7369), pp. 337–42, https://doi.org/10.1038/nature10452.
41 Cherlet, M. et al. (eds) (2018), *World Atlas of Desertification*, Luxembourg: Publication Office of the European Union, https://wad.jrc.ec.europa.eu.
42 Potapov, P. et al. (2022), 'Global maps of cropland extent and change show accelerated cropland expansion in the twenty-first century', *Nature Food*, 3(1), pp. 19–28, https://doi.org/10.1038/s43016-021-00429-z.
43 Cherlet et al. (eds) (2018), *World Atlas of Desertification*; Cassidy, E. S., West, P. C., Gerber, J. S. and Foley, J. A. (2013), 'Redefining agricultural yields: from tonnes to people nourished per hectare', *Environmental Research Letters*, 8(3), p. 034015, https://doi.org/10.1088/1748-9326/8/3/034015.
44 Ray, D. K., Mueller, N. D., West, P. C. and Foley, J. A. (2013), 'Yield Trends Are Insufficient to Double Global Crop Production by 2050', *PLoS ONE*, 8(6), p. e66428, https://doi.org/10.1371/journal.pone.0066428.

Figure 7. The global cropland footprint in 2000 and the proportion used for food production



Note: Dark pink: all cropland is used to grow crops for human consumption; dark green: all cropland is used for non-food crops.
Sources: Cherlet, M. et al. (eds) (2018), *World Atlas of Desertification*, Luxembourg: Publication Office of the European Union, https://wad.jrc.ec.europa.eu; Cassidy, E. S., West, P. C., Gerber, J. S. and Foley, J. A. (2013), 'Redefining agricultural yields: from tonnes to people nourished per hectare', *Environmental Research Letters*, 8(3), p. 034015, https://doi.org/10.1088/1748-9326/8/3/034015.

2.3.2 Forests and deforestation

Forest ecosystems perform globally important functions, including regulating climate, stabilizing terrestrial carbon storage, regulating water supplies, and hosting and supporting biodiversity richness. All such functions are threatened by changes in forest cover.[45] Deforestation occurred at a fairly consistent rate between 2000 and 2015, with around 5 million ha lost each year.[46] Tree cover loss is a broader phenomenon than deforestation: it does not need to be human-caused, and includes changes in both natural and planted forests. In total, some 230 million ha of forests (an area equivalent to the Democratic Republic of the Congo) were lost globally between 2000 and 2012, compared with only 80 million ha of forest gains. A quarter of the gains were on land previously deforested over this period, but most losses and gains were in separate areas.

Over the same 2000–12 period, more tree cover loss occurred in the tropics than in any other climate zone: tropical rainforests accounted for a third of global losses (with nearly half of the losses in tropical rainforests occurring in South America), while South American tropical dry forests suffered the greatest rate of losses.[47] More recent data show that the tropics lost 11.1 million ha of tree cover in 2021, including 3.75 million ha – equivalent to the area of Bhutan (or 10 football pitches per minute) – of primary forest critical to limiting global heating and biodiversity loss. Tropical primary forest loss in 2021 resulted in 2.5 gigatonnes of carbon dioxide ($GtCO_2$) emissions, equivalent to the annual fossil fuel emissions of India.[48]

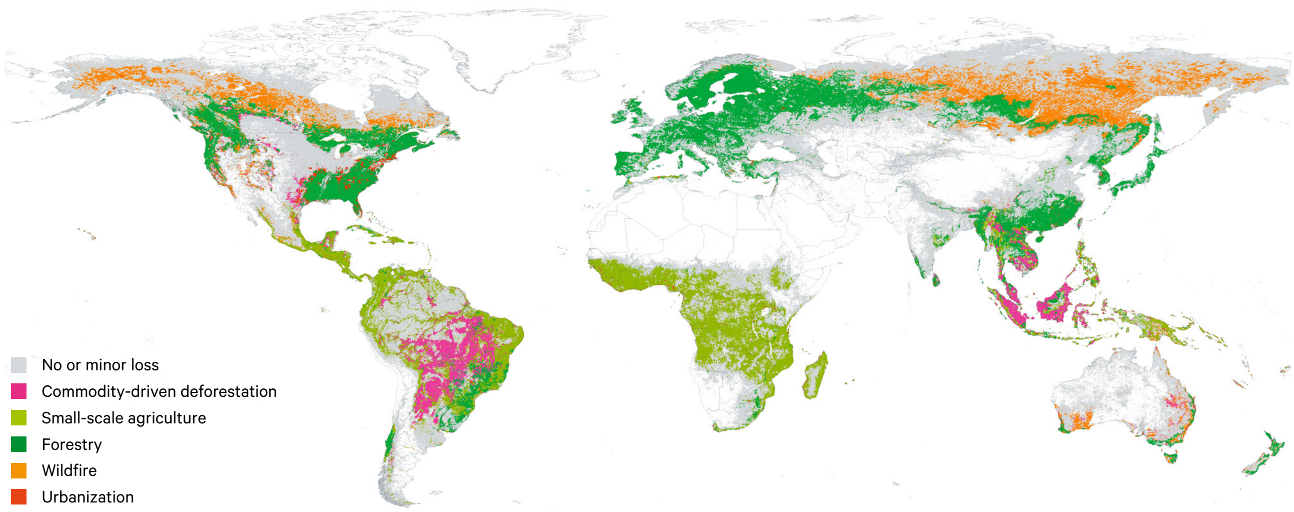
45 Hansen, M. C. et al. (2013), 'High-Resolution Global Maps of 21st-Century Forest Cover Change', *Science*, 342(6160), pp. 850–53, https://doi.org/10.1126/science.1244693.
46 Curtis, P. G. et al. (2018), 'Classifying drivers of global forest loss', *Science*, 361(6407), pp. 1108–11, https://doi.org/10.1126/science.aau3445.
47 Hansen et al. (2013), 'High-Resolution Global Maps of 21st-Century Forest Cover Change'.
48 World Resources Institute (2022), 'How much forest was lost in 2021?', Forest Pulse, https://research.wri.org/gfr/latest-analysis-deforestation-trends#how-much-forest-was-lost-in-2021 (accessed 1 Aug. 2022).

Beyond the tropics, boreal regions have lost the most forest cover (with 2021 a record year),[49] largely as a result of fires and forestry operations.[50] However, these regions still contain the greatest extent of intact forest landscapes (IFLs). IFLs are seamless mosaics of forests and naturally treeless ecosystems; they are large enough to maintain all native biological diversity and have no notable human activity or habitat fragmentation, rendering them particularly valuable sources of ecosystem services.[51]

Globally, permanent deforestation has been driven principally by commodity production, including agriculture, mining and energy infrastructure clearances, mostly in South America and Southeast Asia.[52] Farming is by far the most damaging activity from this perspective, with one study estimating that around 73 per cent of permanent deforestation is caused by agriculture, 10 per cent by urban expansion, 10 per cent by infrastructure and 7 per cent by mining.[53]

Until 2016, annual commodity-related forest losses in Brazil this century were trending downwards.[54] However, these achievements have been offset by increasing tropical losses elsewhere in South America (particularly in Paraguay, Bolivia and Argentina,[55] due to the conversion of forest for row-crop cultivation and cattle grazing) and in Southeast Asia (especially in Indonesia and Malaysia, due to the expansion of oil palm plantations).[56] Since 2016, Brazil's annual forest losses have also returned to much higher levels than in the previous decade.[57]

Figure 8. Primary drivers of forest cover loss, 2001–15

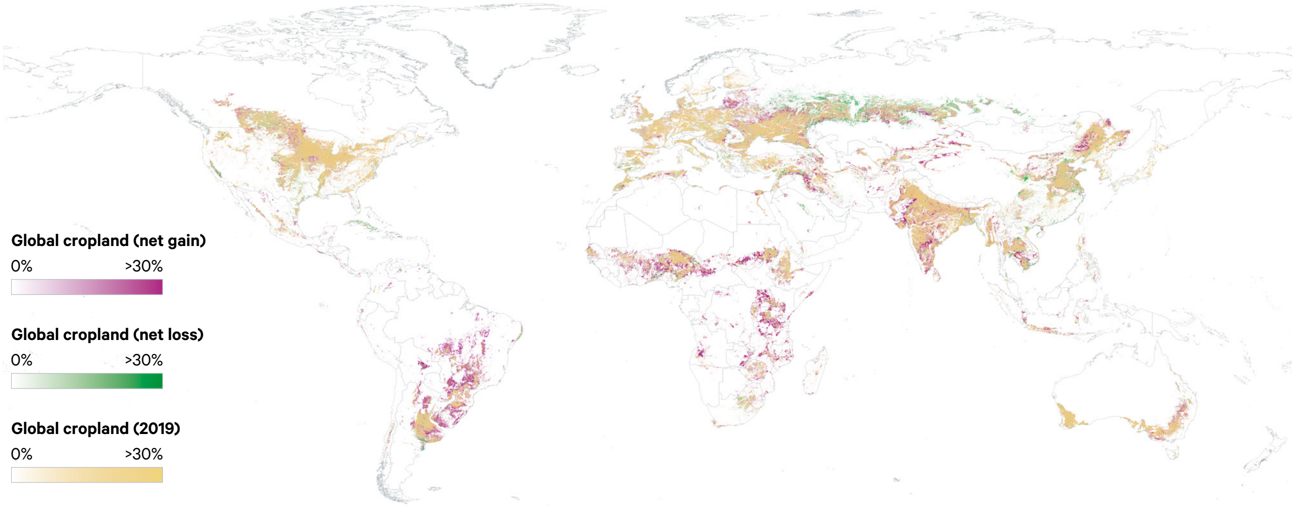


Source: Curtis, P. G. et al. (2018), 'Classifying drivers of global forest loss', *Science*, 361(6407), pp. 1108–11, https://doi.org/10.1126/science.aau3445.

49 Ibid.
50 Hansen et al. (2013), 'High-Resolution Global Maps of 21st-Century Forest Cover Change'.
51 Intact Forest Landscapes (2022), 'Concept', https://intactforests.org/concept.html.
52 Curtis et al. (2018), 'Classifying drivers of global forest loss'.
53 Pendrill, F. et al. (2019), 'Agricultural and forestry trade drives large share of tropical deforestation emissions', *Global Environmental Change*, 56, pp. 1–10, https://doi.org/10.1016/j.gloenvcha.2019.03.002.
54 Curtis et al. (2018), 'Classifying drivers of global forest loss'.
55 Hansen et al. (2013), 'High-Resolution Global Maps of 21st-Century Forest Cover Change'.
56 Curtis et al. (2018), 'Classifying drivers of global forest loss'.
57 World Resources Institute (2022), 'Brazil Deforestation Rates & Statistics', Global Forest Watch, https://www.globalforestwatch.org/dashboards/country/BRA.

Commodity-driven permanent deforestation was responsible for just over a quarter (27 per cent) of total tree cover losses globally from 2001 to 2015. The remaining losses were due, in almost equal proportions, to forestry harvests in managed plantations, conversion to small-scale agriculture, and wildfires (Figure 8). However, unlike commodity-related deforestation, such losses have not always been associated with permanent changes in land use, as they are sometimes followed by subsequent forest regrowth.[58] In the case of small-scale agriculture, for example, some of the recorded land-use conversion reflects temporary shifts in farming patterns. That said, it is also the case that in Africa nearly all permanent expansion of agriculture is caused by the activities of smallholders – the area of cropland on the continent increased by a third between 2003 and 2019 (Figure 9).[59]

Figure 9. Global cropland extent and change, 2000–19



Source: Potapov, P. et al. (2022), 'Global maps of cropland extent and change show accelerated cropland expansion in the twenty-first century', *Nature Food*, 3(1), pp. 19–28, https://doi.org/10.1038/s43016-021-00429-z.

New analysis on recent high-fire years suggests that forest losses due to fire increased between 2001 and 2019, and that these accounted for 26–29 per cent of total forest losses over this period, including over half the losses in Australasia and in boreal forests.[60] Climate change and land-use change threaten to make wildfires more frequent and intense, including in the previously immune Arctic: the incidence of extreme fires is expected to increase by up to 14 per cent by 2030, 30 per cent by 2050, and 50 per cent by the end of the century.[61]

58 Curtis et al. (2018), 'Classifying drivers of global forest loss'.
59 Potapov et al. (2022), 'Global maps of cropland extent and change show accelerated cropland expansion in the twenty-first century'.
60 Tyukavina, A. et al. (2022), 'Global Trends of Forest Loss Due to Fire From 2001 to 2019', *Frontiers in Remote Sensing*, 3, https://doi.org/10.3389/frsen.2022.825190.
61 UNEP (2022), *Spreading like Wildfire: The Rising Threat of Extraordinary Landscape Fires*, Nairobi: UNEP, https://www.unep.org/resources/report/spreading-wildfire-rising-threat-extraordinary-landscape-fires.

Box 2. Indigenous communities and marginalized land stewards

Often lost in the discussion of land-use pressures, and of the potential scaling up of climate and nature-positive solutions, are the roles and rights of the communities and individuals who actually use the land. Especially in developing countries, historic land appropriations have resulted in high state ownership of land and tenure conditions that are contested, overlapping and insecure. In the 36 most forested countries, accounting for around 85 per cent of the world's forests, national governments have statutory ownership of around 60 per cent of lands.[62] Governments have official control of about a third of the forested area in Latin America, about two-thirds in Asia and virtually all of the forests in Africa.[63] This matters because people with communal or unclear land tenure may be displaced if governments launch forest carbon sequestration efforts,[64] or if lands are sold to foreign investors.

Some 12 per cent of people in low-income countries live on tropical forest land with restoration potential.[65] Communities that work on the land have often fulfilled stewardship roles for generations, and depend on local resources for food, fuel and grazing. Such areas often also have cultural value as indigenous homelands. Despite the important role played by indigenous peoples and local communities in protecting forests and nature, only a small proportion enjoy secure rights to own, manage and control land and resources, or have access to the support and services required to protect forests and nature and pursue sustainable livelihoods.[66]

Through exclusion from decision-making processes that seek to provide scalable solutions to land pressures, local communities are also at risk of having their livelihoods undermined and of missing out on new financial opportunities. Where financial incentives are introduced, these may reveal the extent and complexity of weak tenure arrangements that have previously been overlooked.[67] Evidence from existing forest carbon projects shows that, without adequate safeguards, the primary financial benefits may accrue to foreign investors, domestic power elites, and local elites given special access rights to lands from which communities have otherwise been displaced.[68]

If local communities are not consulted in the planning of sustainable land-use projects, then decisions are likely to be made remotely by policymakers who may lack understanding of local context. This can create inappropriate expectations. Proposed solutions may lead to resistance and conflict, hampering any initiative's potential positive impact. If scalable solutions to the 'land crunch' are to be successful, equitable and sustainable, and a resource rush averted, then local rights-holders must be consulted and involved in decision-making (see Chapter 9, Recommendation 2d). Insecurities of tenure need to be resolved, and assurances provided that existing livelihoods and

62 Sunderlin, W. D. et al. (2014), 'How are REDD+ Proponents Addressing Tenure Problems? Evidence from Brazil, Cameroon, Tanzania, Indonesia, and Vietnam', *World Development*, 55, pp. 37–52, https://doi.org/10.1016/j.worlddev.2013.01.013.
63 Ibid.
64 Buck, H. J. (2016), 'Rapid scale-up of negative emissions technologies: social barriers and social implications', *Climatic Change*, 139(2), pp. 155–67, https://doi.org/10.1007/s10584-016-1770-6.
65 Erbaugh, J. T. et al. (2020), 'Global forest restoration and the importance of prioritizing local communities', *Nature Ecology & Evolution*, 4(11), pp. 1472–76, https://doi.org/10.1038/s41559-020-01282-2.
66 UK Presidency, UN Climate Change Conference UK 2021 (2021), 'COP26 IPLC forest tenure joint donor statement', 2 November 2021, https://ukcop26.org/cop26-iplc-forest-tenure-joint-donor-statement.
67 Sunderlin et al. (2014), 'How are REDD+ Proponents Addressing Tenure Problems? Evidence from Brazil, Cameroon, Tanzania, Indonesia, and Vietnam'.
68 Buck (2016), 'Rapid scale-up of negative emissions technologies: social barriers and social implications'.

rights will not be compromised.[69] In many cases, community engagement will also necessitate building capacities within local and national governments to strengthen and enforce rights.

There is increasing recognition of these issues in the international community. In 2019, the United Nations Convention to Combat Desertification (UNCCD) adopted a decision inviting 'Parties to ensure that measures to combat desertification, land degradation, and drought are carried out in a non-discriminatory and participatory way so that they promote equal tenure rights and access to land for all, in particular vulnerable and marginal groups'.[70] Another example of international attention to local land rights is the pledge by 14 public and philanthropic donors at the COP26 climate summit in 2021 to commit at least $1.7 billion between 2021 and 2025 to advance the forest tenure rights of indigenous peoples and local communities, and to support their role as guardians of forests and nature.[71] The challenge now is to translate these pledges into transformative action.[72]

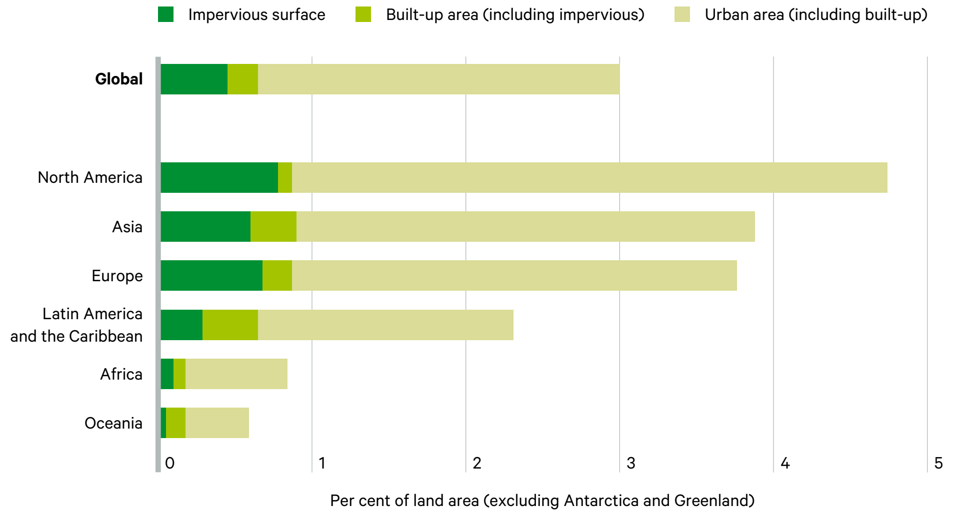
2.3.3 Urban areas and human settlements

Although human settlements and infrastructure account for a small proportion of total land use, this share is growing rapidly as a result of demographic and urbanization trends. Not all urban land is covered with impervious surfaces: beyond built-up areas dominated by human construction, administrative urban spaces can contain significant areas in which vegetation cover (parks and golf courses, for example) dominates. These can make valuable contributions to the biophysical and socio-economic urban environment, such as reducing pollution and heat island effects and providing recreation opportunities for urban dwellers, but nonetheless add to urban sprawl and the fragmentation of broader landscapes.

Although North America has particularly sprawling urban areas, built-up areas account for a slightly larger share of the total land area in Asia (Figure 10).[73] De-densification trends mean that cities are becoming more expansive per head of population, and urban expansion in general is increasingly encroaching on more productive agricultural areas, multiplying the impacts on remaining land availability. Between 2003 and 2019, construction and infrastructure development constituted the second largest driver of gross cropland loss, responsible for 16 per cent of the reduction globally and 35 per cent in Southeast Asia.[74] Urbanization in the present decade (until 2030) is expected to result in the loss of around 2 per cent of global croplands, with around 80 per cent of these losses occurring in Asia and Africa – particular hotspots include eastern China, northeast India, coastal Nigeria, the Egyptian Nile, and an area across the Uganda–Kenya border (Figure 11).[75]

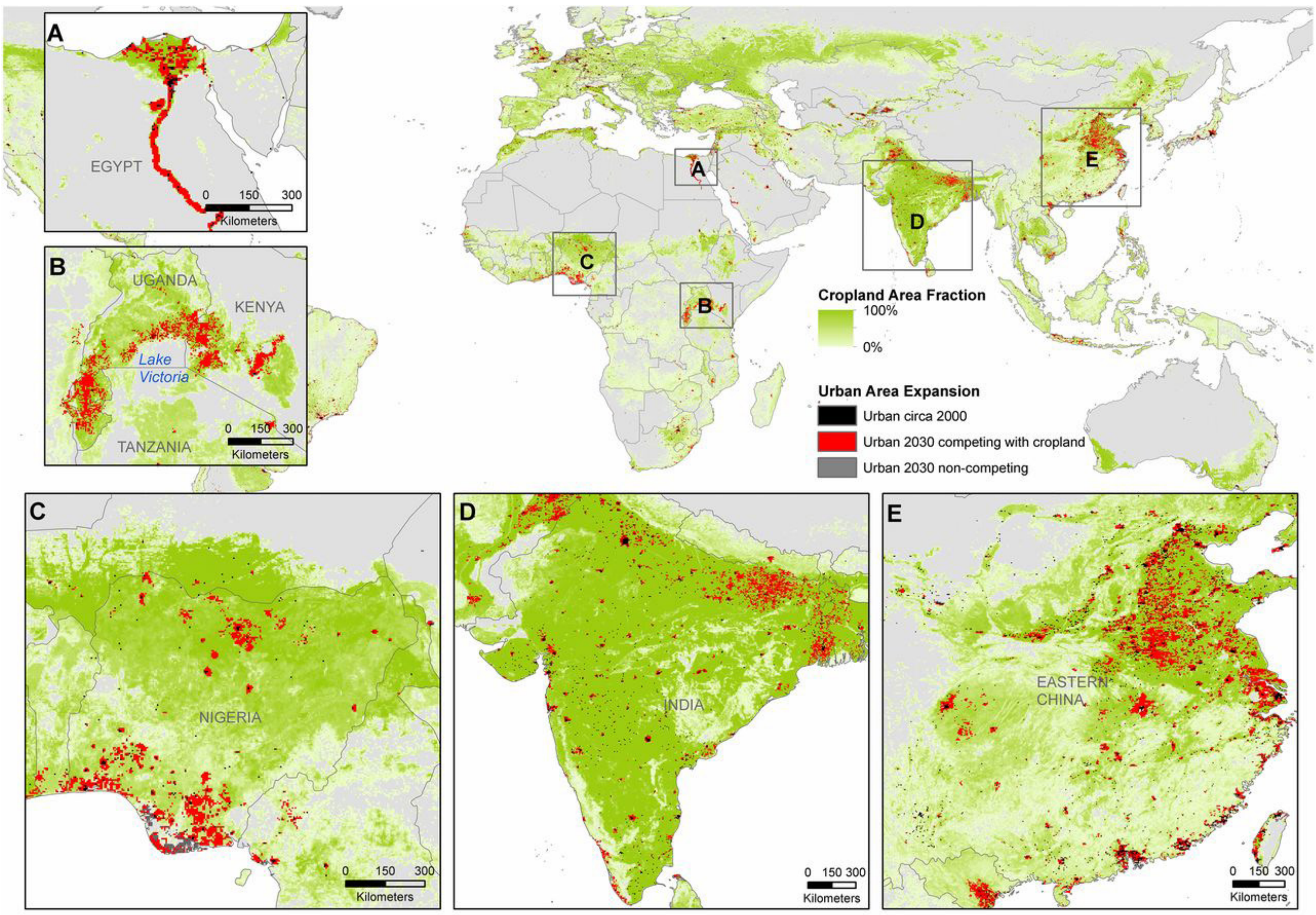
69 Sunderlin et al. (2014), 'How are REDD+ Proponents Addressing Tenure Problems? Evidence from Brazil, Cameroon, Tanzania, Indonesia, and Vietnam'.
70 UNCCD (2019), 'Decision 26/COP.14 on Land tenure', adopted at the 14th meeting of the Conference of the Parties on 13 September 2019, https://www.unccd.int/sites/default/files/sessions/documents/2019-11/26-cop14.pdf.
71 UK Presidency, UN Climate Change Conference UK 2021 (2021), 'COP26 IPLC forest tenure joint donor statement'.
72 Chazarin, F., Kanashiro Uehara, T. and Hoare, A. (2022), 'Why local communities are critical to protecting the world's forests', Chatham House Expert Comment, 18 March 2022, https://www.chathamhouse.org/2022/03/why-local-communities-are-critical-protecting-worlds-forests.
73 Liu, He, Zhou and Wu (2014), 'How much of the world's land has been urbanized, really?'.
74 Potapov et al. (2022), 'Global maps of cropland extent and change show accelerated cropland expansion in the twenty-first century'.
75 Bren d'Amour et al. (2017), 'Future urban land expansion and implications for global croplands'.

Figure 10. Urban land cover hierarchy and respective land takes



Source: Liu, Z., He, C., Zhou, Y. and Wu, J. (2014), 'How much of the world's land has been urbanized, really? A hierarchical framework for avoiding confusion', *Landscape Ecology*, 29 (5), pp. 763–71, https://doi.org/10.1007/s10980-014-0034-y.

Figure 11. Projected urban expansion until 2030 expected to result in cropland loss



Source: Bren d'Amour, C. et al. (2017), 'Future urban land expansion and implications for global croplands', *Proceedings of the National Academy of Sciences*, 114(34), pp. 8939–44, https://doi.org/10.1073/pnas.1606036114.

2.3.4 Sea-level rise

Periodic and permanent seawater encroachments not only directly affect the inundated areas, but also have the potential to force the relocation of people, infrastructure and activities inland, increasing the competition for land.

Prime agricultural lands are also at risk from seawater encroachment, as many such areas and their population concentrations are in coastal regions and river deltas. Such lands are exposed to periodic inundation, salinization and erosion – all phenomena associated with more extreme coastal storms. They are also susceptible to longer-run losses due to sea-level rise. Both rises in sea level and the frequency of extreme storms are expected to be aggravated by climate change. Global mean sea-level rises by the end of this century (half a metre under the middle-of-the-road RCP 4.5 emissions pathway) are expected to be unevenly distributed, with above-average rises occurring predominantly in the southern hemisphere and on the Atlantic coast of North America.[76] Periodic and permanent seawater encroachments not only directly affect the inundated areas, but also have the potential to force the relocation of people, infrastructure and activities inland, increasing the competition for land elsewhere.[77]

2.3.5 Desertification and the remaining land

The remaining 31 per cent of global land classified as 'other' by FAO (Figure 4) is made up of multiple land types that differ vastly in their ecological benefits and availability for human appropriation. In addition to urban areas (discussed above), this category includes lands such as savannahs, covered by shrubs and sparse vegetation, that maintain and restore environmental functions; and areas used for other human activities such as aquaculture. However, the majority of 'other' land, occupying nearly a quarter of the global land surface, is barren (Figure 3). This includes permanent snow and ice, consolidated surfaces such as rocky terrain and hardpans, and unconsolidated bare areas such as sandy deserts.

Some of this barren land is remote, mountainous, inaccessible and of limited potential in terms of human activity – though it is not necessarily devoid of ecological value and often supports fragile ecosystems. Other bare lands have the potential either to be reclaimed with vegetation (such as under the initiative for regreening the Sahel)[78] or to be used for human infrastructure such as settlements, renewable energy generation, or agricultural production under artificial conditions (see Box 3). Significant environmental footprints (increased water consumption, for example) will be associated with such land uses, but in purely spatial terms the land could be said to be 'available'.

Sparsely vegetated marginal lands are at risk from agricultural encroachment as farming spreads or 'extensifies' to meet demand and cope with stagnating yields on existing lands. But if properly managed, these marginal lands could offer sustainable feedstocks for bioenergy and the bioeconomy.

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76 Carson, M. et al. (2016), 'Coastal sea level changes, observed and projected during the 20th and 21st century', *Climatic Change*, 134 (1–2), pp. 269–81, https://doi.org/10.1007/s10584-015-1520-1.
77 Hauer, M. E. (2017), 'Migration induced by sea-level rise could reshape the US population landscape', *Nature Climate Change*, 7(5), pp. 321–25, https://doi.org/10.1038/nclimate3271.
78 Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) (2018), *The IPBES assessment report on land degradation and restoration*, Bonn: Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, https://doi.org/10.5281/zenodo.3237393.

Desertification – land degradation in dryland ecozones, which collectively cover just under half of the global land area and are home to some 3 billion people – reduces agricultural productivity and incomes, causes losses in biodiversity and ecosystem services, and depletes groundwater.[79] The drivers of desertification are multiple and complex. They include cropland and settlement expansion; unsustainable land management; the spread of invasive plants; and climate change-exacerbated phenomena such as droughts, sandstorms and increased evapotranspiration[80] rates. Desertification is undermining the resilience of fragile dryland ecosystems and the people who depend on them. The problem is exacerbated by the typically low capacity of affected communities to adapt to climate change.[81]

Box 3. Putting sparse land to use

As pressure on land resources grows, areas of sparsely vegetated and barren land are increasingly being used or converted for human activities. With careful management and selection, supported by technological advancements, some of this land might be used sustainably. But the fact remains that development can damage sparse land's often fragile ecosystems – which can be slow to recover once disturbed, due to their climate, delicate soils and slow pace of ecological succession.

Efforts to tackle desertification have led to initiatives focused on the regreening of drylands in arid zones. One of the more ambitious projects is the Great Green Wall (GGW) of the Sahara and the Sahel, a pan-African programme with a strong reforestation focus, which aims to restore 100 million ha of degraded land across more than 20 dryland countries by 2030.[82]

Since the project's launch in 2007, progress has generally been slow, with only 15 per cent of the targets reached after a decade; efforts in some countries have been restricted by the poor survival rates of trees, as well as by political and fiscal constraints.

In recognition of the limitations of the initial approach, there has been a recent shift in focus from large tree-planting projects towards working more with local communities to promote low-cost natural regeneration. Early adopters of this technique, such as Niger and Ethiopia, have already seen the transformation of some previously barren landscapes; and such initiatives have in turn enabled the strengthening of social capital through improvements in crop yields and income generation that are helping to alleviate poverty.

Recent innovations in agricultural technology have also allowed previously uncultivable land to be reclaimed for food production. In the United Arab Emirates (UAE), the government-backed development of greenhouse technologies and hydroponic

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79 Mirzabaev, A. et al. (2019), 'Desertification', in Shukla, P. R. et al. (eds) (2019), *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*, Geneva: Intergovernmental Panel on Climate Change (IPCC), https://www.ipcc.ch/srccl/chapter/chapter-3.
80 Evapotranspiration refers to the processes through which water moves from the Earth's surface into the atmosphere, including from soil, vegetation and water bodies on land.
81 Mirzabaev et al. (2019), 'Desertification'.
82 United Nations Convention to Combat Desertification (UNCCD) (2022), 'Great Green Wall Initiative', https://www.unccd.int/our-work/ggwi.

farming has enabled crop cultivation to take place in the harsh desert environment.[83] In a country where up to 90 per cent of food produce is imported, the increasing use of modern agricultural methods offers the potential to improve local food self-sufficiency, although maintaining large-scale production in the desert has proved challenging given the significant input costs.[84] Heavy public subsidies are in place for these projects. There are also rising concerns about the impact of agricultural expansion on the country's non-renewable groundwater sources, which have already suffered a deterioration in water quality and, on current trends, could be depleted within the next few decades.

With the global transition towards low-carbon energy, marginal land is increasingly being used for renewable energy infrastructure, especially in arid regions with recognized high solar insolation and wind resource values. In California, most renewable energy production is generated through large-scale projects in the Mojave and Sonoran deserts. Among such projects is the Ivanpah solar thermal system, which has the capacity to generate electricity for over 140,000 homes. While the state has become a leader in clean energy, this has come at the cost of disrupting the desert's ecosystem and endangering rare endemic species.[85] As the world's largest concentrated solar power (CSP) plant on its completion in 2014, the Ivanpah facility has nearly doubled the amount of solar thermal energy produced in the US. Although criticized for its environmental footprint, the Ivanpah plant has served as a trailblazer in providing information to improve the technical capacity of similar solar projects.[86]

Some areas of barren land in strategic locations may also have the potential to be converted for human habitation. One example is the planned development of the controversial 'mega-city' of Neom in the Saudi Arabian desert. The city is projected to cover over 2.65 million ha of arid terrain, an area nearly equivalent in size to Belgium, and will use advanced low-carbon technologies, including artificial intelligence (AI)-driven systems, with the aim of becoming a global technological hub. While the ambitious project presents opportunities for job creation and economic diversification away from fossil fuels, such a large-scale development in the limited environment of the desert could create extensive resource problems. One estimate suggests that its construction alone could emit more than 1.8 billion tonnes of carbon dioxide. There is significant scepticism that the project's ambitions will be fully realized, although construction of the foundations for one particularly audacious element – 'The Line', a 200-metre-wide, 170-km-long strip bounded on either side by 500-metre-high mirrored walls – started in 2022.[87]

83 Oxford Business Group (2016), *The Report: Abu Dhabi 2016*, https://oxfordbusinessgroup.com/reports/uae-abu-dhabi/2016-report.
84 Nejatian, A. (2016), 'Factors affecting the adoption of soilless production systems in UAE', *International Journal of Agricultural Extension*, 4, pp. 119–31, https://esciencepress.net/journals/index.php/IJAE/article/view/1684.
85 Parker, S. S., Cohen, B. S. and Moore, J. (2018), 'Impact of solar and wind development on conservation values in the Mojave Desert', *PLoS ONE*, 13(12), p. e0207678, https://doi.org/10.1371/journal.pone.0207678.
86 Ballard, B. (2019), 'The unexpected environmental drawbacks of concentrated solar power plants', *The New Economy*, 12 June 2019, https://www.theneweconomy.com/energy/the-unexpected-environmental-drawbacks-of-concentrated-solar-power-plants.
87 Chulov, M. (2022), 'Saudi Arabia plans 100-mile-long mirrored skyscraper megacity', *Guardian*, 27 July 2022, https://www.theguardian.com/world/2022/jul/27/saudis-unveil-eye-popping-plan-for-mirrored-skyscraper-eco-city; Moore, R. (2022), 'Saudi's 100-mile mega-city is meant to blow our minds – so we forget the crimes of its rulers', *Guardian*, 23 October 2022, https://www.theguardian.com/commentisfree/2022/oct/23/saudi-mega-city-meant-to-blow-our-forget-crimes-of-its-rulers; Neom (2022), 'NEOM: Made to Change' https://www.neom.com/en-us.

2.4 Consequences of land use and land-use change

Alongside human-caused climate change, a combination of growing demand for land and consequent changes in, and competition between, land uses is placing mounting pressures on biodiversity, fresh water and ecosystems. The ecosystem services thus threatened include 'provisioning services', such as the supply of food and raw materials; 'regulating services', such as carbon sequestration, flood control and pollination, that keep ecosystem processes in check; 'cultural services' that deliver non-material benefits such as recreation and enjoyment; and 'supporting services', such as nutrient cycling, that maintain the conditions for life on Earth (Table 1).[88]

Table 1. The four forms of ecosystem services threatened by unsustainable land use and land-use change

Provisioning services	Cultural services	Regulating services	Supporting services
Food	Aesthetic value	Air quality regulation	Nutrient cycling
Fresh water	Recreation and ecotourism	Climate regulation	Photosynthesis
Raw materials	Mental and physical health	Water regulation	Soil formation
Medicinal resources	Spiritual and religious value	Erosion regulation	
		Water purification and waste treatment	
		Disease and pest regulation	
		Pollination	
		Extreme event moderation	

Note: Broadly human services are shaded pink and broadly environmental services are shaded green.
Source: WWF (Grooten, M. and Almond, R. E. A. (eds)), (2018), *Living Planet Report 2018: Aiming Higher*, Gland: WWF, https://www.worldwildlife.org/pages/living-planet-report-2018.

2.4.1 Land-use threats to biodiversity

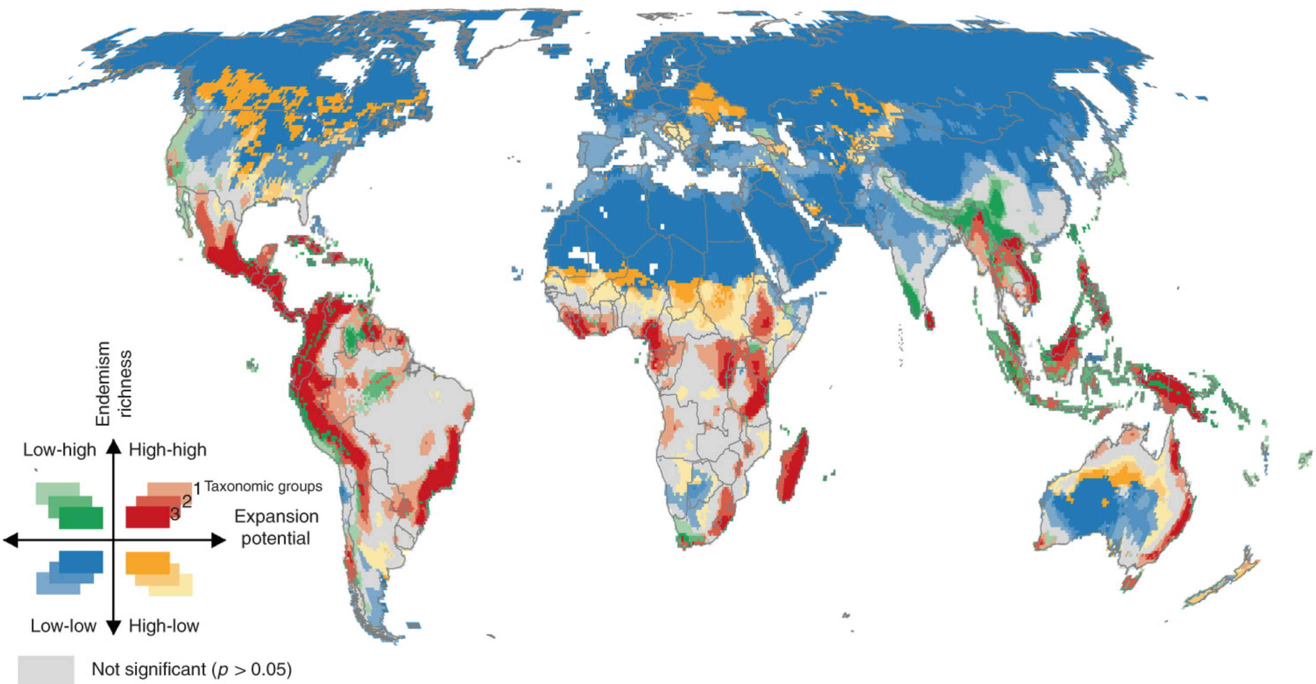
There is mounting evidence that the world is on the cusp of the sixth mass extinction of species, unprecedented in human history and following only five others in the past 540 million years. The latest comprehensive study of the state of the world's biodiversity by the Intergovernmental Science-Policy Platform

88 Millennium Ecosystem Assessment (2005), *Ecosystems and Human Well-being: A Framework for Assessment*, https://www.millenniumassessment.org/en/Framework.html.

on Biodiversity and Ecosystem Services (IPBES),[89] published in 2019, estimates that, in the animal and plant groups assessed, an average of around 25 per cent of species are threatened and that around 1 million species are at risk of extinction – many within the next few decades. This alarming rate of extinction, thought to be at least tens to hundreds of times greater than the average over the past 10 million years, is a direct result of human activity, which has significantly altered more than three-quarters of the land-based environment.

Human-driven environmental change has threatened many aspects of biodiversity, including local richness of species, total abundance of species, and species population sizes – all of which are well below the levels expected. According to the 2019 IPBES assessment, the average abundance of native species in most major land-based habitats has already fallen by at least 20 per cent, mostly since 1900.[90] The quality of habitats that support this biodiversity has also declined, with a 30 per cent reduction in global terrestrial habitat integrity[91] caused by habitat loss, fragmentation and deterioration.[92] Ecosystems are moving closer to critical thresholds that, if crossed, will result in persistent and irreversible environmental damage.

Figure 12. Biodiversity threats from agricultural expansions



Note: Areas under greatest threat are marked in red. Areas marked in yellow have low biodiversity; an expansion of agricultural land in these regions would therefore mean less biodiversity loss.
Source: Zabel, F. et al. (2019), 'Global impacts of future cropland expansion and intensification on agricultural markets and biodiversity', *Nature Communications*, 10(1), p. 2844, https://doi.org/10.1038/s41467-019-10775-z.

89 IPBES (2019), *Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*, Bonn: Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, https://doi.org/10.5281/zenodo.3831673.
90 Ibid.
91 As measured by the Biodiversity Habitat Index, a composite measure to assess global progress in reducing habitat losses for plants, vertebrates and invertebrate species.
92 IPBES (2019), *Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*.

The main driver of global biodiversity degradation has been land-use change, primarily the conversion of native habitats for agriculture, forestry, urbanization or infrastructure development. In particular, the rapid pace of agricultural expansion into environmentally fragile 'hotspots', especially in tropical regions, is considered one of the greatest threats to biodiversity.[93] Most studies indicate that South America, Australia and parts of Asia are at particular risk (Figure 12), although biodiversity losses have been sustained in all climate zones and on every continent. Climate change is likely to amplify the impacts of habitat degradation and pollution, leading to shifts in species distribution and disrupting interactions between species.

Biodiversity decline is not only an environmental issue: it also has profoundly negative economic, social and ethical consequences. Land degradation and biodiversity decline are adversely affecting the well-being of at least 3.2 billion people, and are estimated to cost more than 10 per cent of gross world product in lost ecosystem services.[94] Action to halt and reverse biodiversity loss needs to be scaled up dramatically and quickly.

A new post-2020 framework, the Kunming-Montreal Global Biodiversity Framework (GBF), was agreed at the 15th meeting of the Conference of the Parties (COP15) to the Convention on Biological Diversity (CBD) in late 2022.[95] This presents a critical opportunity to bring about the transformative changes needed to ensure biodiversity conservation and sustainable growth (see Chapter 6, Box 13). The new framework commits parties to a set of goals and targets to end biodiversity loss. Target 3 has received particular attention for its potential to galvanize action, and has been compared with the Paris Agreement's 1.5°C temperature target. Commonly referred to as '30×30', it calls on countries to ensure that at least 30 per cent of terrestrial, inland water, and coastal and marine areas are conserved by 2030. The GBF also aims to mobilize at least $200 billion of nature funding per year by 2030 from all sources – domestic, international, public and private. This target includes at least $30 billion per year by 2030 of international finance flows from developed countries to developing countries.[96]

93 Zabel, F. et al. (2019), 'Global impacts of future cropland expansion and intensification on agricultural markets and biodiversity', *Nature Communications*, 10(1), p. 2844, https://doi.org/10.1038/s41467-019-10775-z.
94 IPBES (2018), *The IPBES assessment report on land degradation and restoration*.
95 The second, substantive part of CBD COP15 took place in Montreal, Canada under China's presidency in December 2022, following an initial online event in October 2021.
96 Convention on Biological Diversity (2022), 'COP15: Nations adopt four goals, 23 targets for 2030 in landmark UN biodiversity agreement', press release, 19 December 2022, https://www.cbd.int/article/cop15-cbd-press-release-final-19dec2022.

Box 4. Land-use threats to water security

Forests and wetlands together supply three-quarters of the world's fresh water, so changes to land use in these areas increase the risks to water security.[97] An estimated 80 per cent of the world's population lives with high levels of threats to water security,[98] and 4 billion people (nearly half of them in India and China) live under conditions of severe water scarcity for at least one month a year.[99] Areas with high population density, heavily irrigated agriculture, and increasing urbanization and industrialization are particularly at risk, as are naturally arid areas (Figure 13).[100] Urban expansion and agricultural intensification are major drivers of surface water and aquifer depletion.[101] Agriculture accounts for 70 per cent of global freshwater withdrawals,[102] while industrial processes in mining, geothermal energy, waste disposal, hydraulic fracturing (fracking) and underground construction are all heavy users of water.[103]

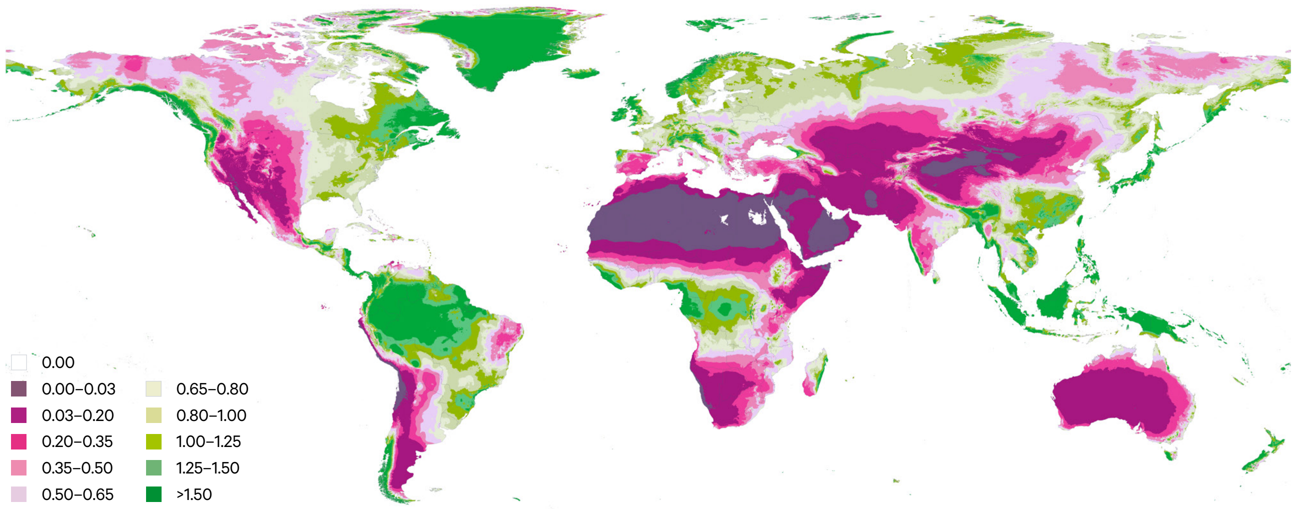
While groundwater use has plateaued in North America, Europe, North Africa and parts of South Asia and China, it is rising across much of sub-Saharan Africa, Latin America and Southeast Asia.[104] Of the world's seven largest aquifers, five are found in Asia and are overexploited.[105] Global domestic water use has increased by almost 400 per cent since 1950.[106] Forecasts indicate that a further 50–250 per cent increase is likely by 2050,[107] the result of growing populations and urbanization. By mid-century, cities in North America, South America, South Asia, East Asia, southern Africa and the northwest Pacific are expected to experience severe urban surface-water deficits.[108]

Of course, neither the drivers of land and biodiversity degradation nor their consequences are always confined to the original locations in which they occur. They often form a part of broader dynamics, either in the same landscape (causing downstream flooding, for example) or at planetary scales through teleconnections to economic and Earth system processes elsewhere in the world. How any tract of land is used, preserved or restored is therefore clearly a matter of concern to groups of individuals, organizations and nation states far beyond its immediate

97 IPBES (2019), *Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*.
98 Ibid.
99 Mekonnen, M. M. and Hoekstra, A. Y. (2016), 'Four billion people facing severe water scarcity', *Science Advances*, 2(2), https://doi.org/10.1126/sciadv.1500323; Gaddis, E. et al. (2019), 'Freshwater', in UN Environment (ed.) (2019), *Global Environment Outlook – GEO-6: Healthy Planet, Healthy People*, Cambridge: Cambridge University Press, https://doi.org/10.1017/9781108627146.
100 Ibid.
101 Gaddis et al. (2019), 'Freshwater'.
102 FAO (2011), *The State of the World's Land and Water Resources for Food and Agriculture (SOLAW): Managing Systems at Risk*, Rome: FAO and London: Earthscan, http://www.fao.org/3/i1688e/i1688e.pdf.
103 Gaddis et al. (2019), 'Freshwater'.
104 Shah, T. (2014), *Groundwater Governance and Irrigated Agriculture*, Stockholm: Global Water Partnership, https://www.gwp.org/globalassets/global/toolbox/publications/background-papers/gwp_tec_19_web.pdf.
105 UNEP (2016), *GEO-6 Regional Assessment for West Asia and the Pacific,* Nairobi: UNEP, http://wedocs.unep.org/bitstream/handle/20.500.11822/7668/GEO_West_Asia_201611.pdf.
106 Flörke, M. et al. (2013), 'Domestic and industrial water uses of the past 60 years as a mirror of socio-economic development: A global simulation study', *Global Environmental Change*, 23(1), pp. 144–56, https://doi.org/10.1016/j.gloenvcha.2012.10.018.
107 Wada, Y. et al. (2016), 'Modeling global water use for the 21st century: the Water Futures and Solutions (WFaS) initiative and its approaches', *Geoscientific Model Development*, 9(1), pp. 175–222, https://doi.org/10.5194/gmd-9-175-2016.
108 Flörke et al. (2013), 'Domestic and industrial water uses of the past 60 years as a mirror of socio-economic development'.

boundaries – in other words, to stakeholders excluded from the particular ownership arrangements that govern its use. And as different tracts of land support different ecosystems embodying or providing different services, values, qualities, sizes, rarities, vulnerabilities and spatial configurations, so the pressures on these lands and the constituencies that depend on them for marketable or public goods (such as food provision, carbon storage) vary across space and time.[109]

Figure 13. Global aridity index



Note: Greens represent more humid conditions, purples and pinks represent higher aridity.
Source: CGIAR-CSI (2022), 'Global Aridity Index and Potential Evapotranspiration Climate Database v3', https://cgiarcsi.community/2019/01/24/global-aridity-index-and-potential-evapotranspiration-climate-database-v3.

Countries vary in their natural capital and land management practices, and this creates complex cross-border interdependencies. Some countries depend almost entirely on foreign land for their provisioning requirements. Ecologically richer countries may find their own interests at odds with those of countries that depend on, or otherwise place value in, the global common resources of which these better-endowed countries are custodians. These dynamics, and their geopolitical implications, are considered further in Chapters 7 and 8 of this report.

2.5 Redistributing global land resources

The vast geographic variations in land types, uses and qualities mean there are strong motivations and justifications for redistributing land-based resources through global trade, foreign direct investment, large-scale land acquisitions and other transfer mechanisms. At best, such an approach maximizes comparative advantages between countries and regions, so that those with abundant natural capital can sustainably provide goods to countries and regions with lands less suited to producing particular resources, and can be appropriately remunerated for doing so. For example, arid countries typically use food imports as a means

109 Lafortezza, R. and Chen, J. (2016), 'The provision of ecosystem services in response to global change: Evidences and applications', *Environmental Research*, 147, pp. 576–79, https://doi.org/10.1016/j.envres.2016.02.018.

of circumventing local water scarcity,[110] while the participation of low-income countries in food trade – both exporting and importing – typically improves the affordability of nutrients available to their own populations.[111]

But at worst, the mechanisms of redistribution can result in unsustainable exploitation and expropriation of lands, driven by consumption that is physically dislocated from the site of impact. In such instances, it is all too easy for market participants to be unaware of, or unconcerned with, the harmful environmental and social impacts of their consumption. This may be particularly the case where historical colonial demarcation of borders and appropriation of lands have resulted in long-established trading relationships. In such cases, colonizing powers may not only have proved instrumental in determining the extent and richness of lower-income countries' lands, but may have subsequentially exploited those lands for their own benefit.

On a global net basis, many of the per capita benefits (from a capital investment, consumption, and final demand perspective) that come from land in lower-income countries are transferred to beneficiaries in higher-income countries – through food trade, for example.[112] Looked at from the perspective of capital investment, a median square metre of land can be said to contribute more to people *outside*, not inside, the country where that land is located.[113]

The environmental and social impacts of such arrangements can be severe, particularly where the exploited land is in countries with high rates of land-use change, unsustainable farming practices and weak governance – or where broad failures and lack of capacity in political, economic and civic institutions undermine citizens' rights. Familiar examples of activities associated with damaging impacts include the export-oriented production of palm oil in Indonesia, where an estimated 18 per cent of new plantations between 2010 and 2015 displaced rainforest;[114] beef farming in Brazil, where livestock production, especially cattle ranching, drives expansion of pastures into the Amazon rainforest;[115] and timber production in Papua New Guinea, where illegal logging is a major problem.[116]

Traded goods (manufactures as well as foods and fibres) are often measured in terms of the 'embodied' land area required for their production. From this perspective, a very significant proportion of land is at least partially embodied in international trade, with forested land more likely than croplands or pastures to be tied to the consumption of manufactured goods and services (Figure 14).[117]

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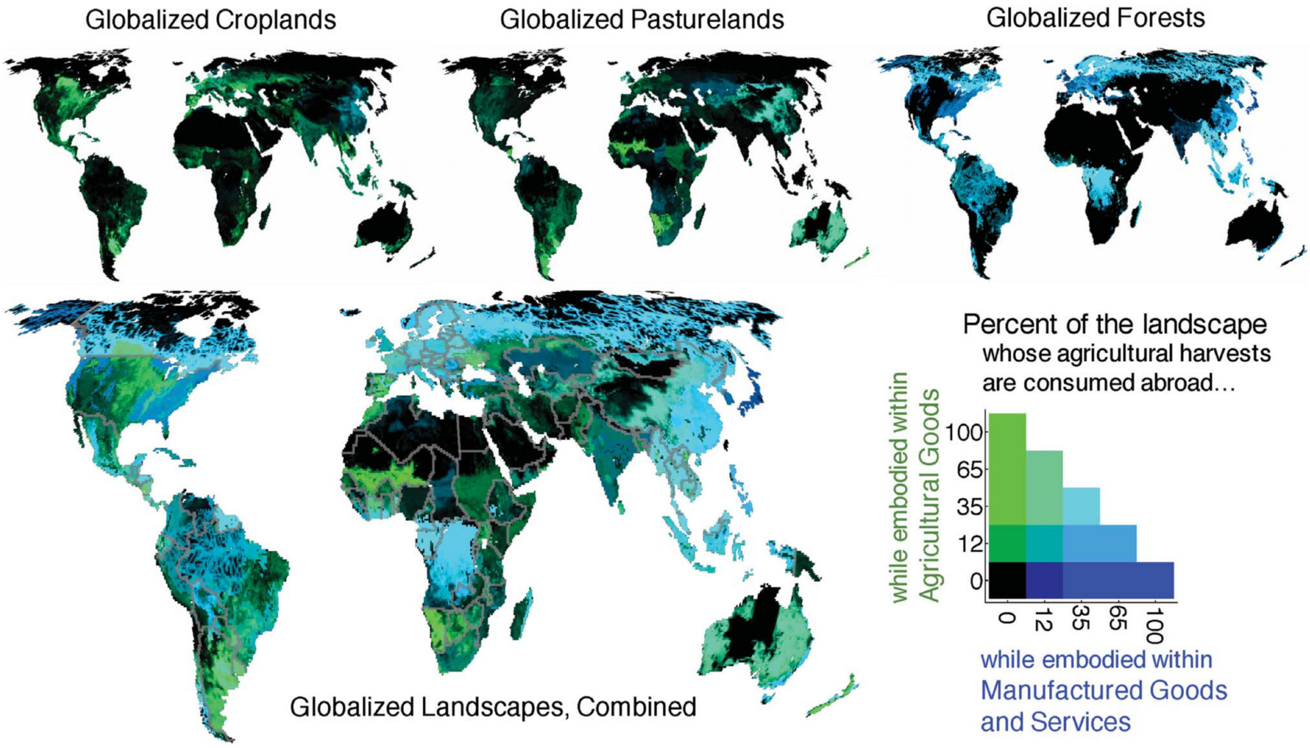
110 Delbourg, E. and Dinar, S. (2020), 'The globalization of virtual water flows: Explaining trade patterns of a scarce resource', *World Development*, 131, p. 104917, https://doi.org/10.1016/j.worlddev.2020.104917.
111 Traverso, S. and Schiavo, S. (2020), 'Fair trade or trade fair? International food trade and cross-border macronutrient flows', *World Development*, 132, p. 104976, https://doi.org/10.1016/j.worlddev.2020.104976.
112 Bergmann, L. and Holmberg, M. (2016), 'Land in Motion', *Annals of the American Association of Geographers*, 106(4), pp. 932–56, https://doi.org/10.1080/24694452.2016.1145537.
113 Ibid.
114 Austin, K. G. et al. (2017), 'Shifting patterns of oil palm driven deforestation in Indonesia and implications for zero-deforestation commitments', *Land Use Policy*, 69, pp. 41–48, https://doi.org/10.1016/j.landusepol.2017.08.036.
115 Müller-Hansen, F. et al. (2019), 'Can Intensification of Cattle Ranching Reduce Deforestation in the Amazon? Insights From an Agent-based Social-Ecological Model', *Ecological Economics*, 159, pp. 198–211, https://doi.org/10.1016/j.ecolecon.2018.12.025.
116 Chatham House (2022), 'What are the trends in forest governance?', Chatham House Forest Governance and Legality, https://forestgovernance.chathamhouse.org.
117 Bergmann and Holmberg (2016), 'Land in Motion'.

Figure 14. Relative roles played by agricultural commodities versus manufactures and services in globalizing lands



Source: Bergmann, L. and Holmberg, M. (2016), 'Land in Motion', *Annals of the American Association of Geographers*, 106(4), pp. 932–56, https://doi.org/10.1080/24694452.2016.1145537.

2.6 Mounting pressures

The picture painted in this chapter is one of globally mounting pressures that seriously challenge the capacity of land to sustain global ecological and social well-being in the long run. Although the essential challenges are ubiquitous, the specific distributions of land resources and patterns of land use are highly heterogeneous across latitudes and borders. Physical and political geography – the latter sometimes also shaped by historical colonial control and the drawing of borders by foreign powers – may have determined each country's land resources, but each nation's management of its resources is of global consequence, potentially affecting international trade, geopolitics and planetary health.

As already signalled, these dynamics are the principal subject of Chapters 7 and 8 of this report, which examine land's role as a strategic resource. First, however, Chapters 3–6 examine in more detail the three principal factors that will determine the scale and scope of future land pressures, outlining how these competing pressures could worsen a 'land crunch'.

03 Land and climate pressures

Land use is at the centre of many potential solutions for reducing greenhouse gas emissions, removing carbon dioxide from the atmosphere and boosting resilience to natural disasters. But the window of opportunity in which to realize many of these benefits is closing rapidly.

3.1 Introduction

The evolution of global land use and the stability of the global climate are inextricably entwined. As demand grows for land to provide food, bioenergy and other bioeconomy products, so too do the imperatives to reduce greenhouse gas emissions from agriculture and land-use change (principally deforestation), and to make better use of land to adapt to a changing climate. If climate change and the risks of breaching environmental tipping points (Box 5) are to be minimized, rapid and dramatic emissions reductions on their own will not suffice: a diverse and widespread portfolio of actions to protect and enhance land's ability to sequester carbon will also be needed. The problem is that this objective is in direct competition with many other land uses.

This chapter considers the current state of land use-related emissions and carbon sequestration, the challenges of various approaches to increasing terrestrial carbon capture, and how these approaches can be best managed to support – and avoid undermining – other ecosystem services and land uses. The tensions between competing land-use objectives will only be manageable if action is urgently taken to reduce economy-wide emissions and land-use requirements, so that reliance on carbon dioxide removal (CDR) can be restricted to approaches appropriate to the socio-environmental and ecological conditions of the specific locations in which such technologies are deployed.

Box 5. Climate change tipping points and land use

As global temperatures rise, the risk of breaching critical thresholds within the Earth system increases. Such a breach could trigger abrupt and self-perpetuating changes that may increase temperatures further and, in turn, create an unmanageable cascade of climate effects.[118] Examples of such effects include permafrost thawing, tropical and boreal forest dieback, disruption of the Atlantic Meridional Overturning Circulation (AMOC), melting of the Arctic summer sea ice, and collapse of the Greenland and Antarctic ice sheets. In recent years, worrying signs have emerged that the thresholds for the Greenland ice sheet,[119] the AMOC[120] and the Amazon rainforest[121] are fast approaching.

Dieback of the Amazon forest would not only emit a huge pulse of greenhouse gases into the atmosphere; it would transform weather and climate in many breadbasket regions, with serious implications for global agriculture.

Individually, each trigger event might have major consequences for land use. For example, large-scale tropical deforestation is, through various teleconnections, likely to affect mid-latitude regions. Dieback of the Amazon forest would not only emit a huge pulse of greenhouse gases into the atmosphere; it would transform weather and climate in many breadbasket regions, with serious implications for global agriculture.[122] A collapse of the AMOC could alter weather patterns in Western Europe, Central and South America, India and sub-Saharan Africa, with catastrophic impacts on agriculture – such as a 30 per cent decline in European cereal yields, a 10 per cent decline in Indian rice yields, or the cessation of agriculture in large parts of the Sahel.[123]

But because many of these elements act on others and accelerate greenhouse gas emissions, there is the possibility of successive events activating runaway dynamics. For example, melting of the Greenland ice sheet could trigger a weakening of the AMOC, in turn contributing to more rapid melting of the Antarctic ice sheet, leading to sea-level rise and warmer oceans. These changes could influence atmospheric circulation patterns, contributing to Amazon rainforest dieback and increases in atmospheric carbon. At the same time, melting ice and warmer oceans might trigger the release of large quantities of methane, a potent greenhouse gas, stored in sub-sea sediments.

In sum, unchecked climate change has the potential to alter the land system profoundly, rapidly and irreversibly, with calamitous implications for land's provisioning capability, not least food production. Although such outcomes are unlikely over the course of the current century, the possibility of their occurring cannot be discounted. Scientists have suggested that, if global temperatures increase more than 2°C relative to pre-industrial levels, the risk of cascading effects will become non-trivial as, at this level of warming, the activation of multiple and in many cases mutually reinforcing tipping elements could ultimately lead to a 'hothouse Earth' scenario. Global temperatures have already risen by about 1.1°C since the pre-industrial era;[124] even on a Paris-compliant emissions

118 Steffen, W. et al. (2018), 'Trajectories of the Earth System in the Anthropocene', *Proceedings of the National Academy of Sciences*, 115(33), pp. 8252–59, https://doi.org/10.1073/pnas.1810141115.
119 Boers, N. and Rypdal, M. (2021), 'Critical slowing down suggests that the western Greenland Ice Sheet is close to a tipping point', *Proceedings of the National Academy of Sciences*, 118(21), https://doi.org/10.1073/pnas.2024192118.
120 Boers, N. (2021), 'Observation-based early-warning signals for a collapse of the Atlantic Meridional Overturning Circulation', *Nature Climate Change*, 11(8), pp. 680–88, https://doi.org/10.1038/s41558-021-01097-4.
121 Boulton, C. A., Lenton, T. M. and Boers, N. (2022), 'Pronounced loss of Amazon rainforest resilience since the early 2000s', *Nature Climate Change*, 12(3), pp. 271–78, https://doi.org/10.1038/s41558-022-01287-8.
122 Lawrence, D. and Vandecar, K. (2015), 'Effects of tropical deforestation on climate and agriculture', *Nature Climate Change*, 5(1), pp. 27–36, https://doi.org/10.1038/nclimate2430.
123 Benton, T. G. et al. (2017), *Environmental tipping points and food system dynamics: Main Report*, Swindon: UK Global Food Security Programme, https://www.foodsecurity.ac.uk/publications/environmental-tipping-points-food-system-dynamics-main-report.pdf.
124 World Meteorological Organization (2022), 'WMO update: 50:50 chance of global temperature temporarily reaching 1.5°C threshold in next five years', 9 May 2022, https://public.wmo.int/en/media/press-release/wmo-update-5050-chance-of-global-temperature-temporarily-reaching-15°c-threshold.

pathway (RCP 2.6), the likelihood of exceeding 2°C approaches 40 per cent in the second half of this century. On a business-as-usual pathway (RCP 8.6), the probability exceeds 50 per cent within the first half of the century; and for all pathways other than RCP 2.6 it exceeds 80 per cent towards the end of the century.[125]

3.2 Land-based emissions and sequestration today

3.2.1 Emissions from agriculture, forestry and other land uses

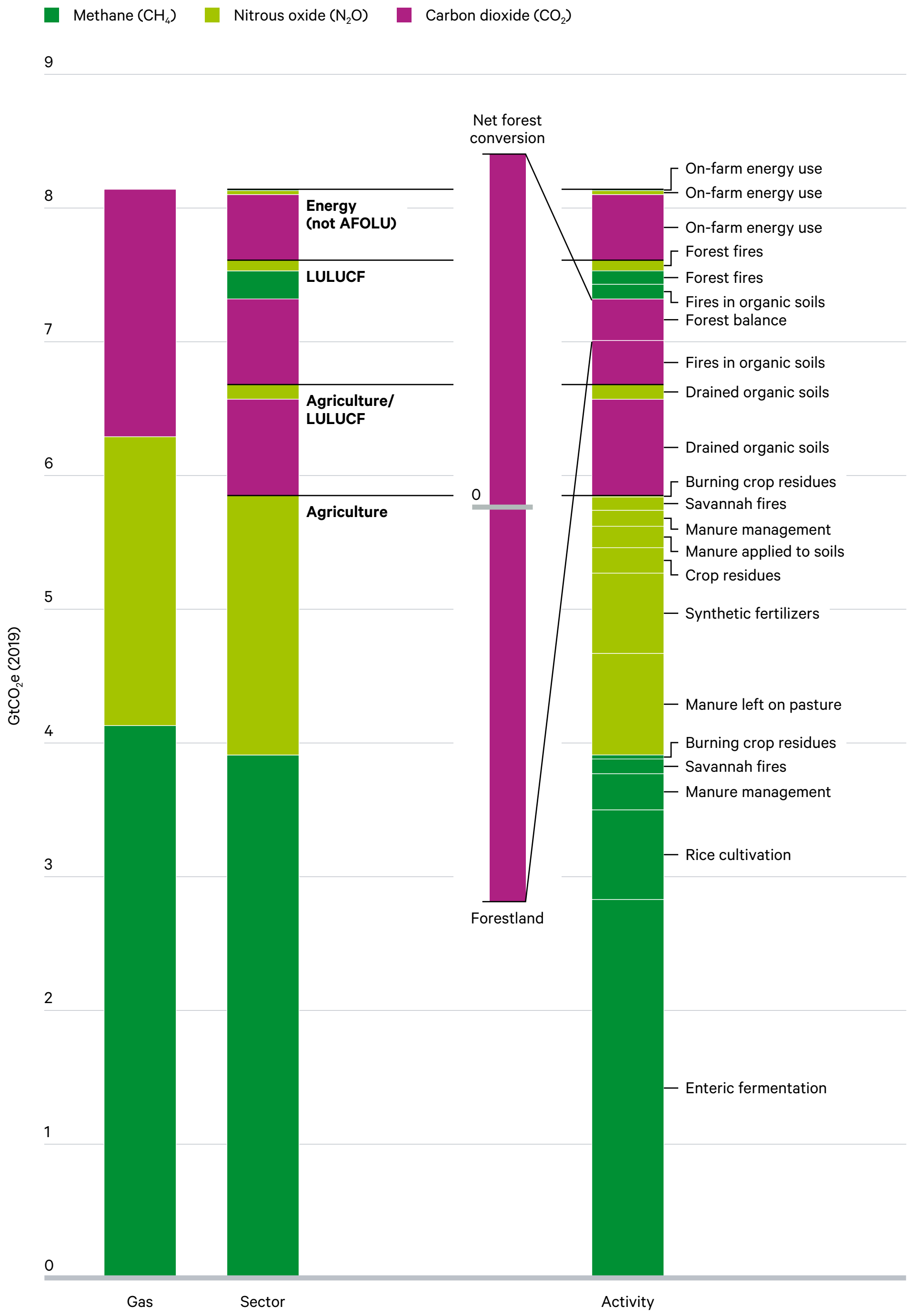
Greenhouse gas emissions from agriculture, forestry and other land uses (AFOLU) currently account for just under a quarter (23 per cent) of all anthropogenic (i.e. human-caused) emissions. Around 11 per cent of emissions are from forestry and other land uses (FOLU) and another 12 per cent are generated by agriculture (excluding energy use by the sector). Emissions from the global food system,[126] including from non-AFOLU pre- and post-production activities, account for around a third of all human-caused emissions, with around a tenth of all anthropogenic emissions coming from non-AFOLU activities such as fertilizer production, food processing, packaging, transport, retail, consumption and waste disposal.[127] The emissions, across all stages in the food system, associated with food that is ultimately lost and wasted similarly make up around 10 per cent of all human-caused emissions.[128]

Which *types* of gases are emitted by particular land-use sectors is also significant, as around two-thirds of AFOLU emissions are of methane (CH_4) and nitrous oxide (N_2O). Both are more potent greenhouse gases than carbon dioxide (CO_2) but also much more short-lived, remaining in the atmosphere for 10–100 years compared with thousands of years for carbon dioxide (see Box 6).

Carbon dioxide accounts for the vast majority (around 90 per cent) of non-agricultural land-use emissions: in non-agricultural contexts, only the burning of biomass generates methane and nitrous oxide. However, the latter two gases account for virtually all *agricultural* emissions: methane (55–65 per cent of the total) is emitted predominantly from enteric fermentation by livestock and from rice cultivation, while nitrous oxide (35–45 per cent) comes mainly from manure and synthetic fertilizers (Figure 15).

125 Collins, M. et al. (2013) 'Long-term Climate Change: Projections, Commitments and Irreversibility', in Stocker T. F. et al. (eds) (2013), *The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge and New York: Cambridge University Press.
126 Land-based agriculture only – excludes emissions from fisheries; includes emissions from non-food agriculture.
127 Tubiello, F. N. et al. (2022), 'Pre- and post-production processes increasingly dominate greenhouse gas emissions from agri-food systems', *Earth System Science Data*, 14(4), pp. 1795–1809, https://doi.org/10.5194/essd-14-1795-2022; and FAO (2022), 'Emissions shares', https://www.fao.org/faostat/en/#data/EM/visualize (accessed 1 Jun. 2022). Also see Crippa, M. et al. (2021), 'Food systems are responsible for a third of global anthropogenic greenhouse gas emissions', *Nature Food*, 2(3), pp. 198–209, https://doi.org/10.1038/s43016-021-00225-9.
128 Intergovernmental Panel on Climate Change (IPCC) (2019), 'Summary for Policymakers', in Shukla, P. R. et al. (eds) (2019), *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*, Geneva: IPCC, https://www.ipcc.ch/srccl/chapter/summary-for-policymakers.

Figure 15. Agriculture and land-use change emissions by source and gas



Note: AFOLU = agriculture, forestry and other land use; LULUCF = land use, land-use change and forestry. AFOLU and LULUCF are categories of activities defined by the IPCC in the context of emissions accounting. The AFOLU category includes LULUCF and agriculture.
Source: FAO (2022), 'FAOSTAT > Emissions Totals', https://www.fao.org/faostat/en/#data/GT (accessed 1 Jun. 2022).

Together, agriculture (especially livestock farming) and the burning of biomass are responsible for around half of all human-caused methane emissions.[129] Unlike carbon dioxide, atmospheric concentrations of methane are now rising

129 Ibid.

faster than at any other time over the past two decades – driven by agriculture and waste, especially in Asia, and by fossil fuel production.[130] Since 2013, global methane concentrations have been above the levels projected by all bar the most greenhouse-gas-intensive climate scenarios.[131] But, given the short-lived atmospheric residence of methane (around 10 years), reducing these land-sector methane emissions offers significant and rapid mitigation potential: currently available measures could reduce methane emissions by as much as 45 per cent by 2030 (see also Box 6), making a cost-effective contribution towards reaching Paris targets.[132] Action would need to be accompanied by effective efforts to reduce carbon dioxide emissions from land use, reduce methane leaks from fossil fuel facilities and increase carbon sequestration.

Box 6. Methane and nitrous oxide: relative impacts

Global warming potential (GWP) is a widely used measure for equating the climate impacts of different greenhouse gases to volumes of carbon dioxide emissions, presented in comparable units of carbon dioxide equivalence (CO_2e).

However, this measure does not fully reflect the long-term temperature effects of different gases, as they have different atmospheric residence periods. Methane has a GWP 28 times that of carbon dioxide over 100 years (i.e. 1 tonne of methane equates to 28 tonnes of CO_2e), but methane only remains in the atmosphere for around a decade after emission. Nitrous oxide has a 100-year GWP 265 times that of carbon dioxide, and typically remains in the atmosphere for around a century.[133]

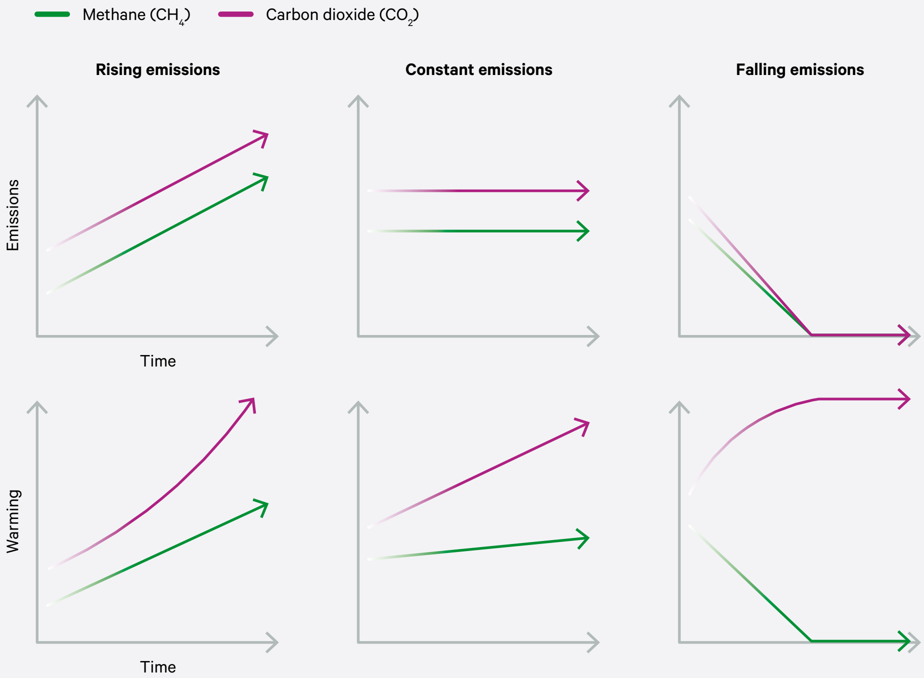
As a measure, GWP masks the fact that short-lived gases, such as methane from agriculture, have a strong warming influence immediately after emission, but very little impact after a century as they are no longer present in the atmosphere, whereas emissions of an equivalent volume of carbon dioxide continue to contribute to warming for centuries at the same rate as when first released. The relationship between emissions and warming responses for carbon dioxide is fundamentally different from that for methane (Figure 16).

As an illustration, a decommissioned fossil-fuelled power station that *previously* emitted carbon dioxide has a warming impact similar to that from a stable cattle herd with consistent methane emissions. When the power station was operating, it increased global temperatures (Figure 16, column 1); it now has a stable contribution to warming (column 3). When the cattle herd was being established and the number of cattle was increasing, its emissions also raised global temperatures (column 1); but now livestock levels in the herd are constant, so too is the contribution to warming (column 2).

130 Global Carbon Project (2020), 'Global Methane Budget 2020', https://www.globalcarbonproject.org/methanebudget/20/presentation.htm; Jackson, R. B. et al. (2020), 'Increasing anthropogenic methane emissions arise equally from agricultural and fossil fuel sources', *Environmental Research Letters*, 15(7), p. 071002, https://doi.org/10.1088/1748-9326/ab9ed2.
131 Global Carbon Project (2020), 'Global Methane Budget 2020'.
132 United Nations Environment Programme (UNEP) (2021), *Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions*, Nairobi: UNEP, https://www.unep.org/resources/report/global-methane-assessment-benefits-and-costs-mitigating-methane-emissions.
133 United States Environmental Protection Agency (2022), 'Understanding Global Warming Potentials', https://www.epa.gov/ghgemissions/understanding-global-warming-potentials; IPCC (2019), 'Summary for Policymakers', in Shukla et al. (eds) (2019), *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*.

In other words, emission of the same amount of additional methane into the atmosphere each year (equivalent to the same amount of additional carbon dioxide being emitted each year from the closed power station) is no longer increasing global temperatures. But sustained decreases in methane emissions by reducing the herd size would contribute to future cooling (column 3).

Figure 16. The different relationships between emissions and warming responses for carbon dioxide and methane



Source: Oxford Martin School (2022), *Climate metrics for ruminant livestock*, Oxford: University of Oxford, https://www.oxfordmartin.ox.ac.uk/downloads/reports/ClimateMetricsforRuminentLivestock_Brief_July2022_FINAL.pdf.

An alternative measure, what has been termed GWP*, has been proposed to better capture these non-equivalent impacts between greenhouse gases. GWP* would express *changes in non-carbon dioxide emission rates* in terms of tonnes of carbon dioxide, or 'carbon dioxide forcing-equivalence' (CO_2-fe). This would more accurately indicate the varying impacts of emissions of long-lived and short-lived pollutants on radiative forcing and temperatures over different timescales. It would also provide a more just basis for taxing non-carbon dioxide emissions: the cattle farmer would not be penalized for maintaining the herd (just as the closed power station is not taxed), but would be taxed for establishing a new herd – or, conversely, rewarded for destocking.[134] However, the proposed GWP* measure has attracted some criticism,

134 In reality, the actual temperature changes associated with methane are slightly greater than indicated by GWP* because this proposed metric ignores warming due to climate–carbon cycle feedbacks from methane emissions, which result in more prolonged temperature impacts than suggested by residence times alone. See Cain, M. (2018), 'A new way to assess "global warming potential" of short-lived pollutants', Carbon Brief, 7 June 2018, https://www.carbonbrief.org/guest-post-a-new-way-to-assess-global-warming-potential-of-short-lived-pollutants; Allen, M. R. et al. (2018), 'A solution to the misrepresentations of CO_2-equivalent emissions of short-lived climate pollutants under ambitious mitigation', *npj Climate and Atmospheric Science*, 1(1), p. 16, https://doi.org/10.1038/s41612-018-0026-8; Reisinger, A. (2018), *The contribution of methane emissions from New Zealand livestock to global warming*, New Zealand Agricultural Greenhouse Gas Research Centre, https://www.pce.parliament.nz/media/196482/contribution-of-methane-emissions-from-nz-livestock-to-global-warming.pdf.

as it has been used by the livestock industry to downplay the impacts of large but stable herds in high-income countries when compared with much smaller, but growing, herds in lower-income countries: in effect, this gives the large established herds an inequitable advantage as a result of their historic pollution.[135]

Ultimately, more methane in the atmosphere results in more heating, the rapid growth in methane emissions needs reversing, and the gas's short residence time affords a near-term opportunity to quickly decelerate and reverse global heating and improve the chances of remaining within Paris Agreement temperature targets. This is an opportunity that urgently needs to be grasped: a recent UN global assessment shows that human-caused methane emissions could be reduced by up to 45 per cent this decade, which would avoid nearly 0.3°C of global heating by 2045.[136]

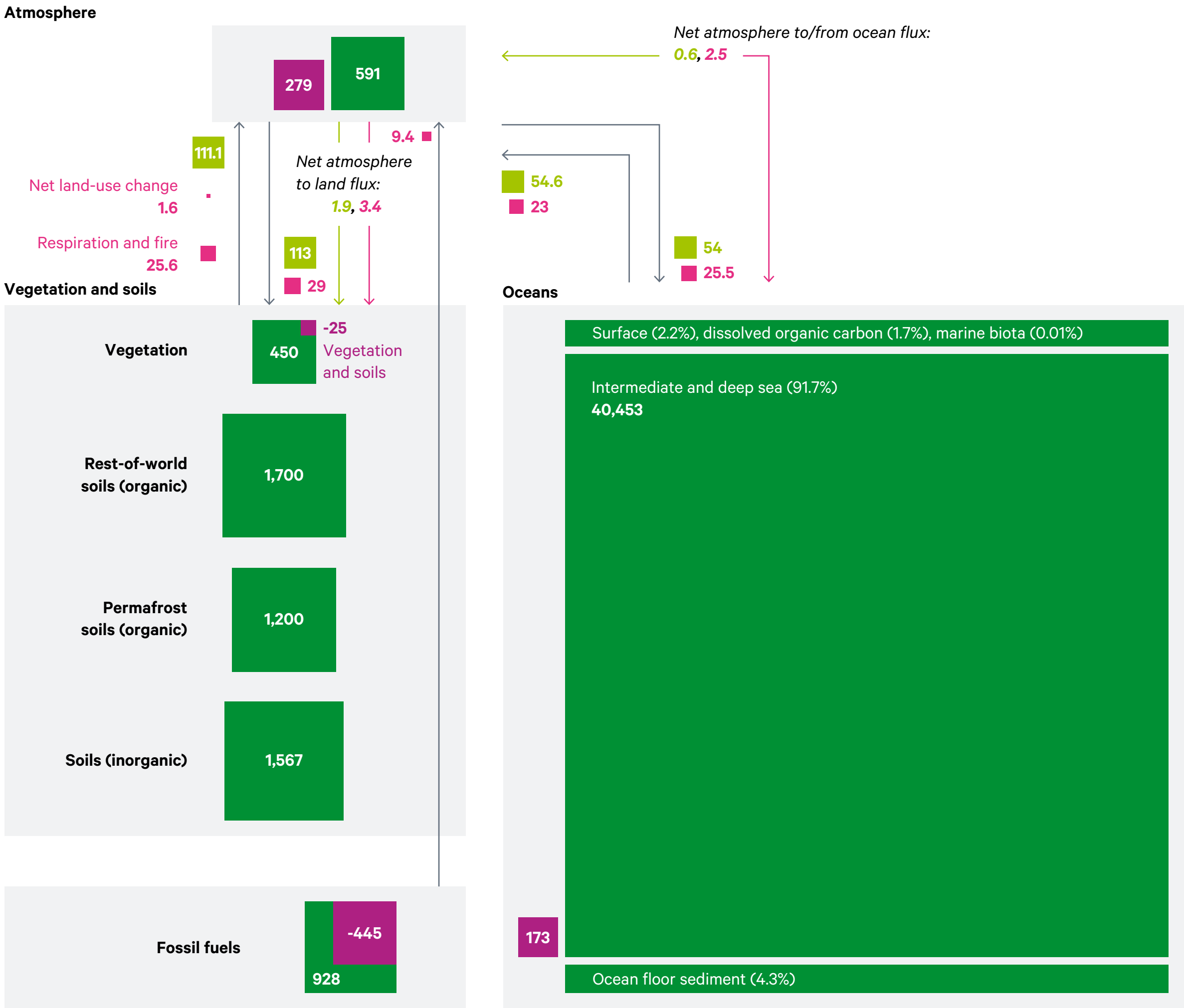
3.2.2 Sequestration and land carbon stores

Land is a huge repository of carbon, which is stored both in vegetation and in soils. Vegetation on the land's surface contains the equivalent of around half of all carbon in the atmosphere,[137] but the soil carbon content is even greater: 2.4 to 3.5 times more carbon than is contained in the atmosphere is stored as soil organic carbon (SOC),[138] and a further 1.8 times more carbon is stored as soil inorganic carbon (SIC) (Figure 17).[139]

Soils that are rich in organic carbon (including fresh plant remains, humus and charcoal) are strongly associated with biodiversity, water cycling, agricultural productivity, and climate change mitigation and adaptation benefits.[140] Inorganic mineral carbon is the dominant form of soil carbon in desert climates, and is generally less vulnerable to land-use changes than are SOC and carbon stored in vegetation.[141]

135 Elgin, B. (2021), 'Beef Industry Tries to Erase Its Emissions With Fuzzy Methane Math', Bloomberg, 19 October 2021, https://www.bloomberg.com/news/features/2021-10-19/beef-industry-falsely-claims-low-cow-carbon-footprint?srnd=green.
136 UNEP (2021), *Global Methane Assessment*.
137 Mean estimates of 450 GtC in vegetation compared with 870 GtC (≈ 3,200 $GtCO_2$) in the atmosphere.
138 Up to around 3,000 GtC according to estimates in Sanderman, J., Hengl, T. and Fiske, G. J. (2017), 'Soil carbon debt of 12,000 years of human land use', *Proceedings of the National Academy of Sciences*, 114(36), pp. 9575–80, https://doi.org/10.1073/pnas.1706103114; or around 2,000 GtC according to estimates in Batjes, N. H. (2016), 'Harmonized soil property values for broad-scale modelling (WISE30sec) with estimates of global soil carbon stocks', *Geoderma*, 269, pp. 61–68, https://doi.org/10.1016/j.geoderma.2016.01.034.
139 SOC and SIC estimates are for the upper 200 cm of soil. Batjes (2016), 'Harmonized soil property values for broad-scale modelling (WISE30sec) with estimates of global soil carbon stocks', with supplemental materials at https://data.isric.org/geonetwork/srv/eng/catalog.search#/metadata/dc7b283a-8f19-45e1-aaed-e9bd515119bc.
140 Vermeulen, S. et al. (2019), 'A global agenda for collective action on soil carbon', *Nature Sustainability*, 2(1), pp. 2–4, https://doi.org/10.1038/s41893-018-0212-z.
141 Batjes, N. H. (1996), 'Total carbon and nitrogen in the soils of the world', *European Journal of Soil Science*, 47(2), pp. 151–63, https://doi.org/10.1111/j.1365-2389.1996.tb01386.x.

Figure 17. Carbon stocks and annual fluxes, natural and human-caused, to scale

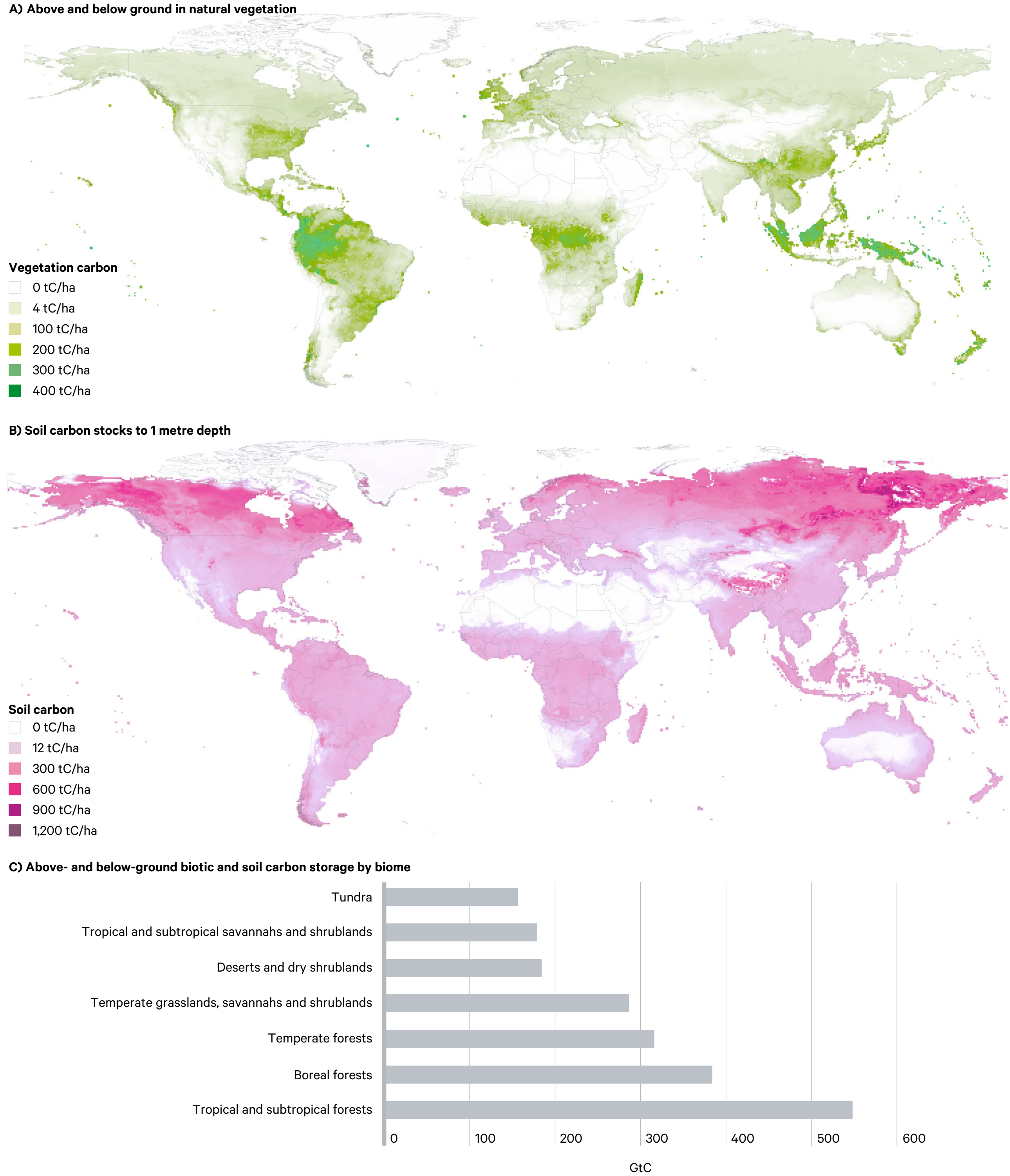


Note: Stocks and transfers associated with the natural carbon cycle, for the time prior to the industrial era, are shown in green. Subsequent anthropogenic changes to stocks are illustrated in dark pink. Average annual anthropogenic fluxes over the period 2010–19 are shown in light pink. Units are gigatonnes (billion tonnes), or petagrams of carbon for stocks and gigatonnes per year for annual fluxes.
Sources: Redrawn based on Figure 5.12 in Canadell, J. G. et al. (2021), 'Global Carbon and other Biogeochemical Cycles and Feedbacks', in Masson-Delmotte, V. et al. (eds) (2021), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge and New York: Cambridge University Press, https://doi.org/10.1017/9781009157896.007; soil inorganic carbon data from Batjes, N. H. (2016), 'Harmonized soil property values for broad-scale modelling (WISE30sec) with estimates of global soil carbon stocks', *Geoderma*, 269, pp. 61–68, https://doi.org/10.1016/j.geoderma.2016.01.034, with supplemental materials, https://data.isric.org/geonetwork/srv/eng/catalog.search#/metadata/dc7b283a-8f19-45e1-aaed-e9bd515119bc.

Deforestation, changes in land use and climate change can all rapidly alter the amount of organic carbon in the upper layers of soil, especially in sensitive biomes such as wetlands and other areas with peaty soils.[142] Where managed effectively, pastures can yield increases in soil carbon, but most land used for agriculture has lost soil organic matter (at a similar scale to losses from deforestation). In absolute terms, a slim majority of such losses have come from grazing lands because these cover more than twice the area of croplands; croplands, though, have lost a greater proportion of their SOC than have grazing lands, due to more intensive farming.[143]

142 Strassburg, B. B. N. et al. (2010), 'Global congruence of carbon storage and biodiversity in terrestrial ecosystems', *Conservation Letters*, 3(2), pp. 98–105, https://doi.org/10.1111/j.1755-263X.2009.00092.x.
143 Sanderman, Hengl and Fiske (2017), 'Soil carbon debt of 12,000 years of human land use'.

Figure 18. Global distribution of organic carbon stocks, 2001–10



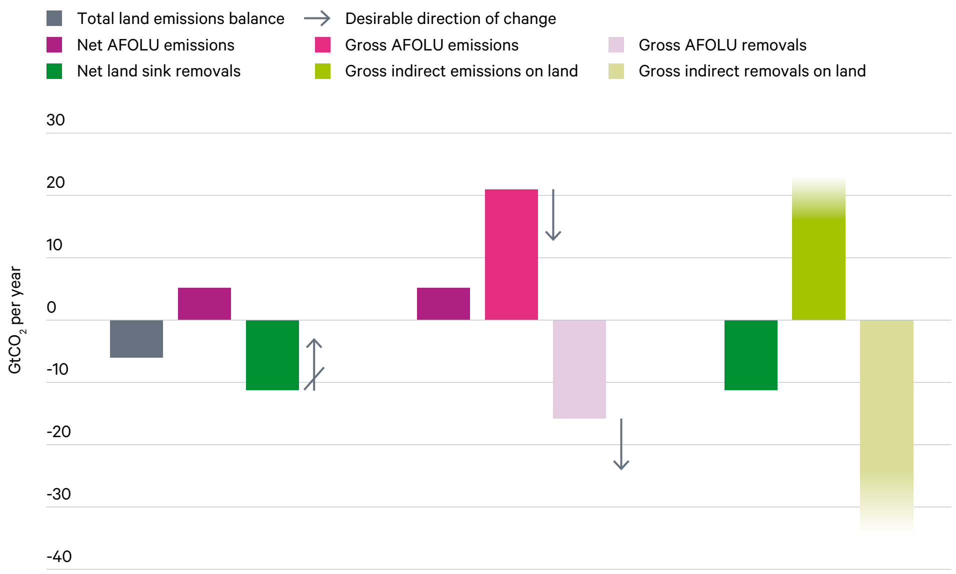
Sources: Soil carbon stocks to 1 metre depth: Searchinger, T. D., Wirsenius, S., Beringer, T. and Dumas, P. (2018), 'Assessing the efficiency of changes in land use for mitigating climate change', *Nature*, 564, pp. 249–53, https://doi.org/10.1038/s41586-018-0757-z and BASE calculations supplement, https://doi.org/10.1594/PANGAEA.893761. Above- and below-ground biotic and soil carbon storage by biome: GRID-Arendal (2015), 'World biomes and carbon storage', https://www.grida.no/resources/6940.

The geographic distribution of terrestrial carbon differs depending on whether it is stored in biomass or in soils. Above- and below-ground biotic carbon (i.e. carbon stored in biomass) is concentrated in the tropics, whereas soil carbon is most abundant in boreal latitudes (Figure 18a and 18b). Combining both, tropical and subtropical forests contain the greatest total amount of carbon of all the world's biomes, followed by boreal and temperate forests (Figure 18c).

3.3 Contemporary challenges

Overall, land is a net sink of carbon dioxide (if natural land-atmospheric fluxes such as photosynthesis uptake and respiration and fire releases are included). However, narrower anthropogenic land *use* (including afforestation and reforestation) remains a net source of *emissions*. Transforming land use from a source to a sink will require drastic reductions in AFOLU emissions (associated with the activities discussed in Chapter 4) and large increases in carbon storage and sequestration (see also Chapter 5). Additionally, existing carbon sinks (especially forests, peatlands, wetlands and natural grasslands) need to be enhanced rather than further depleted (Figure 19).

Figure 19. Net and gross fluxes of carbon dioxide from land (annual averages for 2008–17)



Note: This shows the challenges of turning AFOLU emissions net negative and ensuring existing land sink removals are maintained – land sinks absorbed 29 per cent of all global anthropogenic emissions of carbon dioxide over this period.
Source: Adapted from Figure 2.4 in IPCC (2019), *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*, Geneva: IPCC, https://www.ipcc.ch/srccl. Note uncertainties concerning indirect emissions/removals on land, reflected in the gradients of shading in the relevant bars. Removals over this period were largely due to plant growth, fertilized by rising atmospheric carbon dioxide and nitrogen deposits. Climate change effects such as lengthening growing seasons in northern temperate and boreal areas also contributed to removals. See IPCC (2019), *Climate Change and Land*, Chapter 2 for further details.

Collectively, these mitigation requirements pose significant challenges to many existing land-use practices, especially given the increasing demand for the goods and services that those practices currently provide. Beyond much greater contributions to mitigating climate change, land uses also need to support climate change adaptation responses and efforts to reduce risks from natural disasters. All approaches need to consider not just climate impacts *per se*, but how actions taken can best support ecologies and provide biodiversity benefits.

3.3.1 Turning land-use emissions net negative: carbon dioxide removal

Meeting internationally agreed climate targets will not only require rapid reductions in greenhouse gas emissions – including, notably, from AFOLU – and the preservation of existing carbon stores and sinks. It will also very likely require significant *additional* removals of carbon dioxide from the atmosphere: most climate models suggest global emissions must stabilize and start declining by around 2030, and turn net negative by 2070, to meet the 2015 Paris Agreement's target of keeping global temperature rises to well below 2°C relative to pre-industrial levels.[144] As the majority of the global economy will only be able to achieve carbon neutrality at best, and as some residual sectors will find it impossible to reduce emissions to zero, meeting these objectives will require significant areas of land for sequestration and CDR. Notwithstanding the possibility that this requirement will be tempered to a small extent if novel land-sparing CDR approaches are rapidly scaled up, it is clear that land use as a whole will need to achieve net negative emissions rather than 'just' net zero emissions.

The feasibility and scale of CDR requirements will be determined to a large extent by the residual levels of fossil fuel, industry and agricultural emissions that need to be offset. Mitigation throughout the economy will require the reduction and reshaping of demand for goods and services, efficiency improvements in many areas of daily life, and the electrification and decarbonization of supply-side processes. If mitigation is delayed or insubstantial, then significantly more CDR will be needed. If decarbonization is rapid and expansive, then it will be possible for CDR to play a lesser role. Nonetheless, the vast majority of 1.5°C- and 2°C-compatible emissions pathways in climate scientists' integrated assessment models (IAMs)[145] assume *very significant* deployment of negative emissions technologies (NETs) by the end of the century.

144 Roe, S. et al. (2017), *How Improved Land Use Can Contribute to the 1.5°C Goal of the Paris Agreement*, Amsterdam: Climate Focus, https://nature4climate.org/science/featured-science/test-science-2.
145 IAMs provide a quantitative description of key processes in human and Earth systems and their interactions. They are intended to provide policy-relevant insights into global environmental change and sustainable development issues and are used by the IPCC to assess decarbonization pathways. For further information, see United Nations Climate Change (2022), 'Integrated Assessment Models (IAMs) and Energy-Environment-Economy (E3) models', https://unfccc.int/topics/mitigation/workstreams/response-measures/modelling-tools-to-assess-the-impact-of-the-implementation-of-response-measures/integrated-assessment-models-iams-and-energy-environment-economy-e3-models.

Among the principal NETs included in IAMs is bioenergy with carbon capture and storage (BECCS). This involves burning carbon dioxide-absorbing biofuels, capturing the emissions and storing them in long-term underground reservoirs.[146] Even under the more conservative 2°C scenarios previously elaborated in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), 90 per cent assumed a role for BECCS. And half of all 2°C scenarios relied on BECCS – alongside afforestation and reforestation – to remove at least one-third of all cumulative carbon emissions between now and 2100 (a volume equivalent to over three-quarters of the remaining 2°C carbon budget). Achieving this would require significant proactive use of CDR by around 2030.[147]

BECCS presents considerable difficulties for balancing global land use. The area required for growing additional energy crops implies reduced availability of land for food production, or for preservation as natural habitats.

Under the more recent and ambitious 1.5°C scenarios, reliance on CDR is even more acute and the need for its introduction more urgent. As the IPCC's sixth assessment cycle special report on climate change and land, published in 2019, concluded: 'All assessed modelled pathways that limit warming to 1.5°C or well below 2°C require land-based mitigation and land-use change, with most including different combinations of reforestation, afforestation, reduced deforestation and bioenergy (*high confidence*).'[148]

As discussed in Chapter 5, BECCS presents considerable difficulties for balancing global land use. The area required for growing additional energy crops implies reduced availability of land for food production, or for preservation as natural habitats. Depending on the energy crop used and the efficiency of production, the extent of BECCS deployment suggested by many 2°C scenario models[149] may require the equivalent of anywhere from half to five times the current land area used to grow the world's entire current cereal harvest (720 million ha).[150]

Despite the heavy reliance of IAMs on BECCS, along with afforestation and reforestation, for their modelled greenhouse gas removals, many other CDR approaches – some nature-based, some technological – have the potential to contribute to stabilizing the climate. These options vary considerably in their feasibility, degree of readiness, co-benefits, trade-offs and impacts on land use. Many technological solutions present comparable resource use challenges – for instance, requiring large amounts of energy and water. Nature-based CDR options such as afforestation and reforestation could be similarly expansive in terms of land area needed, and risk being easily reversed at some future date. None of the options offer a panacea or are sufficient on their own, and it is likely that many of them will need to be deployed in some degree.

146 Brack, D. and King, R. (2020), *Net Zero and Beyond: What Role for Bioenergy with Carbon Capture and Storage?*, Research Paper, London: Royal Institute of International Affairs, https://www.chathamhouse.org/2020/01/net-zero-and-beyond-what-role-bioenergy-carbon-capture-and-storage. This section also in part reproduces and adapts material from Brack, D. and King, R. (2021), 'Managing Land-based CDR: BECCS, Forests and Carbon Sequestration', *Global Policy*, 12(S1), pp. 45–56, https://doi.org/10.1111/1758-5899.12827, © 2020 Durham University and John Wiley & Sons Ltd.
147 Anderson, K. and Peters, G. (2016), 'The trouble with negative emissions', *Science*, 354(6309), pp. 182–83, https://doi.org/10.1126/science.aah4567.
148 IPCC (2019), 'Summary for Policymakers', in Shukla et al. (eds) (2019), *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*.
149 Requiring atmospheric removals of 3.3 GtC per year by 2100.
150 Fajardy, M. and Mac Dowell, N. (2017), 'Can BECCS deliver sustainable and resource efficient negative emissions?', *Energy & Environmental Science*, 10(6), pp. 1389–1426, https://doi.org/10.1039/C7EE00465F.

3.3.1.1 Nature-based sequestration solutions

Afforestation and reforestation (AR) – which involve planting new trees and restoring felled or degraded forests – can increase carbon stocks either through rewilding or as part of sustainable forestry operations. For example, marginal lands could be afforested to provide construction timber as a substitute for concrete, creating an additional pool of carbon that would reside in the built environment while forest regrowth sequestered additional carbon.[151] Alternatively, such lands could be reverted to closed-canopy forests to provide long-term carbon sequestration and storage, climate regulation, and other ecosystem services and (potentially) biodiversity benefits. These co-benefits depend on the type of afforestation and reforestation chosen: restoring landscapes to maximize biodiversity and ecological resilience is preferable to developing large-scale homogeneous plantations that may have carbon and timber benefits but less ecological value. The sequestration potential (which comes not only from the trees themselves but also from improving soil quality) is also greater if the lands are restored to natural forest rather than repurposed for mixed uses such as agroforestry, plantations or rotational logging.[152]

As well as providing near-term sequestration, some forms of afforestation will retain the option of providing BECCS feedstocks in the second half of this century, if these are still required. Afforestation and reforestation offer relatively cheap means of delivering negative emissions, with negligible energy requirements. But, depending on how and where they are implemented, they can compete for land and water with food (or biofuel) production, while albedo effects also limit the latitudes at which this strategy is effective:[153] forests are not very reflective of sunlight, and so – especially at temperate and boreal latitudes – often absorb more radiation than alternative land covers do, thereby warming the Earth's surface.[154] Afforestation and reforestation could also have a similar water intensity to that of BECCS. However, unlike with BECCS, the potential for carbon dioxide storage is limited by the fact that trees become saturated with carbon over time if not harvested and replanted.[155] Areas used for afforestation and reforestation are also vulnerable to wildfires and deforestation, with the consequent risk that they could go from being net negative carbon sinks to net positive sources of carbon.[156]

Soil carbon sequestration (SCS) involves increasing soil carbon content through actions such as agroecology, agroforestry, conservation agriculture and landscape management.[157] It has co-benefits for agricultural resilience and productivity, food security, biodiversity, water cycling, and climate change mitigation and

151 Climate Change Committee (2018), *Biomass in a low-carbon economy*, London: Climate Change Committee, https://www.theccc.org.uk/publication/biomass-in-a-low-carbon-economy.
152 Drawing on material in part reproduced and adapted from Brack and King (2021), 'Managing Land-based CDR: BECCS, Forests and Carbon Sequestration', © 2020 Durham University and John Wiley & Sons Ltd.
153 Drawing on material in part reproduced and adapted from Brack and King (2021), 'Managing Land-based CDR: BECCS, Forests and Carbon Sequestration', © 2020 Durham University and John Wiley & Sons Ltd.
154 Davin, E. L. and de Noblet-Ducoudré, N. (2010), 'Climatic Impact of Global-Scale Deforestation: Radiative versus Nonradiative Processes', *Journal of Climate*, 23(1), pp. 97–112, https://doi.org/10.1175/2009JCLI3102.1.
155 Brack and King (2020), *Net Zero and Beyond: What Role for Bioenergy with Carbon Capture and Storage?*.
156 Fuss, S. et al. (2014), 'Betting on negative emissions', *Nature Climate Change*, 4(10), pp. 850–53, https://doi.org/10.1038/nclimate2392.
157 The section on soil carbon sequestration draws on material in part reproduced and adapted from Brack and King (2021), 'Managing Land-based CDR: BECCS, Forests and Carbon Sequestration', © 2020 Durham University and John Wiley & Sons Ltd.

adaptation.[158] Increasing attention is being paid to SCS as a result of the international '4 per 1000' initiative, launched by France when it hosted the 2015 UN Climate Change Conference in Paris (COP21). The initiative aims to increase agricultural soil carbon content at an aspirational rate of 0.4 per cent (2–3 gigatonnes of carbon – GtC)[159] per year. However, the technical and economic feasibility of increasing soil carbon content at the scale envisioned has been called into question. Some argue that the required increase in nitrogen uptake by plants is unrealistic.[160] Others point to a variety of constraints on universal adoption of best management practices; bottom-up estimates of the maximum biophysical potential on cropping and grazing land suggest that around 10–30 per cent (8–28 GtC) of the remaining global theoretical SOC sink potential[161] could be filled.[162] Nonetheless, in particular locations, especially where existing soil carbon content is low, best management practices could achieve an annual increase in SCS of up to 1 per cent for 20 years.[163]

As with afforestation and reforestation, annual increases in SOC will decline as carbon saturates the storage medium (i.e. soils, in this case).[164] Moreover, just as afforestation and reforestation require complementary efforts to halt deforestation, so the potential adoption of SCS will occur in a context in which most agricultural soils are losing rather gaining carbon. If soil carbon losses, such as through peat drainage, are not stemmed, they are likely to negate and outweigh the benefits of increasing soil carbon content elsewhere. Nonetheless, even if the potential of SCS is not as extensive as sometimes suggested, reducing soil carbon losses and increasing SCS offer a relatively low-cost, 'no regrets'[165] means of mitigation with significant co-benefits for soil quality and food security.

Habitat restoration is a closely related solution that aims to restore carbon-dense habitats such as peatlands, and coastal and marine habitats such as salt marshes, mangroves and seagrass beds ('blue carbon habitats'), to increase their absorption of atmospheric carbon dioxide. A recent estimate suggests that habitat restoration approaches, including in woodlands, could compensate for up to a third of the UK's carbon emissions.[166] Because the focus is on the habitat as a whole, such approaches typically support greater biodiversity alongside increased carbon uptake. This in itself can be crucial to maximizing carbon capture – emerging evidence on coastal habitats, for example, suggests a full trophic system[167] with intact predator populations is required to maximize carbon-cycling potential.[168]

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158 Vermeulen et al. (2019), 'A global agenda for collective action on soil carbon'.
159 Lal, R. (2016), 'Beyond COP 21: Potential and challenges of the "4 per Thousand" initiative', *Journal of Soil and Water Conservation*, 71(1), pp. 20A–25A, https://doi.org/10.2489/jswc.71.1.20A; and Minasny, B. et al. (2017), 'Soil carbon 4 per mille', *Geoderma*, 292, pp. 59–86, https://doi.org/10.1016/j.geoderma.2017.01.002.
160 van Groenigen, J. W. et al. (2017), 'Sequestering Soil Organic Carbon: A Nitrogen Dilemma', *Environmental Science & Technology*, 51(9), pp. 4738–39, https://doi.org/10.1021/acs.est.7b01427.
161 88 GtC (323 $GtCO_2$), equating to the recovery of around two-thirds of total SOC losses.
162 Sanderman, Hengl and Fiske (2017), 'Soil carbon debt of 12,000 years of human land use'.
163 Minasny et al. (2017), 'Soil carbon 4 per mille'.
164 European Academies Science Advisory Council (2018), *Opportunities for soil sustainability in Europe*, EASAC policy report, 36, https://easac.eu/publications/details/opportunities-for-soil-sustainability-in-europe.
165 That is to say, with co-benefits that offset implementation costs and without hard trade-offs with other policy objectives.
166 The Wildlife Trusts (2020), *Let Nature Help: How nature's recovery is essential for tackling the climate crisis*, Oxford: The Wildlife Trusts.
167 A full trophic system is one containing organisms in each of the sequential, hierarchical levels in a food chain.
168 Atwood, T. B. et al. (2015), 'Predators help protect carbon stocks in blue carbon ecosystems', *Nature Climate Change*, 5(12), pp. 1038–45, https://doi.org/10.1038/nclimate2763.

Biochar, a charcoal formed from the thermal decomposition of biomass in the absence of oxygen, can be buried in soils to improve soil fertility and increase the carbon saturation limits of soils, as additional carbon is stored in the biochar.

3.3.1.2 Technological solutions

Direct air carbon capture and storage (DACCS) involves capturing carbon dioxide from the atmosphere using a chemical agent and storing the carbon dioxide in underground reservoirs. DACCS is significantly more attractive than BECCS from a land-use perspective, but it is very energy-intensive (so does not feature prominently in cost-optimizing IAMs). That equation may improve for DACCS if carbon-neutral renewable energy becomes abundant, as marginal electricity costs decline, and as DACCS is able to exploit its potential to use surplus electricity generated on a daily basis. Because direct air capture can occur anywhere, there are options to co-locate facilities with cost-effective renewable energy generation and carbon dioxide storage infrastructure (such as saline aquifers). Currently, direct air capture and use technologies can produce synfuels that have the potential to make significant contributions to decarbonizing aviation and maritime transport. Moreover, land-use needs (required primarily for photovoltaic arrays) in such cases would be minimal, in contrast to those for producing first- and second-generation biofuels. But to get to net negative emissions, DACCS installations will require economies of scale that are only likely to materialize with a carbon price upwards of $100 per tonne of carbon dioxide (tCO_2).[169]

Enhanced weathering (EW) takes advantage of the carbon-fixing that naturally occurs in silicate rocks over geological timescales. By pulverizing rocks to massively increase their exposed surface area and then spreading them on agricultural soils, EW enables a vast acceleration in the chemical reactions with air and water that convert carbon dioxide into stable carbonates.[170] Deploying EW on existing croplands, especially when using industrial silicate waste, offers opportunities to improve food and soil security and better align agriculture and climate policy. However, as with other solutions, it also requires appropriate regulatory and incentive frameworks. Scaling deployment could be particularly challenging for EW since it depends on widespread application by many smallholders and requires public acceptance of a balanced trade-off between local mining activities and global carbon sequestration.[171] (See Figure 20 for further details on the costs and benefits of EW.)

169 $100 per tonne is commonly regarded as a threshold for affordability, with solutions realizable under this price regarded as affordable. So, while there is potential for this technology, it is not yet commercially viable at scale without supporting subsidies, given prevailing carbon prices of around $70–80 per tonne.
170 Climate Change Committee (2018), *Biomass in a low-carbon economy*.
171 Beerling, D. J. et al. (2020), 'Potential for large-scale CO_2 removal via enhanced rock weathering with croplands', *Nature*, 583(7815), pp. 242–48, https://doi.org/10.1038/s41586-020-2448-9.

Box 7. Other geoengineering solutions? Solar radiation modification

Solar radiation modification refers to a further suite of technological fixes for addressing rising global average temperatures. These technologies aim to reduce the amount of incoming solar radiation reaching the Earth's surface, or to permit increased levels of infrared radiation to escape from Earth, to reduce temperatures.

Options include releasing sulfate aerosols into the stratosphere, mimicking volcanic eruptions (stratospheric aerosol injection); making artificial and natural land surfaces brighter to reflect solar radiation (ground-based albedo modification – GBAM); seeding clouds above ocean surfaces to reflect sunlight back into space (marine cloud brightening); and cirrus cloud thinning, to allow more infrared radiation to escape from Earth.

These are all being discussed as supplemental measures to large-scale carbon dioxide removal (CDR), as they could temporarily reduce any overshooting of temperature targets.[172] Although they have next to no land footprint (other than GBAM, which could have significant impacts on land use), these forms of geoengineering are highly speculative, with neither the technological track record, established governance arrangements, or sufficient understanding of their impacts on sustainable development or biodiversity[173] to make reliance on them a sensible option.

3.3.2 Sequestration without undermining ecosystems

Given the scale of additional carbon sequestration that needs to be developed in the next couple of decades, and the increasing pressures on existing carbon sinks, there is an inherent tension between managing land uses to achieve climate security and maximizing co-benefits that preserve the viability of other essential land uses, biodiversity and ecosystem services.

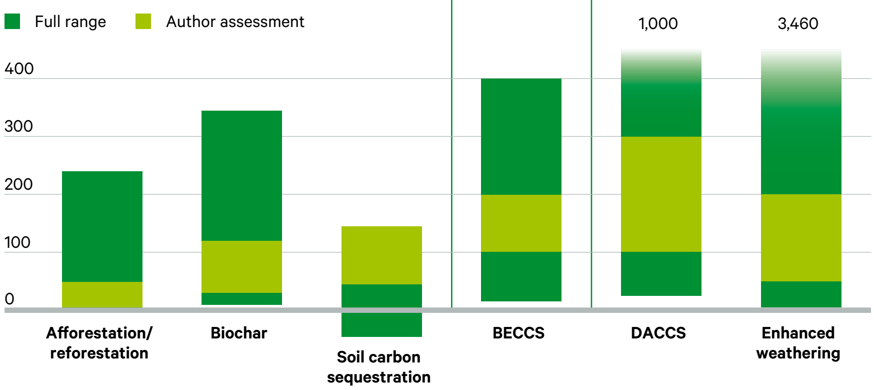
These competing imperatives are not easy to resolve. Developing a sufficient and optimized mix of CDR approaches from environmental, social and economic perspectives will be a substantial challenge, requiring active management and international cooperation. The potential benefits, costs, resource footprints and side effects of the various CDR approaches discussed above are summarized in Figure 20, based on a systematic review of the literature.

172 C2G2 (2018), *Governing Solar Radiation Modification (SRM)*, Carnegie Climate Geoengineering Governance Initiative, https://www.c2g2.net/wp-content/uploads/C2G2_Solar-Brief-hyperlink.pdf; and de Coninck, H. et al. (2018), 'Strengthening and Implementing the Global Response', in Masson-Delmotte, V. et al. (eds) (2018), *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty,* Cambridge and New York: Cambridge University Press, https://doi.org/10.1017/9781009157940.006.
173 Secretariat of the Convention on Biological Diversity (2016), *Update On Climate Geoengineering In Relation To The Convention On Biological Diversity: Potential Impacts And Regulatory Framework*, CBD Technical Series, 84, https://www.cbd.int/doc/publications/cbd-ts-84-en.pdf.

Figure 20. Evidence on land-based carbon dioxide removal (CDR) abatement costs, deployment potentials, and key side effects

	Land-demanding					
	Saturable					
	Afforestation/ reforestation	**Biochar**	**Soil carbon sequestration**	**BECCS**	**DACCS**	**Enhanced weathering**
Deployability and analysis						
Technology readiness level (/10)	8–9	6–7	8–9	5–6	6	3–4
Role in mitigation pathways	Substantial role in IAMs and bottom-up sectoral studies	In development – not in IAM-based global mitigation pathways	In development – not in IAM-based global mitigation pathways	Substantial contribution in IAMs	Complements other CDR methods in a few IAMs	Complements other CDR methods in a few IAMs
Sequestration potential						
Potential sequestration rate by 2050 ($GtCO_2$ y^{-1})[b]	0.5–3.6	0.5–2	2–5	0.5–5	0.5–5	2–4
Potential rate by 2100 ($GtCO_2$ y^{-1})	0.5–7	1–35	0.5–11	1–20+	1–20+	1–27
Cumulative potential by 2100 ($GtCO_2$ y^{-1})	80–260	78–477	104–130	100–1,170	100–1,000+	100–367
Required 2100 annual removals in 2°C scenarios ($GtCO_2$ y^{-1})[c]	4 [12]	–	–	12	12	1 [4]
Saturation and permanence[b]	Saturation of forests; vulnerable to disturbance; post-AR forest management essential	Mean residence times: decades to centuries depending on soil type, management, and environmental conditions	Soil sinks saturate and can reverse if poor management practices were to resume	Long-term governance of storage; limits on rates of bioenergy production and carbon sequestration	Long-term governance of storage	Saturation of soil; residence time from months to geological time scales
Costs						

2050 cost (2011$ per tCO_2)[b] Author judgments (central band) and full range



[a] Assessed by IPCC (2022).
[b] Assessed ranges by Fuss et al. (2018).
[c] Based on 2100 estimate for mean [max] potentials by Smith et al. (2016).

Sources: Compiled from: IPCC (2022), *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge and New York: Cambridge University Press, https://doi.org/10.1787/72a9e331-en; de Coninck, H. et al. (2018), 'Strengthening and Implementing the Global Response', in Masson-Delmotte, V. et al. (eds) (2018), *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*, Cambridge and New York: Cambridge University Press, https://doi.org/10.1017/9781009157940.006;

	Land-demanding					
	Saturable					
	Afforestation/ reforestation	**Biochar**	**Soil carbon sequestration**	**BECCS**	**DACCS**	**Enhanced weathering**
Resource requirements and impacts (2100)[c]						
Total land required (Mha)	320 [970]	–	–	380–700	Very low (unless solar PV used for energy)	2 [10]
Land required (Mha $GtCO_2$ y^{-1})	80	16–100	0	31–58	0	3
Total water required (km^3 y^{-1})	370 [1,040]	–	–	720	10–300	0.3 [1.5]
Water required (km^3 $GtCO_2$ y^{-1})	92	0	0	60	0.8–24.8	0.4
Impact on nutrients (mt N, P, K y^{-1})	0.5	N: 8.2 P: 2.7 P: 2.7	N: 21.8 P: 5.5 K: 4.1	Variable	0	0
Side effects (scale-dependent)						
Air pollution	–	–	–	✗	?	✗
Albedo[c]	✗ (or reduced GHG benefit where not negative)	–	–	Variable, depends on source of biofuel (higher albedo for crops than for forests) and on land management (e.g. no-till farming for crops)	?	–
Biodiversity	✗	–	–	✗	?	–
Ecosystem changes	–	–	–	–	?	–
Food security	✗	✗	✓	✗	?	–
Ground/ water pollution	–	–	–	–	?	✗
Soil quality	✓	✓	✓	–	?	✓
Mining and extraction	–	–	–	–	?	✗
Trace GHGs	–	✓	✗	✗	?	–

✓ Desirable change ✗ Undesirable change – No significant change ? No estimate available

[a] Assessed by IPCC (2022).
[b] Assessed ranges by Fuss et al. (2018).
[c] Based on 2100 estimate for mean [max] potentials by Smith et al. (2016).

Sources (cont.): Morrow, D. R. et al. (2018), *Why talk about carbon removal?*, Washington, DC: American University, https://doi.org/10.17606/M6H66H; Fuss, S. et al. (2018), 'Negative emissions - Part 2: Costs, potentials and side effects', *Environmental Research Letters*, 13(6), https://doi.org/10.1088/1748-9326/aabf9f; and Smith, P. et al. (2016), 'Biophysical and economic limits to negative CO_2 emissions', *Nature Climate Change*, 6(1), pp. 42–50, https://doi.org/10.1038/nclimate2870. A version of this figure first appeared in Brack, D. and King, R. (2021), 'Managing Land-based CDR: BECCS, Forests and Carbon Sequestration', *Global Policy*, 12(S1), pp. 45–56, © 2020 Durham University and John Wiley & Sons Ltd, https://doi.org/10.1111/1758-5899.12827. Modified to include additional deployability and analysis rows.

Some research, however, is more bullish on the potential mitigation contributions to be achieved by a portfolio of nature-based solutions (NBS) that protect intact lands, restore degraded native forests and wetlands, and improve the management of working lands used for crops, grazing and timber.[174] Many NBS can be deployed cost-effectively (at a carbon price of less than $100/tCO_2$) in the near term. Moreover, they could sequester an estimated 10 $GtCO_2$ per year – more than the annual emissions from the global transport sector – by 2025 (see Figures 20 and 21). Most (85 per cent) of this contribution would come from improving existing land management without compromising agricultural yields. However, implementation would have to occur at a massive scale, with NBS used on 2.5 billion ha of land by 2050. To be effective, deployment of NBS would also need to be accompanied by action to stop the destruction of 270 million ha of forests, and to restore 678 million ha of ecosystems (an area more than twice the size of India). By comparison, modelling for BECCS indicates that 380–700 million ha of land would be required for feedstock production by 2100.[175]

Figure 21. Cost-effective nature-based solutions, potential annual mitigation contributions by 2025 ($GtCO_2$ per year)

* Non-CO_2 impacts
Source: Girardin, C. A. J. et al. (2021), 'Nature-based solutions can help cool the planet — if we act now', *Nature*, 593(7858), pp. 191–94, https://doi.org/10.1038/d41586-021-01241-2.

Certainly, there exist significant nature-based sequestration opportunities that, if implemented appropriately (see Box 8), can provide wider environmental and social co-benefits.[176] Strategies such as avoided deforestation, afforestation,

174 Girardin, C. A. J. et al. (2021), 'Nature-based solutions can help cool the planet — if we act now', *Nature*, 593(7858), pp. 191–94, https://doi.org/10.1038/d41586-021-01241-2.
175 Ibid.
176 Bailey, R. and Tomlinson, S. (2016), *Post-Paris: Taking Forward the Global Climate Change Deal*, Briefing Paper, London: Royal Institute of International Affairs, https://www.chathamhouse.org/2016/04/post-paris-taking-forward-global-climate-change-deal.

wetland restoration and soil carbon management offer proven means of sequestering carbon at an affordable cost. These are far from problem-free or complete solutions, however. For example: soils are limited as sinks by saturation levels (even with biochar application); ensuring and verifying that appropriate land management techniques are being implemented is challenging; and many NBS are easily reversible and therefore vulnerable to social, political and economic developments that could change land management or governance arrangements within each country.

Nonetheless, many of these practices appear to have less downside risk than the deployment of NETs on the scale envisioned by some of the Paris-compliant scenarios: BECCS, for instance, relies on carbon capture and storage (CCS) and significant accompanying infrastructure, and is associated with major challenges in sourcing sustainable feedstock, while land-sparing technologies such as DACCS are unproven and reliant on plentiful renewable electricity. According to a comprehensive synthesis of NETs literature: 'Any single NET is unlikely to sustainably achieve the large NETs deployment observed in many 1.5°C and 2°C mitigation scenarios. Yet, portfolios of multiple NETs, each deployed at modest scales, could be invaluable for reaching the climate goals.'[177]

Many nature-based solutions are easily reversible and therefore vulnerable to social, political and economic developments that could change land management or governance arrangements within each country.

A further challenge to mobilizing NBS is securing and sustaining adequate financing. Several governments have introduced economic policies – often under the term 'payments for ecosystem services' (PES) – that incentivize environmentally beneficial land management practices, including those that deliver non-productive outputs, and that compensate stakeholders negatively affected by conservation. By incentivizing better land stewardship, PES schemes enable new actors to play a role in conservation and can also promote reform among incumbents. The approach also promotes a more sustainable relationship between people and nature by emphasizing the value of the ecosystem services that biodiversity supports.

PES approaches can address 'scale mismatches', whereby the benefits of conservation are felt at a regional, national or global scale but where the short-term economic cost is borne by local communities at a smaller scale. And PES can be implemented in innovative ways, such as by reforming subsidy regimes or developing new market mechanisms. One such example involves agricultural producers participating in carbon markets, where they sell offset credits generated by emissions reduction projects. Agriculture is a recognized sector for carbon sequestration under the EU's successful Emissions Trading System, and in the US under the Growing Climate Solution Act; the latter offered measures for farmers to monetize conservation practices and was included in the US omnibus spending act signed into law at the end of 2022.[178] The market for PES is growing: it is currently estimated to be worth around $40 billion a year, including payments from non-governmental and private buyers. Among the largest areas of the market are payments for watershed

177 Minx, J. C. et al. (2018), 'Negative emissions—Part 1: Research landscape and synthesis', *Environmental Research Letters*, 13(6), p. 063001, https://doi.org/10.1088/1748-9326/aabf9b.
178 S&P Global (2022), 'Carbon Farming: Opportunities for Agriculture and Farmers to Gain From Decarbonization', 28 July 2022, https://www.spglobal.com/esg/insights/topics/carbon-farming-opportunities-for-agriculture-and-farmers-to-gain-from-decarbonization; and United States Congress (2022), 'H.R.2617 - Consolidated Appropriations Act, 2023', https://www.congress.gov/bill/117th-congress/house-bill/2617.

management and biodiversity, with most payments for emissions reductions coming from forest projects, including through the REDD+[179] mechanism.[180]

However, the effectiveness of PES schemes is debated. Payments are often low in relation to the opportunity costs associated with other land uses. Outcome-based payments, rather than activity-based payments, are typically more likely to encourage novel and innovative approaches to land management.

Box 8. Growing interest in nature-based solutions – but solutions to what?

There is considerable appetite among policymakers and investors to support the use of nature-based solutions (NBS): two-thirds of signatories to the Paris Agreement on climate change incorporate NBS in their nationally determined contributions (NDCs), with 60 per cent of this subset of countries including NBS in both the mitigation and adaptation components of their NDCs, and 40 per cent including NBS under either mitigation or adaptation.[181]

The NBS Coalition, led by China and New Zealand, now includes 32 countries, along with the European Commission, 21 civil society organizations and eight private sector groups, all of which have signed the 2019 NBS for Climate Manifesto. New sources of funding for NBS were announced at the 2019 UN Climate Action Summit.[182] At the 2021 UN Climate Change Conference (COP26), representatives of 141 countries (collectively accounting for a land area containing 91 per cent of the world's forests) pledged to halt and reverse forest loss and land degradation by 2030.[183]

However, such initiatives and statements of intent rarely translate into measurable, evidence-based targets, and there is no clear roadmap for how private and public finance can be translated and directed into on-the-ground action. As signalled by undertakings such as the Trillion Trees Platform, launched at the 2020 World Economic Forum in Davos, the emphasis is frequently on afforestation and number of trees planted, and the distinction between forests and plantations is often blurred. Planting trees and restoring forests and other degraded ecosystems are important for mitigation, but these activities comprise only one aspect of nature's overall contribution. If measures are limited to the cost-effective near-term areas of potential identified in Figure 21 – which have safeguards for the supply of food and wood-based products, and for biodiversity conservation – then about 20 per cent of the potential carbon savings associated with NBS would be realizable. Restoration needs to focus

179 REDD+ stands for 'Reducing Emissions from Deforestation and Forest Degradation in Developing Countries'. It is a voluntary framework that was developed under the UN Framework Convention on Climate Change to guide activities to this end, as well as to support the sustainable management of forests and the conservation and enhancement of forest carbon stocks in developing countries. First adopted in 2013, REDD+ has since been positioned as an integral element of the Paris Agreement. It is implemented in three phases, starting with the development of national strategies and action plans, followed by implementation, and evolving into results-based actions that should be fully measured, reported and verified, allowing countries to seek and obtain results-based payments from a variety of public, private, bilateral, multilateral and alternative sources. United Nations Climate Change (2022), 'What is REDD+?', https://unfccc.int/topics/land-use/workstreams/redd/what-is-redd.
180 UNEP (2019), *Global Environment Outlook - GEO-6: Healthy Planet, Healthy People*, Nairobi: UNEP, https://www.unep.org/resources/global-environment-outlook-6.
181 Seddon, N. et al. (2020), 'Global recognition of the importance of nature-based solutions to the impacts of climate change', *Global Sustainability*, 3, p. e15, https://doi.org/10.1017/sus.2020.8.
182 Ibid.
183 UN Climate Change Conference UK 2021 (COP26) (2021), 'Glasgow Leaders' Declaration on Forests and Land Use', 2 November 2021, https://ukcop26.org/glasgow-leaders-declaration-on-forests-and-land-use.

on reforesting native diverse forests (rather than on afforestation that introduces alien monocultures) and other ecosystems to promote synergies between mitigation, adaptation and biodiversity.

Often overlooked is the role of 'nature-friendly' farming, which, by the same estimate, could deliver up to 40 per cent of the potential near-term carbon savings from NBS.[184] Achieving the remaining 40 per cent of potential savings, which would come from protecting existing habitats, has become more prominent as a policy issue as a result of the Global Biodiversity Framework agreed in 2022 under the Convention on Biological Diversity (CBD).

If NBS are to deliver positive mitigation and adaptation outcomes, they need to be grounded in context-specific understanding of which actions can best sustain, restore or enhance different ecosystems. Such actions include supporting diversity within ecosystems, ensuring connectivity between ecosystems, and establishing robust social safeguards.[185] Considerable effort is required to align high-level ambition with appropriate, context-specific local action. This means that the science, practitioner, policy and investment communities will need to work together with local communities to clarify what makes NBS effective for people and nature, to determine where and over what spatial and temporal scales investments should be targeted, and to consider how best to ensure the economic viability of investments.

The first-order priority is to protect existing natural habitats that provide adaptation options and that store and sequester carbon. The roles of indigenous peoples and local community leaders are crucial. When their rights are secured, local communities are frequently highly effective defenders and stewards of intact ecosystems and forests.

3.3.2.1 Land-use implications of meeting climate objectives

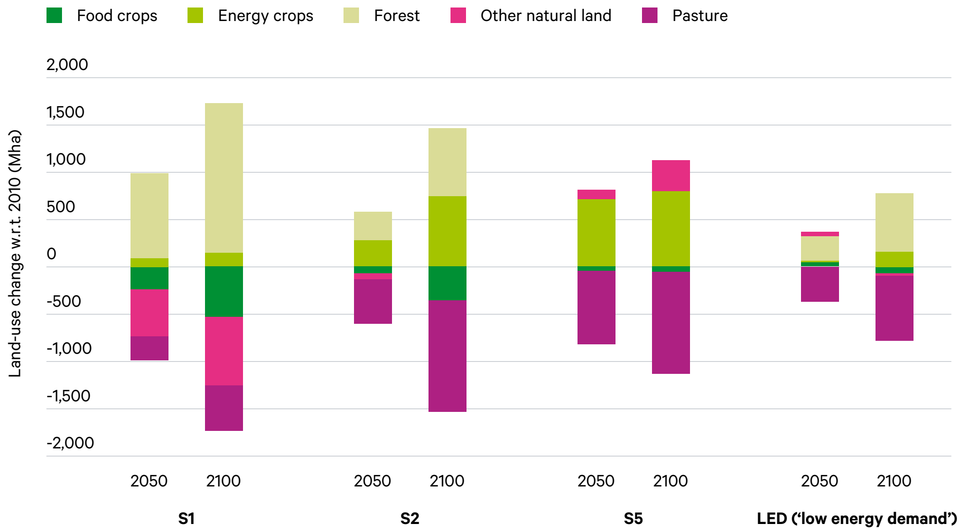
The amount of land required for mitigating climate change is strongly contingent on the speed with which economy-wide emissions reductions can be achieved, and on the precise portfolio of CO_2 removal measures deployed.

The amount of land required for mitigating climate change is strongly contingent on the speed with which economy-wide emissions reductions can be achieved, and on the precise portfolio of CDR measures deployed. The IPCC presents four archetypical emissions pathways compatible with meeting a 1.5°C temperature target, based on differing socio-economic dynamics. Under a non-cooperative high-overshoot archetype (IPCC pathway S5), 724 million ha of energy crops (an area equivalent to well over twice the area of India) would displace pastures (Figure 22). Alternatively, under more progressive archetypes, with limited temperature overshoots and shifts towards healthy and sustainable diets, the additional forest footprint required could be as large as 950 million ha (an area the size of the US) by 2050, necessitating contractions in the footprints of food crops, pastures and other natural land (IPCC pathway S1).[186] Even excluding

184 Girardin et al. (2021), 'Nature-based solutions can help cool the planet — if we act now'.
185 Seddon et al. (2020), 'Global recognition of the importance of nature-based solutions to the impacts of climate change'.
186 Rogelj, J. et al. (2018), 'Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development', in Masson-Delmotte, V. et al. (eds) (2018), *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty,* Cambridge and New York: Cambridge University Press, https://doi.org/10.1017/9781009157940.004.

existing trees, and urban and agricultural areas, it has been suggested[187] – although this is hotly debated[188] – that there is suitable land available (under current climate conditions) for this additional area of canopy cover, with over half the potential present in just six countries (Russia, the US, Canada, Australia, Brazil and China).

Figure 22. Land-use changes in 2050 and 2100 in the IPCC's illustrative 1.5°C-consistent pathway archetypes



Source: Rogelj, J. et al. (2018), 'Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development', in Masson-Delmotte, V. et al. (eds) (2018), *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*, Cambridge and New York: Cambridge University Press, https://doi.org/10.1017/9781009157940.004.

However, the fact of having the biophysical capacity to restore forests or plant energy crops is, in itself, an insufficient – albeit necessary – condition for formulating effective land-use planning decisions. Such decisions, critically, also need to factor in other local social and environmental dynamics, into which global assessments provide only limited insights.[189] For example, monoculture-based reforestation can have negative consequences for biodiversity, carbon storage and water supplies; inappropriate afforestation can increase fire risks and result in wildlife damaging proximal crops; poor governance of restored lands can result in inequitable distribution of costs and benefits, exacerbating economic inequalities.[190] Ultimately,

187 Bastin, J.-F. et al. (2019), 'The global tree restoration potential', *Science*, 365(6448), pp. 76–79, https://doi.org/10.1126/science.aax0848.
188 Science Media Centre (2019), 'Expert reaction to study looking at trees, carbon storage and climate change', 4 July 2019, https://www.sciencemediacentre.org/expert-reaction-to-study-looking-at-trees-carbon-storage-and-climate-change; American Association for the Advancement of Science (2020), 'Erratum for the Report: "The global tree restoration potential" by J.-F. Bastin, Y. Finegold, C. Garcia, D. Mollicone, M. Rezende, D. Routh, C. M. Zohner, T. W. Crowther and for the Technical Response "Response to Comments on 'The global tree restoration"', *Science*, 368(6494), https://doi.org/10.1126/science.abc8905.
189 IPCC (2018), 'Summary for Policymakers', in Masson-Delmotte, V. et al. (eds.) (2018) *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty,* Cambridge and New York: Cambridge University Press, https://doi.org/10.1017/9781009157940.001.
190 Chazdon, R. and Brancalion, P. (2019), 'Restoring forests as a means to many ends', *Science*, 365, pp. 24–25, https://doi.org/10.1126/science.aax9539.

the core challenge associated with reconfiguring global land use to minimize its emissions and maximize its potential as a carbon sink is how to do so in a way that accounts for the other ecosystem services and socio-economic benefits that land supports at local to global scales.[191]

3.3.3 Supporting adaptation and disaster risk reduction

Not only do land-use sectors need to switch rapidly from being sources to sinks of greenhouse gases; land resources must also be managed to provide resilience in the face of climate challenges. This includes protecting and enhancing the role of land resources in preventing and reducing weather-related disasters, addressing climate-related health issues, safeguarding agricultural production and trophic dependencies, providing reliable safe water supplies, and providing a viable haven for people and animals displaced by climate change.

A healthy biosphere and intact (or restored) natural landscapes offer many protections against weather extremes. Benefits include flood control, drought recovery, fire prevention, storm and coastal protections, and improved long-term food and water security.[192] For example, healthy soils have high rainfall infiltration capacities that protect them against being washed away; floodplains and river catchment vegetation naturally dissipate excess run-off to protect against flooding; and forests and vegetation act as natural barriers against floods, storms, landslides and desertification.[193]

However, human-induced changes to land cover and atmospheric compositions are increasing the risks of natural disasters, as well as the economic, social and political costs of recovering from them. Deforestation and loss of native vegetation, for example, have increased the frequency and duration of flooding in many developing countries. In dryland areas with fragile ecosystems, years with extreme low rainfall have been associated with increases in violent conflict.[194]

Sustainable land-use practices can incorporate ecosystem-based adaptation and disaster risk reduction measures such as revegetating and restoring degraded lands, managing floodplains and watersheds, and conserving natural infrastructure. These may not always be as effective as engineered solutions against the most extreme conditions (and in some places may no longer be viable, especially if climate tipping points are breached); they may also require greater land areas, and typically take longer to become effective.[195] Nonetheless, they are generally 'low-regret' options

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191 The National Food Strategy for England was an independent review that recently took such a holistic view of land use in the context of one nation's food system. For further details, see Department for Environment, Food & Rural Affairs (2021), 'National food strategy for England', https://www.gov.uk/government/publications/national-food-strategy-for-england.
192 Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) (2018), *The IPBES assessment report on land degradation and restoration*, Bonn: Secretariat of the IPBES, https://doi.org/10.5281/zenodo.3237393; and United Nations Convention to Combat Desertification (UNCCD) (2017), *The Global Land Outlook*, first edition, https://www.unccd.int/actions/global-land-outlook-glo.
193 Whitmee, S. et al. (2015), 'Safeguarding human health in the Anthropocene epoch: report of The Rockefeller Foundation–Lancet Commission on planetary health', *The Lancet*, 386(10007), pp. 1973–2028, https://doi.org/10.1016/S0140-6736(15)60901-1; and Munang, R. et al. (2013), 'The role of ecosystem services in climate change adaptation and disaster risk reduction', *Current Opinion in Environmental Sustainability*, 5(1), pp. 47–52, https://doi.org/10.1016/j.cosust.2013.02.002.
194 IPBES (2018), *The IPBES assessment report on land degradation and restoration*.
195 Royal Society (2014), *Resilience to extreme weather*, https://royalsociety.org/~/media/policy/projects/resilience-climate-change/resilience-full-report.pdf.

that are much lower in cost and often provide co-benefits, including enhancing climate change mitigation and carbon sequestration and preserving biodiversity and food chains.[196]

Ecosystem-based approaches are also more likely than engineered approaches to protect against multiple hazards, and are less likely to result in maladaptation. The importance of strengthening ecosystem and natural resource management approaches that incorporate disaster risk reduction is recognized by the Sendai Framework for Disaster Risk Reduction (2015–30).[197]

There may be trade-offs between using land to mitigate against climate impacts and using it to adapt to them; but, in general, ensuring that land-based natural capital is as robust as possible and sustainably managed has benefits for mitigation, adaptation and broader resilience.[198]

3.4 Conclusions

Soils, the flora and fauna they support, and how they are managed play a huge role in the planet's carbon, nitrogen and methane cycles. Further destruction and degradation of soil-dependent habitats, and further use of the resources they provide, will inevitably accelerate global heating to an unmanageable degree. Already, it appears virtually certain that avoiding catastrophic climate change will rely on much greater volumes of greenhouse gas removals than at present.

It appears virtually certain that avoiding catastrophic climate change will rely on much greater volumes of greenhouse gas removals than at present. Many of the approaches involved are likely to have significant land footprints.

Many of the approaches involved are likely to have significant land footprints. But the greater the inertia, the greater the jeopardy: the less, and the slower, the mitigation actions taken, the greater the land area needed and the greater the associated risks. Equally, as adverse climate events intensify and become more frequent and less predictable, these same terrestrial ecosystems will be crucial to reducing the vulnerabilities of affected communities. How humanity collectively manages land resources is therefore vital to achieving global climate security and ensuring resilience at community to planetary levels.

As habitats and geographies differ vastly in their natural resources, no universal blueprint can be prescribed. Rather, a portfolio of context-specific approaches will be needed that concurrently sequester more emissions, support lives and livelihoods, and enhance ecosystems. Combining diverse solutions in this way will greatly reduce the negative impacts of large-scale CDR deployment, but it will be challenging both to mobilize resources on the scale necessary and to ensure that approaches are implemented in ways that do more good than harm in the specific locations in which they are deployed.

Integrated national plans that account for climate, nature and the bioeconomy potential of land offer a logical first step, but international efforts will also be required to maximize cross-border comparative advantages in public and private goods and ecosystem services. Each prospective deployment will need to be

196 Whitmee et al. (2015), 'Safeguarding human health in the Anthropocene epoch'.
197 UN Sustainable Development Goals Knowledge Platform (2022), 'Sendai Framework for Disaster Risk Reduction 2015–2030', https://sustainabledevelopment.un.org/frameworks/sendaiframework.
198 UNCCD (2017), *The Global Land Outlook*, first edition.

evaluated holistically against the parameters of a broad and consistent risk-adjusted framework – which should include location-based social and environmental criteria – as well as against calculations of the carbon balances likely to be attainable.[199] Nonetheless, some general principles are discernible:

- First, proactive natural infrastructure planning is required to realize all the benefits of NBS. This means factoring in not just each solution's contribution to mitigating emissions and sequestering carbon, but also its wider potential utility for climate change adaptation, disaster risk reduction, biodiversity preservation and enrichment, and support of livelihoods. In many instances, mitigation benefits may even be secondary to the other opportunities, but climate funds allocated for mitigation may be the most promising and lucrative source of financing. Whatever the funding mechanism, efforts should be made to deploy chosen solutions in reference to holistic objectives that emphasize the maximization of all co-benefits.

- Second, the comparative advantages in terms of sequestration and food, forestry and other land resource production opportunities differ between countries (see Chapter 7). The revenue-generating potential and market value of the options available to each country are equally uneven at present. Estimates suggest that annual biodiversity 'financing gaps'[200] may reach around $700 billion by 2030,[201] and over $4.1 trillion by 2050.[202] Without a step change in public and private investment, it will be extremely challenging to persuade state and private actors to pursue land-use options with the greatest possible environment-regulating benefits if these entail short-term economic opportunity costs. Improved global cooperation and governance frameworks are needed to ensure environmentally 'low-regret' options are prioritized and the requisite financial flows mobilized. Financial mechanisms will need to be bolstered by robust land rights legislation to protect landowners, land users and land with high ecological value, and to reform land rights where ownership and benefits accrue to those benefiting from historical colonial land allocations. This is especially urgent in jurisdictions where land governance is weak, weakly enforced or contested, including where customary tenure arrangements may be vulnerable to being overturned.[203] There is a danger that the scale of large multi-country solutions envisioned will prove unobtainable when faced with the reality of conditions on the ground: nation states may not be as strong, effective or cohesive as imagined, and may meet resistance if landowners or land users are not part of the decision-making process.[204]

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199 This analysis is based on material in part reproduced and adapted from Brack and King (2021), 'Managing Land-based CDR: BECCS, Forests and Carbon Sequestration', © 2020 Durham University and John Wiley & Sons Ltd.
200 The financing gap is the difference between how much is currently spent and how much is needed each year to protect the most important biodiversity and the services it provides.
201 Paulson Institute (2022), *Financing Nature: Closing the Global Biodiversity Financing Gap*, https://www.paulsoninstitute.org/conservation/financing-nature-report.
202 UNEP, World Economic Forum, Economics of Land Degradation Initiative and Vivid Economics (2021), *State of Finance for Nature: Tripling investments in nature-based solutions by 2030*, Nairobi: UNEP, https://www.unep.org/resources/state-finance-nature.
203 Drawing on material in part reproduced and adapted from Brack and King (2021), 'Managing Land-based CDR: BECCS, Forests and Carbon Sequestration', © 2020 Durham University and John Wiley & Sons Ltd.
204 Buck, H. J. (2016), 'Rapid scale-up of negative emissions technologies: social barriers and social implications', *Climatic Change*, 139(2), pp. 155–67, https://doi.org/10.1007/s10584-016-1770-6.

— Third, the window of opportunity in which to maximize the resilience-building climate change mitigation and adaptation contributions of land resources is closing rapidly. Without urgent reductions in emissions, the impacts of climate change on terrestrial carbon stocks are uncertain. Unchecked climate change could reverse carbon sinks by the middle of this century; and if climate tipping points are passed, carbon sinks could even be made impotent in the face of runaway environmental collapse. There are therefore both principled and pragmatic reasons to prioritize the deployment of proven greenhouse gas removal approaches – not least including the preservation of existing carbon- and biodiversity-rich ecosystems – ahead of more speculative technologies. Reforestation and land restoration require almost immediate implementation due to the time needed for them to realize their full sequestration potential. However, this does not mean leaving technological approaches on the shelf: indeed a major scaling-up of activity is required so that research, development, iteration and deployment of promising options can proceed more effectively. Ultimately, both nature-based and technological solutions must be part of the response to the challenges of sustainable land use. This will require significant investment, the development of financial mechanisms and supportive governance arrangements, and the establishment of effective safeguards against unintended land-use changes.

04 Land and agri-food pressures

On current food consumption trends, agricultural output will need to rise dramatically in the coming decades. 'Sustainable intensification' of farming, changes in diets, waste reduction and innovation in food production are all options to limit the resulting unsustainable pressures on land and on the ecosystem services it provides.

4.1 Land use for food production

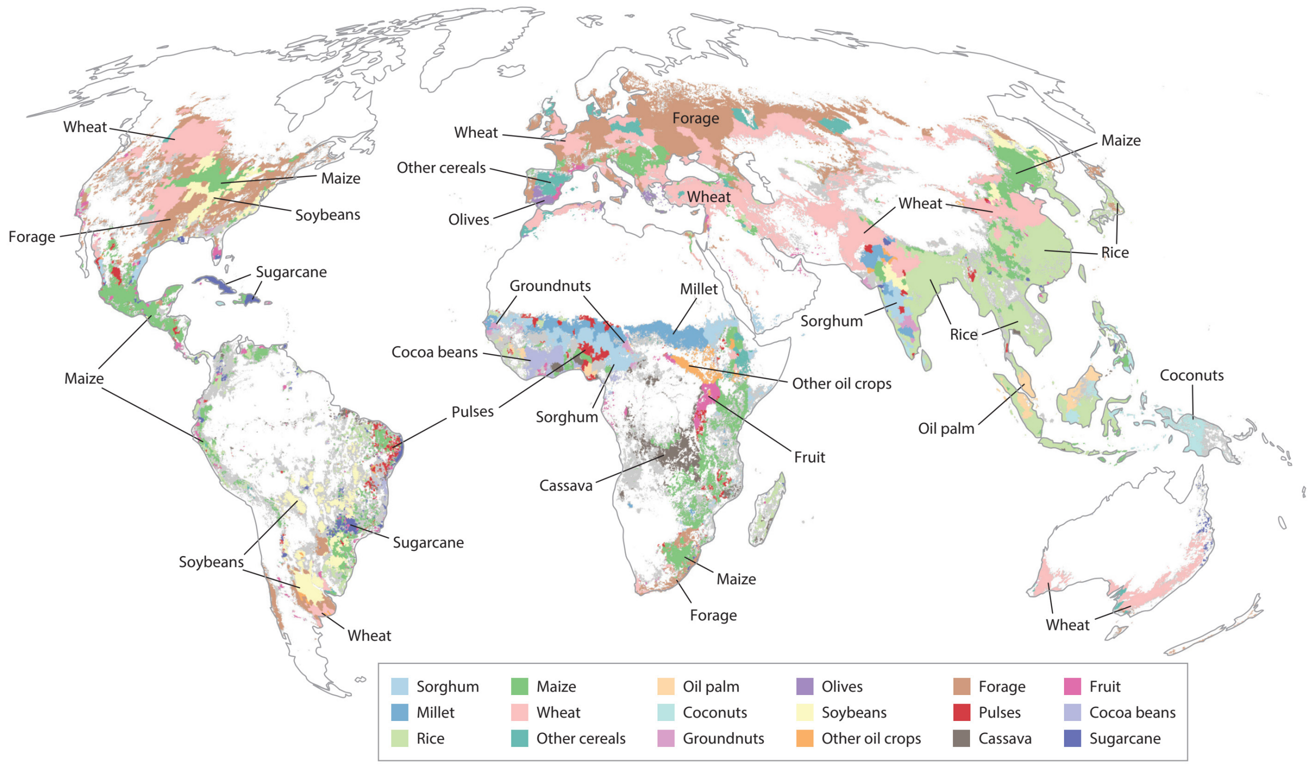
One of land's most fundamental uses is to produce food. But food production is also at the heart of today's escalating pressures on land, with tensions between this essential provisioning role and sustainability imperatives such as climate action and biodiversity protection set to grow further in the coming decades. How will it be possible to feed a larger global population, in other words, without increasing dramatically the area of land given over to agriculture and thereby reducing the land available for other essential uses? Or, especially on a smaller land footprint, without using farming techniques so intensive that the land's viability is compromised?

The modern food system has developed with a narrow focus on meeting increases in demand by raising productivity. Trade liberalization and sustained investment in productivity growth in the decades following the Second World War boosted crop yields, increased food availability and lowered food prices. Although this transformation benefited consumers in obvious ways, it was achieved by the intensification and industrialization of food production. This 'uncritical' approach, in the sense of a failure to consider wider resource impacts, has driven a series of escalating negative consequences.[205]

205 Benton, T. G. and Bailey, R. (2019), 'The paradox of productivity: agricultural productivity promotes food system inefficiency', *Global Sustainability*, 2, p. e6, https://doi.org/10.1017/sus.2019.3.

First, it has made agriculture less diverse, and thus less supportive of human and planetary health. Financial and policy support has typically targeted a small number of crops grown in key breadbasket regions. The result is that today just nine crops together account for around three-quarters of all agricultural calories produced.[206] Maize, wheat, rice, soybeans, palm, sugar, barley, cassava and potatoes – all high-yielding, calorie-dense staple crops well suited to large-scale, intensive, monoculture-based farming systems – dominate global cropland use (Figure 23).

Figure 23. Crop belts of the world (circa 2000)



Note: Shown are the dominant crops or crop groups; not all regionally important crops are indicated.
Source: Ramankutty, N. et al. (2018), 'Trends in Global Agricultural Land Use: Implications for Environmental Health and Food Security', *Annual Review of Plant Biology*, 69(1), pp. 789–815, https://doi.org/10.1146/annurev-arplant-042817-040256.

Second, the intensity of production undermines the landscape's supporting natural capital, degrading soils and biodiversity. As such practices eventually arrest land's productivity, farmers must either increase still further the intensity of input application (e.g. through fertilizer and pesticide use) or bring more land into use to meet demand.

206 West, P. C. et al. (2014), 'Leverage points for improving global food security and the environment', *Science*, 345, pp. 325–28, https://doi.org/10.1126/science.1246067.

Third, greater intensification leads to more greenhouse gas emissions from increased energy and agrochemical use. This is on top of the emissions from land and livestock sector expansion – itself incentivized by cheap food providing the ability to feed cattle on grains and oils instead of grass.

Fourth, low food prices make it economically rational to overconsume and waste food. This contributes to more ill health from overweight and obesity in the general population.

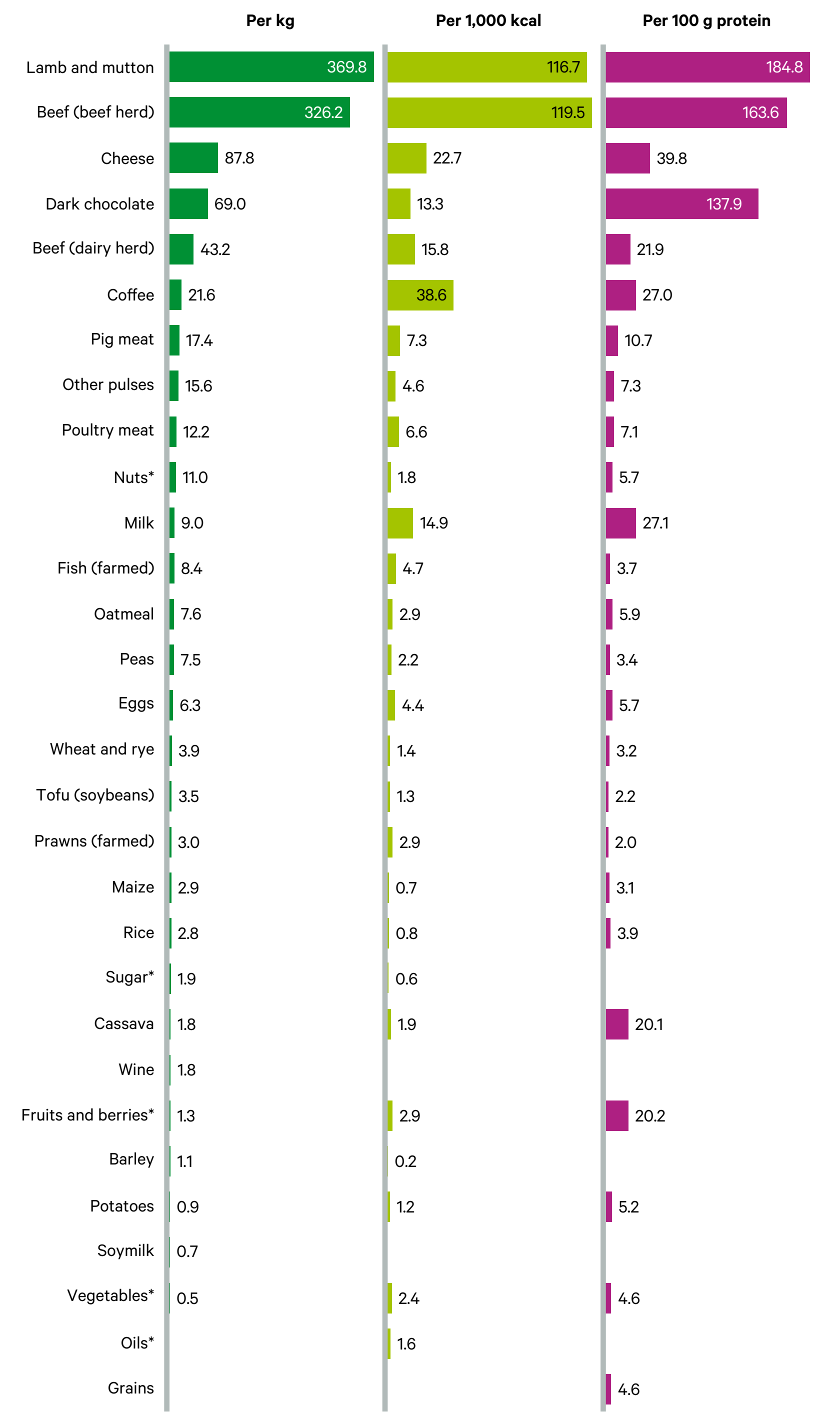
Amplifying many of these impacts is climate change, which further intensifies pressure on land because it reduces crop yields, crop resilience and the nutritional quality of harvested produce. The undesirable knock-on effects are yet more competition for land, more land degradation and more food waste.

A fifth of all land use for crop production is 'displaced' through international trade – that is, dedicated to production for export rather than domestic consumption (Figure 14).[207] Major for-export producers are predominantly large, land-rich industrialized countries such as Australia, Canada and the US,[208] but over the past two decades there have been disproportionately high rates of land-use change in low- and middle-income countries, particularly in the tropics and subtropics, in order to produce crops and animal products for export.[209]

The impact of rising meat consumption on global land use has been significant (Figure 24): just under two-thirds of agricultural land-use change was driven by increased demand for animal products in the 50 years to 2011.[210] The livestock sector now uses one-third of global grain output and three-quarters of global agricultural land.[211] In the Amazon basin, over three-quarters of deforested land is used for grazing livestock or producing livestock feed.[212]

207 MacDonald, G. K. et al. (2015), 'Rethinking Agricultural Trade Relationships in an Era of Globalization', *BioScience*, 65(3), pp. 275–89, https://doi.org/10.1093/biosci/biu225; Kastner, T., Erb, K.-H. and Haberl, H. (2014), 'Rapid growth in agricultural trade: effects on global area efficiency and the role of management', *Environmental Research Letters*, 9(3), p. 034015, https://doi.org/10.1088/1748-9326/9/3/034015.
208 Lee, B., Hepburn, J. and Bellmann, C. (2019), 'Delivering Sustainable Food and Land Use Systems: The Role of International Trade', Chatham House Sustainability Accelerator, 20 September 2019, https://accelerator.chathamhouse.org/article/delivering-sustainable-food-and-land-use-systems-the-role-of-international-trade.
209 Gibbs, H. K. et al. (2010), 'Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s', *Proceedings of the National Academy of Sciences*, 107(38), pp. 16732–37, https://doi.org/10.1073/pnas.0910275107; Meyfroidt, P., Rudel, T. K. and Lambin, E. F. (2010), 'Forest transitions, trade, and the global displacement of land use', *Proceedings of the National Academy of Sciences*, 107(49), pp. 20917–22, https://doi.org/10.1073/pnas.1014773107.
210 Alexander, P. et al. (2015), 'Drivers for global agricultural land use change: The nexus of diet, population, yield and bioenergy', *Global Environmental Change*, 35, pp. 138–47, https://doi.org/10.1016/j.gloenvcha.2015.08.011.
211 Foley, J. A. et al. (2011), 'Solutions for a cultivated planet', *Nature*, 478(7369), pp. 337–42, https://doi.org/10.1038/nature10452; Mottet, A. et al. (2017), 'Livestock: On our plates or eating at our table? A new analysis of the feed/food debate', *Global Food Security*, 14, pp. 1–8, https://doi.org/10.1016/j.gfs.2017.01.001.
212 Machovina, B., Feeley, K. J. and Ripple, W. J. (2015), 'Biodiversity conservation: The key is reducing meat consumption', *Science of The Total Environment*, 536, pp. 419–31, https://doi.org/10.1016/j.scitotenv.2015.07.022.

Figure 24. Land use (m^2) per food item



* Nuts – unweighted average of nuts and groundnuts; fruits and berries – unweighted average of apples, bananas, berries and grapes, citrus fruit, other fruits; Sugar – unweighted average of beet sugar and cane sugar; Vegetables – unweighted average of brassicas, onions and leeks, root vegetables, tomatoes, other vegetables; Oils – unweighted average of olive oil, palm oil, rapeseed oil, sunflower oil.
Source: Poore, J. and Nemecek, T. (2018), 'Reducing food's environmental impacts through producers and consumers', *Science*, 360, pp. 987–92, https://doi.org/10.1126/science.aaq0216.

4.1.1 Land degradation driven by food production

Both the expansion and intensification of food production can drive the degradation of land resources and the loss of terrestrial – and, in some cases, marine or riverine – ecosystems. Agricultural expansion was the cause of half of global forest disturbance between 2001 and 2015,[213] and of up to 80 per cent of deforestation between 2000 and 2010,[214] and was also a leading cause of accelerated peatland degradation in the 20th century.[215]

While individual farms differ significantly in their contributions to land-use change and land degradation, the net impact of industrialized agriculture vastly outweighs that of smallholder farms. Over 70 per cent of global farmland is managed by the 1 per cent of farms of 50 hectares (ha) or more – and half of that land is on farms of over 1,000 ha.[216] Agriculture at this scale is associated with the expansion of production into previously uncultivated forestland, shrubland and grassland.[217]

Globally each year, an area of land the size of Malawi (12 million ha) is estimated to be lost to soil degradation from farming.[218] Heavy use of mechanization and irrigation, together with intensive monoculture-based production, results in soil compaction which, over time, degrades the soil quality and its productive capacity.[219] Conventional tillage methods, where soils are ploughed and stripped of residues from the previous crop before being reseeded, have soil erosion rates that outstrip soil formation rates 100 times over.[220] Fertilizers have been central to growth in global crop yields in recent decades: global fertilizer consumption was more than four times higher in 2019 compared with 1961 (Figure 25).[221] However, fertilizer run-off is a leading cause of nutrient pollution and overloading in waterways.[222] Nitrates and phosphates from fertilizers, together with animal slurry from livestock farming, lead to the eutrophication (excessive nutrient enrichment) of water sources and the formation of algal blooms deadly to marine life and dangerous to human health.[223]

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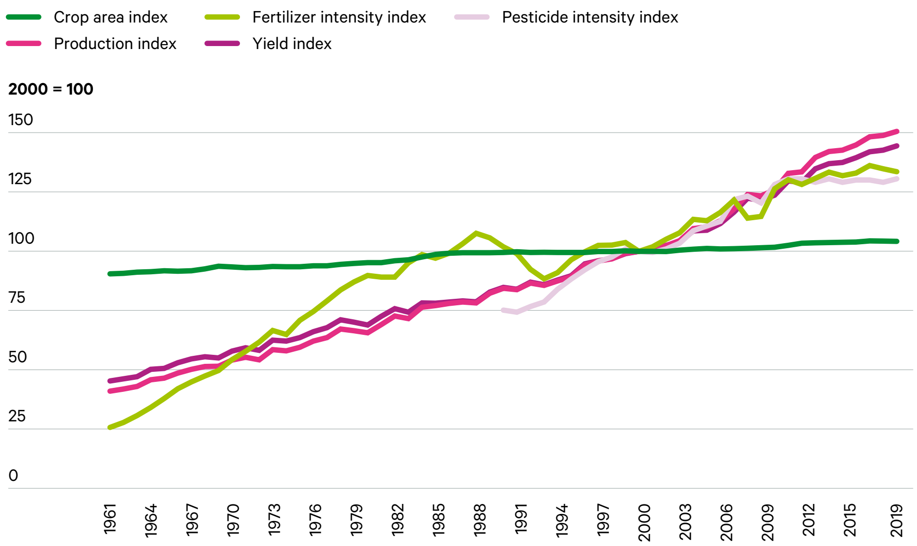
213 Curtis, P. G. et al. (2018), 'Classifying drivers of global forest loss', *Science*, 361, pp. 1108–11, https://doi.org/10.1126/science.aau3445.
214 Kissinger, G., Herold, M. and de Sy, V. (2012), *Drivers of Deforestation: A Synthesis Report for REDD+ Policy-Makers*, Vancouver: Lexeme Consulting.
215 Olsson, L. et al. (2019), 'Land Degradation', in Shukla, P. R. et al. (eds) (2019), *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*, Geneva: Intergovernmental Panel on Climate Change (IPCC) (2019), https://www.ipcc.ch/srccl/chapter/chapter-4.
216 Lowder, S. K., Sánchez, M. V. and Bertini, R. (2021), 'Which farms feed the world and has farmland become more concentrated?', *World Development*, 142, p. 105455, https://doi.org/10.1016/j.worlddev.2021.105455.
217 Oberlack, C. et al. (2021), 'Why do large-scale agricultural investments induce different socio-economic, food security, and environmental impacts? Evidence from Kenya, Madagascar, and Mozambique', *Ecology and Society*, 26(4), p. art18, https://doi.org/10.5751/ES-12653-260418.
218 Rickson, R. J. et al. (2015), 'Input constraints to food production: the impact of soil degradation', *Food Security*, 7(2), pp. 351–64, https://doi.org/10.1007/s12571-015-0437-x.
219 Shah, A. N. et al. (2017), 'Soil compaction effects on soil health and crop productivity: an overview', *Environmental Science and Pollution Research*, 24(11), pp. 10056–67, https://doi.org/10.1007/s11356-017-8421-y.
220 Olsson et al. (2019), 'Land Degradation', in Shukla et al. (eds) (2019), *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*.
221 Food and Agriculture Organization of the United Nations (FAO) (2022), 'FAOSTAT > Fertilizers archive', https://www.fao.org/faostat/en/#data/RA (accessed 1 Jun. 2022).
222 Poore, J. and Nemecek, T. (2018), 'Reducing food's environmental impacts through producers and consumers', *Science*, 360, pp. 987–92, https://doi.org/10.1126/science.aaq0216.
223 OECD (2017), *Diffuse Pollution, Degraded Waters: Emerging Policy Solutions*, Paris: OECD, https://www.oecd.org/env/diffuse-pollution-degraded-waters-9789264269064-en.htm.

Figure 25. Changes in cropland area, production volumes, yields and input intensities, 1961–2019



Sources: Calculated from FAO (2022), 'FAOSTAT > Land Use', https://www.fao.org/faostat/en/#data/RL (accessed 1 Jun. 2022); FAO (2022), 'FAOSTAT > Crops and livestock products', https://www.fao.org/faostat/en/#data/QCL (accessed 1 Jun. 2022); FAO (2022), 'FAOSTAT > Pesticides Use', https://www.fao.org/faostat/en/#data/RP (accessed 1 Jun. 2022); FAO (2022), 'FAOSTAT > Fertilizers by Nutrient', https://www.fao.org/faostat/en/#data/RFN (accessed 1 Jun. 2022).

Beyond impacts on soils and land use, agriculture degrades water sources and contributes to habitat and biodiversity loss. The water footprint of agriculture – both in terms of amounts used and pollution – is the highest of any sector.[224] It is estimated that farming negatively affects more than half of all threatened terrestrial species through habitat destruction, land degradation and landscape homogenization.[225] The negative impacts on biodiversity are particularly significant in tropical regions[226] and in areas where agricultural production is highly intensive.[227]

Crop and livestock production are not the only causes of food-driven land-use change. The aquaculture industry has expanded significantly since the 1970s (see Box 9), leading to extensive land-use change in both coastal and inland areas, particularly in South and Southeast Asia.[228] Intensive aquaculture often relies heavily

224 Yang, H., Pfister, S. and Bhaduri, A. (2013), 'Accounting for a scarce resource: virtual water and water footprint in the global water system', *Current Opinion in Environmental Sustainability*, 5(6), pp. 599–606, https://doi.org/10.1016/j.cosust.2013.10.003.
225 Tanentzap, A. J., Lamb, A., Walker, S. and Farmer, A. (2015), 'Resolving Conflicts between Agriculture and the Natural Environment', *PLOS Biology*, 13(9), p. e1002242, https://doi.org/10.1371/journal.pbio.1002242; Cunningham, S. A. et al. (2013), 'To close the yield-gap while saving biodiversity will require multiple locally relevant strategies', *Agriculture, Ecosystems & Environment*, 173, pp. 20–27, https://doi.org/10.1016/j.agee.2013.04.007.
226 Chaudhary, A. and Kastner, T. (2016), 'Land use biodiversity impacts embodied in international food trade', *Global Environmental Change*, 38, pp. 195–204, https://doi.org/10.1016/j.gloenvcha.2016.03.013.
227 Karp, D. S. et al. (2012), 'Intensive agriculture erodes β-diversity at large scales', *Ecology Letters*, 15(9), pp. 963–70, https://doi.org/10.1111/j.1461-0248.2012.01815.x.
228 Ottinger, M., Clauss, K. and Kuenzer, C. (2016), 'Aquaculture: Relevance, distribution, impacts and spatial assessments – A review', *Ocean & Coastal Management*, 119, pp. 244–66, https://doi.org/10.1016/j.ocecoaman.2015.10.015.

on the use of chemicals and fertilizers to maintain farmed-species stocks and regulate water quality, and on antibiotics to mitigate the risk of disease; these inputs, together with organic waste from fish and other farmed species, can result in nutrient overloading in nearby water sources, contributing to eutrophication, the emergence of algal blooms, and pollution with toxic compounds.[229] But aquaculture also threatens the health of soils: the conversion of coastal wetlands to aquaculture has, in many cases, resulted in the loss of biodiverse ecosystems and the loss or degradation of coastal habitats, such as mangrove forests, that would otherwise provide natural protection against flooding and saltwater intrusion.[230]

Box 9. Aquaculture and agriculture interactions

Aquaculture and agriculture can, in some settings, compete for the same land and water resources. In South, East and Southeast Asia, the growth of inland aquaculture has been enabled by the widespread conversion of rice fields to ponds. This trend is expected to continue, placing fish production in direct competition with crop production. Both inland aquaculture and agriculture are highly water-intensive, often requiring significant freshwater withdrawals to maintain production levels. And, as demand for both fish and other animal products rises, aquaculture and livestock production may increasingly compete with each other for grain and soy – as well as for wild-caught fish resources – used in aquaculture and livestock feeds.

There is nevertheless potential to combine aquaculture and agriculture activities as a means of boosting yields while reducing resource inputs. Innovative solutions to increase fish yields while minimizing their environmental impact include mixed systems such as aquaponics, whereby plants are grown not in soil but in a nutrient-rich solution fed by organic waste from a connected fish tank. The tank, in turn, is a recirculating aquaculture system (RAS) in which water is siphoned off, treated to remove toxic compounds and reused.[231] Other approaches include integrated aquaculture–agriculture systems in which fish are farmed in cages within on-farm irrigation storage reservoirs,[232] and rice–fish systems in which fish are either captured or farmed in rice fields, or are farmed in rotation with rice.[233]

229 Ibid.
230 Schwitzguébel, J.-P. and Wang, H. (2007), 'Environmental impact of aquaculture and countermeasures to aquaculture pollution in China', *Environmental Science and Pollution Research - International*, 14(7), pp. 452–62, https://doi.org/10.1065/espr2007.05.426; Páez-Osuna, F. (2001), 'The Environmental Impact of Shrimp Aquaculture: Causes, Effects, and Mitigating Alternatives', *Environmental Management*, 28(1), pp. 131–40, https://doi.org/10.1007/s002670010212.
231 Edwards, P. (2015), 'Aquaculture environment interactions: Past, present and likely future trends', *Aquaculture*, 447, pp. 2–14, https://doi.org/10.1016/j.aquaculture.2015.02.001.
232 Ingram, B. A., Gooley, G. J., McKinnon, L. J. and De Silva, S. S. (2000), 'Aquaculture-agriculture systems integration: an Australian prospective', *Fisheries Management and Ecology*, 7(1–2), pp. 33–43, https://doi.org/10.1046/j.1365-2400.2000.00182.x.
233 Ahmed, N., Ward, J. D. and Saint, C. P. (2014), 'Can integrated aquaculture-agriculture (IAA) produce "more crop per drop"?', *Food Security*, 6(6), pp. 767–79, https://doi.org/10.1007/s12571-014-0394-9.

4.1.2 Future land demand for food production

If growth in demand for food continues in line with current trends, agricultural production will need to increase by around 50 per cent from 2013 levels by 2050 to keep pace.[234] The gradual homogenization of diets,[235] and rising consumption of high-calorie, high-fat, high-protein foods,[236] will exert increasing pressure on available food supply. On current trajectories, expansion of the land area used for agriculture is inevitable: yield growth rates for staple crops are insufficient to meet additional demand on this scale,[237] due to a combination of the productive potential of land being reached in some regions, and poor or unsustainable land management in others.

If growth in demand for food continues in line with current trends, agricultural production will need to increase by around 50 per cent from 2013 levels by 2050 to keep pace.

Much of this expansion will in effect be 'outsourced' through trade, as countries ramp up imports to meet domestic demand. In other words, consuming countries will indirectly draw down land resources in producer countries with abundant 'spare' land and/or weak land governance. For instance, China, India, Indonesia, Nigeria and the Philippines – countries in which there is a fast-growing middle class and where dietary demand patterns are expected to change rapidly – all have limited spare productive land at home. Moreover, Indonesia, Nigeria and the Philippines already rely on imports to meet 15–20 per cent of domestic caloric supply.[238] For such countries, in the absence of radical solutions to decouple food production from land use, meeting domestic demand will depend on importing food.

For some countries, land-use displacement through imports is necessitated by domestic biophysical limits: countries in North Africa and the Middle East, for example, must contend with arid conditions, while population growth in South and East Asia – particularly in India and China – far outstrips the productive capacity of potentially 'spare' domestic land.[239] Other countries have come to rely on international markets and overseas production as a result of particular economic choices, such as the commoditization of domestic agricultural production to support export-led growth, or the expansion of domestic biofuel production. In the US, for example, over 50 per cent of agricultural production is either for export, animal feed or non-food uses;[240] the US market relies significantly on overseas land use to meet domestic demand for food, particularly fruit and vegetables.[241]

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234 FAO (2017), *The future of food and agriculture: trends and challenges*, Rome: FAO, http://www.fao.org/3/a-i6583e.pdf. Such projections are typically sensitive to the choice of base year. However, a meta-analysis of similar projections published between 2000 and 2018 and standardizing to a consistent base year of 2010 found this projection to be broadly consistent with those in other published studies, which converge on a demand increase of 35–56 per cent to 2050 from 2010 levels. See van Dijk, M., Morley, T., Rau, M. L. and Saghai, Y. (2021), 'A meta-analysis of projected global food demand and population at risk of hunger for the period 2010–2050', *Nature Food*, 2(7), pp. 494–501, https://doi.org/10.1038/s43016-021-00322-9.
235 Khoury, C. K. et al. (2014), 'Increasing homogeneity in global food supplies and the implications for food security', *Proceedings of the National Academy of Sciences*, 111(11), pp. 4001–06, https://doi.org/10.1073/pnas.1313490111.
236 Popkin, B. M., Adair, L. S. and Ng, S. W. (2012), 'Global nutrition transition and the pandemic of obesity in developing countries', *Nutrition Reviews*, 70(1), pp. 3–21, https://doi.org/10.1111/j.1753-4887.2011.00456.x.
237 Ray, D. K., Mueller, N. D., West, P. C. and Foley, J. A. (2013), 'Yield Trends Are Insufficient to Double Global Crop Production by 2050', *PLoS ONE*, 8(6), p. e66428, https://doi.org/10.1371/journal.pone.0066428.
238 FAO (2022), 'FAOSTAT > Suite of Food Security Indicators > Cereal import dependency ratio (3-year average for 2011–2013)', https://www.fao.org/faostat/en/#data/FS (accessed 1 Jun. 2022).
239 Yu, Y., Feng, K. and Hubacek, K. (2013), 'Tele-connecting local consumption to global land use', *Global Environmental Change*, 23(5), pp. 1178–86, https://doi.org/10.1016/j.gloenvcha.2013.04.006.
240 FAO (2022), 'FAOSTAT > New Food Balances – United States of America (2017 data, 'Export quantity', 'Feed' and 'Other uses (non-food)' as a share of 'Production')', https://www.fao.org/faostat/en/#data/FBS (accessed 1 Jun. 2022).
241 Yu, Feng and Hubacek (2013), 'Tele-connecting local consumption to global land use'; Johnson, R. (2016), *The U.S. Trade Situation for Fruit and Vegetable Products,* Congressional Research Service, RL34468, https://fas.org/sgp/crs/misc/RL34468.pdf.

Future agricultural expansion is expected in many of the world's biodiversity 'hotspots'.[242] Some 75 per cent of intact tropical forest and savannah land is cultivable.[243] Countries where particularly significant agricultural expansion is expected – Argentina, Brazil, Indonesia, and states across central and eastern Africa, for example – have enormous carbon stocks in forests and high carbon content in the topsoil. This carbon, if released through clearance or cultivation, would contribute to rising atmospheric greenhouse gas levels. The productive potential of such regions, coupled in many cases with weak governance and minimal protective regulation, renders them prime targets for further agricultural expansion.[244]

Increased demand for animal products will continue to drive land-use change and agricultural expansion. While meat consumption has plateaued in many high-income countries, a similar deceleration in demand growth is not expected in developing countries until the second half of this century.[245] Many developing countries will need to respond to rising domestic demand for meat by increasing their imports of meat products and crops for use as animal feed.[246] A large share of this demand will be met by current major exporters. Brazil, China, the European Union, Russia and the US – along with Argentina, India, Mexico and Vietnam – are all expected to increase domestic livestock herds considerably over the next 20 years.[247] This will exacerbate overexploitation of agricultural land and loss of tree cover and habitats, trends that are among the most pronounced in Argentina, Brazil and Vietnam.

4.2 Approaches to reduce the land footprint of food production

Proposed strategies to reduce the land footprint of agriculture and food production typically fall into four categories:

- Boosting productivity on existing farmland through sustainable means that mitigate negative environmental impacts;
- Dietary change, and more specifically a shift in consumption away from land-intensive foods;
- Reduction in waste, and in food losses along the supply chain, to alleviate the additional pressure that both problems place on land resources; and
- Decoupling of food production from land use through innovative farming techniques and disruptive technologies.

242 Fader, M. et al. (2016), 'Past and present biophysical redundancy of countries as a buffer to changes in food supply', *Environmental Research Letters*, 11(5), p. 055008, https://doi.org/10.1088/1748-9326/11/5/055008.
243 Bajželj, B. et al. (2014), 'Importance of food-demand management for climate mitigation', *Nature Climate Change*, 4(10), pp. 924–29, https://doi.org/10.1038/nclimate2353.
244 Searchinger, T. D. et al. (2015), 'High carbon and biodiversity costs from converting Africa's wet savannahs to cropland', *Nature Climate Change*, 5(5), pp. 481–86, https://doi.org/10.1038/nclimate2584.
245 Davis, K. F. et al. (2016), 'Meeting future food demand with current agricultural resources', *Global Environmental Change*, 39, pp. 125–32, https://doi.org/10.1016/j.gloenvcha.2016.05.004.
246 Rulli, M. C., Saviori, A. and D'Odorico, P. (2013), 'Global land and water grabbing', *Proceedings of the National Academy of Sciences*, 110(3), pp. 892–97, https://doi.org/10.1073/pnas.1213163110.
247 OECD and FAO (2018), *OECD-FAO Agricultural Outlook 2018-2027*, Paris: OECD, https://doi.org/10.1787/agr_outlook-2018-en.

This section outlines potential measures under each of these categories. (Their cumulative land footprint impacts are considered further in Chapter 6, building on some of the scenarios introduced in this section.)

4.2.1 Boosting productivity sustainably

Approaches that will boost productivity sustainably on existing farmland are urgently required, as substantial 'yield gaps' – reflecting the difference between realized and potential yields – persist around the world. Crop yields are less than half of what they could be in 96 countries across Africa, South America, South Asia and Southeast Asia.[248] Even in major breadbasket regions – in China, India, Indonesia and the US, most notably – yield growth rates are either increasing minimally or stagnating, and many countries with populations dependent on domestic production are experiencing similar trends.[249]

In aggregate, closing yield gaps could increase global production volumes by 45–70 per cent for most crops.[250] Many means of achieving this are environmentally harmful, as discussed above, but several approaches aim to boost yields while lowering resource inputs and mitigating negative environmental and social impacts. Such approaches are often referred to collectively as 'sustainable intensification', a somewhat loose and contested term that has nonetheless gained considerable traction among governments, businesses and civil society. The concept encompasses a range of techniques and practices that deploy knowledge, efficiencies of scale, technologies, equipment and chemicals to achieve lower-impact, more nature-friendly production. The most suitable option in any given landscape will depend on that landscape's characteristics, the size of the landholdings, access to resources, and the chosen solution's acceptance by landholders and local communities. The main approaches to sustainable yield growth are summarized below:

— **Regenerative agriculture** aims to reduce input use and maintain the land's natural productivity.[251] It relies on practices such as low- or no-till farming, mulching and crop rotation to boost soil carbon sequestration and protect against soil erosion,[252] although many of these practices can increase dependence on chemical herbicides.

— **Mixed livestock–crop systems** seek to boost yields and increase resource use efficiency through combining livestock rearing and crop production. Under such systems, livestock are fed on crop residues and provide draft power and manure

248 University of Nebraska Lincoln and Wageningen University (2022), 'Global Yield Gap Atlas', http://www.yieldgap.org; Tilman, D. et al. (2017), 'Future threats to biodiversity and pathways to their prevention', *Nature*, 546, pp. 73–81, https://doi.org/10.1038/nature22900.
249 Ray, Mueller, West and Foley (2013), 'Yield Trends Are Insufficient to Double Global Crop Production by 2050'; Ray, D. K. et al. (2012), 'Recent patterns of crop yield growth and stagnation', *Nature Communications*, 3(1), p. 1293, https://doi.org/10.1038/ncomms2296.
250 Mueller, N. D. et al. (2012), 'Closing yield gaps through nutrient and water management', *Nature*, 490, pp. 254–57, https://doi.org/10.1038/nature11420.
251 Hobbs, P. R., Sayre, K. and Gupta, R. (2008), 'The role of conservation agriculture in sustainable agriculture', *Philosophical Transactions of the Royal Society B: Biological Sciences*, 363, pp. 543–55, https://doi.org/10.1098/rstb.2007.2169; LaCanne, C. E. and Lundgren, J. G. (2018), 'Regenerative agriculture: merging farming and natural resource conservation profitably', *PeerJ*, 6, p. e4428, https://doi.org/10.7717/peerj.4428.
252 Lal, R. (2004), 'Soil Carbon Sequestration Impacts on Global Climate Change and Food Security', *Science*, 304, pp. 1623–27, https://doi.org/10.1126/science.1097396.

for fertilizing the soil.[253] On farms implementing regenerative agriculture, low-density, grass-fed ruminant systems can occupy marginal land that is not suitable for crop production. These systems can, under the right conditions, enhance the cycling of nitrogen in soils and so promote the sequestration of soil carbon.[254] In practice, however, soil carbon in grasslands is higher without grazing in most cases.[255]

— **Circular agriculture** provides an alternative way of enhancing nutrient cycling and the reuse of resources – for example, by looping waste streams, such as beet pulp, from the food or energy system into livestock systems for use as feed.[256] Loops may also be established in the other direction, with organic waste from crop and livestock systems recycled for use in the production of biogas, other biomaterials[257] or, in some cases, fish (Box 9).

— **Precision agriculture** uses geographic information systems, global navigation satellite systems and networks of microcomputers to monitor on-farm weather conditions, control agricultural machinery remotely and apply inputs at a precise, sub-field scale, tailored to specific environmental and soil conditions.[258]

— **Gene engineering and gene editing** approaches in crop and livestock farming[259] aim to raise yields. For crop production, techniques include engineering photosynthetic efficiency and altering the root architecture to make plants better at capturing the nitrogen applied. One such approach, known as CRISPR (clustered regularly interspaced short palindromic repeats), offers a relatively low-cost and easy-to-use technique for rapid editing of DNA. It can enhance crop resistance to pests and disease and can boost the nutritional content of plants such as potato,[260] thereby potentially reducing food losses, minimizing the need for herbicide and pesticide use, and delivering more nutrients on less land. Gene editing may also be used to breed healthier, more disease-resistant livestock, allowing for reduced herd sizes while maintaining the same output.[261] However, it can also be used to produce traits driven by less sustainable commercial motivations such as increased and accelerated livestock growth.

253 Herrero, M. et al. (2010), 'Smart Investments in Sustainable Food Production: Revisiting Mixed Crop-Livestock Systems', *Science*, 327, pp. 822–25, https://doi.org/10.1126/science.1183725.
254 van Zanten, H. H. E. et al. (2016), 'Global food supply: land use efficiency of livestock systems', *The International Journal of Life Cycle Assessment*, 21(5), pp. 747–58, https://doi.org/10.1007/s11367-015-0944-1; Soussana, J.-F. and Lemaire, G. (2014), 'Coupling carbon and nitrogen cycles for environmentally sustainable intensification of grasslands and crop-livestock systems', *Agriculture, Ecosystems & Environment*, 190, pp. 9–17, https://doi.org/10.1016/j.agee.2013.10.012.
255 Beillouin, D. et al. (2023), 'A global meta-analysis of soil organic carbon in the Anthropocene', *Nature Communications*, 14, 3700, https://doi.org/10.1038/s41467-023-39338-z.
256 van Zanten et al. (2016), 'Global food supply: land use efficiency of livestock systems'.
257 Dahiya, S. et al. (2018), 'Food waste biorefinery: Sustainable strategy for circular bioeconomy', *Bioresource Technology*, 248, pp. 2–12, https://doi.org/10.1016/j.biortech.2017.07.176.
258 Gebbers, R. and Adamchuk, V. I. (2010), 'Precision Agriculture and Food Security', *Science*, 327, pp. 828–31, https://doi.org/10.1126/science.1183899; Keating, B. A. et al. (2014), 'Food wedges: Framing the global food demand and supply challenge towards 2050', *Global Food Security*, 3(3–4), pp. 125–32, https://doi.org/10.1016/j.gfs.2014.08.004.
259 Fedoroff, N. V. et al. (2010), 'Radically Rethinking Agriculture for the 21st Century', *Science*, 327, pp. 833–34, https://doi.org/10.1126/science.1186834.
260 Eş, I. et al. (2019), 'The application of the CRISPR-Cas9 genome editing machinery in food and agricultural science: Current status, future perspectives, and associated challenges', *Biotechnology Advances*, 37(3), pp. 410–21, https://doi.org/10.1016/j.biotechadv.2019.02.006.
261 Tait-Burkard, C. et al. (2018), 'Livestock 2.0 – genome editing for fitter, healthier, and more productive farmed animals', *Genome Biology*, 19(1), p. 204, https://doi.org/10.1186/s13059-018-1583-1.

— **Techniques and technologies to bring unproductive, degraded and abandoned lands into use** include optimizing agroforestry to rehabilitate land and sequester carbon,[262] establishing desalination projects in arid regions, and employing biosaline agricultural practices in regions with salt-affected soils.[263] Such methods offer considerable potential to boost productivity, but to date have been underused for food production – for reasons including inadequate 'extension services' (technical advice and support to famers) and low adoption rates among smallholder farmers,[264] high capital costs and energy consumption,[265] and competition for biomass residues for use in energy production.[266]

4.2.1.1 The limits of sustainable intensification

The approaches outlined above are not without their trade-offs, which include competition with, or negative impacts on, other goods and services provided by land.[267] Precision farming, for example, though effective at reducing chemical input use, typically requires large machinery and capital investment, implying farming at scale and therefore landscape-level impacts in terms of monocultures and landscape homogeneity.[268] Larger equipment and intensive management also risk degrading the soil's structure and undermining its ability to provide services.

Although context-appropriate sustainable intensification can make valuable contributions to supplying more agricultural resources from the same amount of land, there are still fundamental bioenvironmental limits – at local and planetary scales – to what the land can provide. Beyond these limits, degradation leads to persistent or irreversible productivity losses, as witnessed in the US's Midwest Dust Bowl in the 1930s,[269] thereby further increasing land abandonment[270] and

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262 Dagar, J. C. and Sharma, P. C. (2016), 'Introduction', in Dagar, J. C., Sharma, P. C., Sharma, D. and Singh, A. (eds) (2016), *Innovative Saline Agriculture*, New Delhi: Springer India, pp. 1–4, https://doi.org/10.1007/978-81-322-2770-0_1; Yadav, R. K. and Dagar, J. C. (2016), 'Innovations in Utilization of Poor-Quality Water for Sustainable Agricultural Production', in Dagar, Sharma, Sharma and Singh (eds) (2016), *Innovative Saline Agriculture*.
263 Shahid, S. A. and Al-Shankiti, A. (2013), 'Sustainable food production in marginal lands—Case of GDLA member countries', *International Soil and Water Conservation Research*, 1(1), pp. 24–38, https://doi.org/10.1016/S2095-6339(15)30047-2; Masters, D. G., Benes, S. E. and Norman, H. C. (2007), 'Biosaline agriculture for forage and livestock production', *Agriculture, Ecosystems & Environment*, 119(3–4), pp. 234–48, https://doi.org/10.1016/j.agee.2006.08.003.
264 Shahid and Al-Shankiti (2013), 'Sustainable food production in marginal lands—Case of GDLA member countries'; Wilson, M. and Lovell, S. (2016), 'Agroforestry—The Next Step in Sustainable and Resilient Agriculture', *Sustainability*, 8(6), p. 574, https://doi.org/10.3390/su8060574.
265 Elimelech, M. and Phillip, W. A. (2011), 'The Future of Seawater Desalination: Energy, Technology, and the Environment', *Science*, 333, pp. 712–17, https://doi.org/10.1126/science.1200488; Gude, V. G. (2017), 'Desalination and water reuse to address global water scarcity', *Reviews in Environmental Science and Bio/Technology*, 16(4), pp. 591–609, https://doi.org/10.1007/s11157-017-9449-7.
266 Campbell, J. E., Lobell, D. B., Genova, R. C. and Field, C. B. (2008), 'The Global Potential of Bioenergy on Abandoned Agriculture Lands', *Environmental Science & Technology*, 42(15), pp. 5791–94, https://doi.org/10.1021/es800052w.
267 German, R. N., Thompson, C. E. and Benton, T. G. (2017), 'Relationships among multiple aspects of agriculture's environmental impact and productivity: a meta-analysis to guide sustainable agriculture', *Biological Reviews*, 92(2), pp. 716–38, https://doi.org/10.1111/brv.12251.
268 Benton, T. G., Vickery, J. A. and Wilson, J. D. (2003), 'Farmland biodiversity: is habitat heterogeneity the key?', *Trends in Ecology & Evolution*, 18(4), pp. 182–88, https://doi.org/10.1016/S0169-5347(03)00011-9.
269 Fraser, E. D. G. (2013), 'Coping with food crises: Lessons from the American Dust Bowl on balancing local food, agro technology, social welfare, and government regulation agendas in food and farming systems', *Global Environmental Change*, 23(6), pp. 1662–72, https://doi.org/10.1016/j.gloenvcha.2013.09.001; Hornbeck, R. (2012), 'The Enduring Impact of the American Dust Bowl: Short- and Long-Run Adjustments to Environmental Catastrophe', *American Economic Review*, 102(4), pp. 1477–1507, https://doi.org/10.1257/aer.102.4.1477; Cook, B. I., Miller, R. L. and Seager, R. (2009), 'Amplification of the North American "Dust Bowl" drought through human-induced land degradation', *Proceedings of the National Academy of Sciences*, 106(13), pp. 4997–5001, https://doi.org/10.1073/pnas.0810200106.
270 Rickson, R. J. et al. (2015), 'Input constraints to food production: the impact of soil degradation', *Food Security*, 7(2), pp. 351–64, https://doi.org/10.1007/s12571-015-0437-x.

competition for the remaining productive land.[271] At a global scale, the planetary boundaries imply 'tipping points' beyond which degradation of systems becomes hard to reverse or self-reinforcing (see Box 5). In the absence of sufficient evidence as to exactly when or how such thresholds may be breached, and precisely how production approaches should best be varied between locations, it is difficult to understand the potential upper limits of sustainable intensification, either at planetary level[272] or at the level of more local boundaries.

Socio-economic factors are also likely to limit the potential of sustainable intensification to reduce pressure on land. Using purely sustainable intensification methods to improve yields, increase irrigation efficiency and eliminate over-fertilization could, in theory, reduce the required cropland area in 2050 by 26 per cent (and the total agricultural land area by 9 per cent) relative to a business-as-usual baseline.[273] But this will depend on widespread adoption of alternative and innovative approaches to farming, which in turn will rely on more equitable and more widespread access to knowledge, finance, technology, high-quality seeds and livestock breeds, and extension services.

Even if successfully deployed at scale, sustainable intensification without accompanying demand-side reductions is still likely to result in an agricultural land footprint larger than today's (see Chapter 6).

Box 10. Sustainable intensification in practice

Regenerative, low-input agricultural models of production offer a pathway to sustainable food systems that cause minimal disturbance to the natural environment. For example, agroforestry initiatives in sub-Saharan African countries have been highly effective in improving soil fertility, crop productivity[274] and biodiversity.[275] In Malawi, for instance, the planting of indigenous acacia, known as 'fertilizer trees' for their nitrogen-fixing qualities, has markedly improved yields for crops such as maize when grown under the canopy, with some studies reporting up to 280 per cent more output.[276] For smallholder farmers with limited resources, adoption of this inexpensive agroecological practice can transform agricultural production, reducing food insecurity and building resilience to climate change.[277]

271 Amundson, R. et al. (2015), 'Soil and human security in the 21st century', *Science*, 348, https://doi.org/10.1126/science.1261071.
272 Steffen, W. et al. (2015), 'Planetary boundaries: Guiding human development on a changing planet', *Science*, 347, https://doi.org/10.1126/science.1259855.
273 Bajželj et al. (2014), 'Importance of food-demand management for climate mitigation'.
274 Pretty, J., Toulmin, C. and Williams, S. (2011), 'Sustainable intensification in African agriculture', *International Journal of Agricultural Sustainability*, 9(1), pp. 5–24, https://doi.org/10.3763/ijas.2010.0583.
275 Wurz, A. et al. (2022), 'Win-win opportunities combining high yields with high multi-taxa biodiversity in tropical agroforestry', *Nature Communications*, 13(1), p. 4127, https://doi.org/10.1038/s41467-022-30866-8.
276 Saka, A. R. et al. (1994), 'The effects of Acacia albida on soils and maize grain yields under smallholder farm conditions in Malawi', *Forest Ecology and Management*, 64(2–3), pp. 217–30, https://doi.org/10.1016/0378-1127(94)90296-8; Ajayi, O. C., Place, F., Akinnifesi, F. K. and Sileshi, G. W. (2011), 'Agricultural success from Africa: the case of fertilizer tree systems in southern Africa (Malawi, Tanzania, Mozambique, Zambia and Zimbabwe)', *International Journal of Agricultural Sustainability*, 9(1), pp. 129–36, https://doi.org/10.3763/ijas.2010.0554.
277 Coulibaly, J. Y., Chiputwa, B., Nakelse, T. and Kundhlande, G. (2017), 'Adoption of agroforestry and the impact on household food security among farmers in Malawi', *Agricultural Systems*, 155, pp. 52–69, https://doi.org/10.1016/j.agsy.2017.03.017.

Circular agriculture, another low-external-input approach to farming, is an ecological concept that has become increasingly widespread. In the Netherlands (one of the world's largest agricultural exporters), the agriculture ministry has developed a vision to shift Dutch agriculture towards circular farming. The aim is to stimulate food production methods that place the lowest possible pressure on natural resources.[278] The plan, introduced in 2018, positions the Netherlands as a global leader in developing circular agriculture, with the adoption of practices that prioritize local production, reuse waste flows from the food industry, and permit the arable, livestock and horticulture sectors to use raw materials from each other's supply chains. Although the concept is relatively new, the knowledge and innovations acquired from the Dutch experience could provide useful lessons for developing countries aiming to improve their farming performances and make food systems more sustainable.[279]

Beyond waste collection and reuse, circular approaches are being deployed at the point of production in several developing countries, including in urban contexts. These approaches take advantage of the much lower land, fertilizer and water input requirements of closed-loop systems compared with conventional farming methods. In Ho Chi Minh City, Vietnam, residents have trialled small-scale closed-loop aquaponics and hydroponics to grow cassava, tomato and lettuce.[280] In Kampala, Uganda, farmers have used simple wooden crate constructions to establish a habitat in which earthworms can fertilize crops.[281] In Nairobi, Kenya, some of the city's slum-dwelling population have similarly grown food in sisal 'sack gardens'.[282]

More technologically advanced approaches to sustainable intensification include the use of plant genome editing tools such as CRISPR, with most of the research originating from China and the US.[283] CRISPR is considered cheaper and more versatile than previous biotechnologies, with China having invested heavily in CRISPR-modified organisms as a way to sustainably increase crop production and meet the needs of a growing population.[284] In early field experiments in China, tests of new mutated rice strains have had positive results in terms of both developing abiotic stress resistance and promoting yield growth (with a 25–31 per cent increase recorded for the latter).[285] However, a clear regulatory policy for gene-edited crops has yet to be established; this could impede the rate of progress from research to widespread commercial use.

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278 Ministry of Agriculture, Nature and Food Quality of the Netherlands (2018), *Agriculture, nature and food: valuable and connected: The Netherlands as a leader in circular agriculture*, https://www.government.nl/ministries/ministry-of-agriculture-nature-and-food-quality/documents/policy-notes/2018/11/19/vision-ministry-of-agriculture-nature-and-food-quality---english.
279 Van Berkum, S. and Dengerink, J. (2019), *Transition to sustainable food systems: the Dutch circular approach providing solutions to global challenges*, Wageningen: Wageningen University, https://edepot.wur.nl/495586.
280 *AsiaLife* (2015), 'Urban Farming', 10 June 2015, https://www.asialifemagazine.com/vietnam/urban-farming.
281 Capron, A. (2016), 'Ugandans try "stack farming" as arable land disappears', France 24, 3 August 2016, https://observers.france24.com/en/20160803-arable-land-uganda-vertical-farms.
282 Mayoyo, P. (2015), 'How to grow food in a slum: lessons from the sack farmers of Kibera', *Guardian*, 18 May 2015, https://www.theguardian.com/global-development-professionals-network/2015/may/18/how-to-grow-food-in-a-slum-sack-farmers-kibera-urban-farming.
283 Martin-Laffon, J., Kuntz, M. and Ricroch, A. E. (2019), 'Worldwide CRISPR patent landscape shows strong geographical biases', *Nature Biotechnology*, 37(6), pp. 613–20, https://doi.org/10.1038/s41587-019-0138-7.
284 Cohen, J. (2019), 'To feed its 1.4 billion, China bets big on genome editing of crops', *Science*, https://doi.org/10.1126/science.aay8951.
285 Zeng, Y. et al. (2020), 'Rational Improvement of Rice Yield and Cold Tolerance by Editing the Three Genes OsPIN5b, GS3, and OsMYB30 With the CRISPR–Cas9 System', *Frontiers in Plant Science*, 10, https://doi.org/10.3389/fpls.2019.01663; Miao, C. et al. (2018), 'Mutations in a subfamily of abscisic acid receptor genes promote rice growth and productivity', *Proceedings of the National Academy of Sciences*, 115(23), pp. 6058–63, https://doi.org/10.1073/pnas.1804774115.

4.2.2 Dietary change

Supply-side measures to increase production will not be sufficient to meet future demand for food without accompanying interventions to change consumption patterns.[286] A shift in diets – and particularly a transition away from meat-rich diets – could radically alter future patterns of agricultural land use.[287] Scenario-based modelling has shown that completely replacing consumption of animal products with plant-based foods in high-income countries could result in a 29 per cent reduction in associated global cropland use; the same strategy in upper-middle-income countries would reduce their cropland footprint by 12 per cent compared with business-as-usual projections for 2030.[288] Modelling has also indicated that, at a global level, universal adoption of 'healthy'[289] diets (limiting but not eliminating animal produce) could reduce the required area of cropland by around 5 per cent by 2050, and that of pasture by around 25 per cent, compared with scenarios involving no dietary changes (see Chapter 6).[290]

While there is broad consensus on the environmental and public health advantages of tackling overconsumption of meat in high-consuming countries,[291] there remains considerable debate around the role of livestock and animal-sourced foods in achieving food and nutrition security, alongside environmental sustainability, in developing countries.[292] A number of studies have attempted to determine the parameters for a diet that is nutritious for all – and culturally and environmentally appropriate – while being deliverable from a food system within planetary boundaries.[293] These studies broadly find that such a diet consists primarily of vegetables, fruits, nuts, wholegrains and unsaturated oils, together with small quantities of seafood and poultry, but includes little or no red meat, sugar or refined grains. Important barriers to the adoption of such a diet nevertheless remain, including its affordability[294] and its appropriateness among different cultures. However, a fuller accounting of the costs of diets (including costs associated with diet-related illness and diet-related impacts on climate change, which are not currently reflected in the price of food) demonstrates that healthy and sustainable diets are the least costly option in most countries.[295]

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286 Bajželj et al. (2014), 'Importance of food-demand management for climate mitigation'.
287 Erb, K.-H. et al. (2016), 'Exploring the biophysical option space for feeding the world without deforestation', *Nature Communications*, 7(1), 11382, https://doi.org/10.1038/ncomms11382.
288 Springmann, M. et al. (2018), 'Health and nutritional aspects of sustainable diet strategies and their association with environmental impacts: a global modelling analysis with country-level detail', *The Lancet Planetary Health*, 2(10), pp. e451–e461, https://doi.org/10.1016/S2542-5196(18)30206-7.
289 Parameterized on a regional basis by reshaping existing dietary preferences to cap the average daily consumption of refined sugars and sweeteners, and vegetable oils, meat and dairy as sources of saturated fats, and by prescribing a minimum level of fruit and vegetable consumption. The model ensures that adjusted diets still provide enough protein, and a daily calorie intake of 2,500 kcal per capita, through an increase in consumption of pulses and staples. See supplementary information for Bajželj et al. (2014), 'Importance of food-demand management for climate mitigation'.
290 Bajželj et al. (2014), 'Importance of food-demand management for climate mitigation'.
291 Willett, W. et al. (2019), 'Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems', *The Lancet*, 393(10170), pp. 447–92, https://doi.org/10.1016/S0140-6736(18)31788-4.
292 Röös, E. et al. (2017), 'Greedy or needy? Land use and climate impacts of food in 2050 under different livestock futures', *Global Environmental Change*, 47, pp. 1–12, https://doi.org/10.1016/j.gloenvcha.2017.09.001.
293 Willett et al. (2019), 'Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems'; Gordon, L. J. et al. (2017), 'Rewiring food systems to enhance human health and biosphere stewardship', *Environmental Research Letters*, 12(10), p. 100201, https://doi.org/10.1088/1748-9326/aa81dc; Tilman, D. and Clark, M. (2014), 'Global diets link environmental sustainability and human health', *Nature*, 515, pp. 518–22, https://doi.org/10.1038/nature13959.
294 Hirvonen, K., Bai, Y., Headey, D. and Masters, W. A. (2020), 'Affordability of the EAT–Lancet reference diet: a global analysis', *The Lancet Global Health*, 8(1), pp. e59–e66, https://doi.org/10.1016/S2214-109X(19)30447-4.
295 Springmann, M. et al. (2021), 'The global and regional costs of healthy and sustainable dietary patterns: a modelling study', *Lancet Planetary Health*, 5(11), pp. e797-e807, https://doi.org/10.1016/S2542-5196(21)00251-5.

In countries where consumption of meat is in excess of recommended 'healthy' levels – as defined by the World Health Organization or by national dietary guidelines – a range of interventions have been discussed or trialled as potential means of prompting people to reduce their intake.[296] These interventions span a broad spectrum, including information campaigns, 'nudge' tactics such as changes to menu and label design, and the use of a 'meat tax'.[297]

4.2.3 Reductions in food losses and waste

Around 13 per cent of food is lost post-harvest and in the supply chain; and a further 17 per cent is wasted by households, in food services and in retail.

Given the scale of food losses and waste globally – around 13 per cent is lost post-harvest and in the supply chain; and a further 17 per cent is wasted by households, in food services and in retail[298] – reducing these could result in considerable land savings. Based on current trends in crop yields, a 50 per cent reduction in food waste would result in a projected 14 per cent reduction in cropland requirement (and an 11 per cent reduction in all agricultural land use) by 2050, compared with a business-as-usual scenario (see Chapter 6).[299] One estimate suggests that an additional 235 million people could be fed from the crops used to produce consumer-wasted meat products alone.[300] In 2019, the EAT-*Lancet* Commission on healthy diets from sustainable food systems estimated that, in the absence of radical dietary change, current cropland will be sufficient to meet food demand in 2050 only if food waste is halved and yield gaps are closed by 75 per cent.[301] And as around 10 per cent of all anthropogenic greenhouse gas emissions come from food system processes associated with food that is ultimately lost or wasted,[302] eliminating or minimizing these losses would also have land-sparing benefits by reducing the amount of land needed for compensatory carbon sequestration.

The most effective strategies to tackle food waste and losses will differ from country to country. In countries where waste is concentrated towards the consumption end of the value chain, changes to practices among food manufacturers and

296 Bailey, R. and Harper, D. R. (2015), *Reviewing Interventions for Healthy and Sustainable Diets*, Research Paper, London: Royal Institute of International Affairs, https://www.chathamhouse.org/sites/default/files/field/field_document/20150529HealthySustainableDietsBaileyHarperFinal.pdf; de Boer, J., Schösler, H. and Aiking, H. (2014), '"Meatless days" or "less but better"? Exploring strategies to adapt Western meat consumption to health and sustainability challenges', *Appetite*, 76, pp. 120–28, https://doi.org/10.1016/j.appet.2014.02.002; Wellesley, L., Happer, C. and Froggatt, A. (2015), *Changing Climate, Changing Diets: Pathways to Lower Meat Consumption,* Report, London: Royal Institute of International Affairs, https://www.chathamhouse.org/publication/changing-climate-changing-diets.
297 Wellesley, Happer and Froggatt (2015), *Changing Climate, Changing Diets*; Attwood S., Voorheis, P., Mercer, C., Davies, K. and Vennard, D. (2020), *Playbook for Guiding Diners Toward Plant-Rich Dishes in Food Service*, World Resources Institute Better Buying Lab, https://files.wri.org/s3fs-public/19_Report_Playbook_Plant-Rich_Diets_final.pdf; Springmann, M. et al. (2018), 'Health-motivated taxes on red and processed meat: A modelling study on optimal tax levels and associated health impacts', *PLoS ONE*, 13(11), p. e0204139, https://doi.org/10.1371/journal.pone.0204139.
298 FAO (2023), 'FAOSTAT > SDG Indicators', https://www.fao.org/faostat/en/#data/SDGB (accessed 10 Jan. 2023); United Nations Environment Programme (2021), *Food Waste Index Report 2021*, Nairobi, https://www.unep.org/resources/report/unep-food-waste-index-report-2021.
299 Bajželj et al. (2014), 'Importance of food-demand management for climate mitigation'.
300 Davis, K. F. and D'Odorico, P. (2015), 'Livestock intensification and the influence of dietary change: A calorie-based assessment of competition for crop production', *Science of The Total Environment*, 538, pp. 817–23, https://doi.org/10.1016/j.scitotenv.2015.08.126.
301 According to Willett et al. (2019), in this scenario nitrogen and phosphorous fertilizer use would need to be rebalanced, water management improved, irrigation patterns changed, greenhouse gas emissions kept to today's levels, and enteric fermentation in livestock reduced. Willett et al. (2019), 'Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems'.
302 IPCC (2019), 'Summary for Policymakers', in Shukla, P. R. et al. (eds.) (2019), *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*, Geneva: IPCC, https://www.ipcc.ch/srccl/chapter/summary-for-policymakers.

retailers will be particularly important: for example, reform of 'best before' dates to avoid waste of safe food; or the easing of 'aesthetic' standards that currently mean that large volumes of fresh fruit and vegetables are rejected by retailers and their suppliers. Interventions targeted at consumer behaviour may also be needed to effect waste reductions at scale. These could include communication campaigns, changes to food-labelling requirements, and new technologies such as 'smart' refrigerators – for example, those that include a camera to enable inventory-taking and planning, or those that alert users when food nears its expiry date.[303]

In countries where access to technologies, infrastructure and transport is lacking, with the effect that food is lost predominantly at the post-harvest and supply chain stages, strategies will need to tackle structural conditions such as energy access at farm level, storage capacity, quality of transport infrastructure, and reliability of cold chain logistics. Greater use of surplus food in animal feed production, either as a direct ingredient or as a feedstock for insect meal, may offer another important means of reducing overall nutrient losses along the food value chain while easing pressure on land use for feed production.[304]

Measures to mitigate food waste at the point of consumption will also become increasingly important as efficiency improves at the point of production and processing. To date, innovations in the storage, transport and conservation of food have already led to lower rates of food loss, and have done much to improve food access and availability. However, in also lowering food prices, such efficiency gains have in turn induced consumers and retailers to waste more food.[305]

4.2.4 Decoupling food production from land use

Innovation has emerged in recent years that focuses on decoupling food production from land use, principally through so-called 'landless' systems and novel alternatives to conventionally produced meat. Landless farming encompasses a range of methods to produce food crops in controlled environments. Key among these are hydroponics, where crops are grown in soil-free, suspended 'farms' with their roots bathed in a nutrient-rich solution; and aeroponics, in which the roots are sprayed with a nutrient-rich solution. Lighting, humidity and temperature can all be carefully controlled to provide the optimum conditions for plant growth and minimize evaporation, thus conserving water. 'Landless' systems are in the early stages of development, and are currently used predominantly for high-value horticultural crops rather than staple cereals. But they have the potential to boost production in land-scarce settings such as cities, as well as in regions where water is limited or soil quality is poor.[306]

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303 Hebrok, M. and Boks, C. (2017), 'Household food waste: Drivers and potential intervention points for design – An extensive review', *Journal of Cleaner Production*, 151, pp. 380–92, https://doi.org/10.1016/j.jclepro.2017.03.069.
304 WWF (2021), *No Food Left Behind Part IV: Benefits & Trade-offs of Food Waste-to-Feed Pathways*, https://www.worldwildlife.org/publications/benefits-trade-offs-of-food-waste-to-feed-pathways; Salemdeeb, R. et al. (2017), 'Environmental and health impacts of using food waste as animal feed: a comparative analysis of food waste management options', *Journal of Cleaner Production,* 140(2), pp. 871–80, https://doi.org/10.1016/j.clepro.2016.05.049.
305 Bianchi, E. et al. (2018), 'Redirecting investment for a global food system that is sustainable and promotes healthy diets', *Economics Discussion Papers*, No. 2018-69, Kiel: Kiel Institute for the World Economy, https://www.econstor.eu/bitstream/10419/182388/1/1031322396.pdf.
306 Benke, K. and Tomkins, B. (2017), 'Future food-production systems: vertical farming and controlled-environment agriculture', *Sustainability: Science, Practice and Policy*, 13(1), pp. 13–26, https://doi.org/10.1080/15487733.2017.1394054.

Production of cultured meat may require a land area as small as 1 per cent of that used to produce conventional meat.

Novel alternatives to meat offer a more radical means of decoupling food production from land use, reducing inputs and mitigating agricultural emissions. Plant-based meat substitutes use plant-derived ingredients to mimic the look, taste and texture of meat, while 'cultured meat' involves isolating stem cells from an animal and then cultivating these cells in a laboratory or bioreactor with the help of a growth medium.[307] One prominent estimate suggests that replacing half of global animal-product consumption with consumption of plant-based substitutes such as soybean curd (tofu) could reduce agricultural land use by 35 per cent, while a 29 per cent reduction could be achievable if cultured meat is used.[308] (See Chapter 6 for a further discussion of this issue.) Other estimates suggest that production of cultured meat may require a land area as small as 1 per cent of that used to produce conventional meat.[309] Both plant-based imitations and cultured meat are the focus of rapidly growing industries as technologies advance and, in the case of cultured meat, as products begin to enter the market (plant-based substitutes already being more established).[310] In 2021, capital investment in companies making plant-based meat, dairy and egg products amounted to 30 per cent of the all-time total, while investment in cultured-meat companies was up 236 per cent year on year. However, in a more difficult economic context, investments in all forms of meat alternatives have since fallen back.[311]

Algae and insects are also increasingly recognized as novel protein sources, with the potential to bring significant land savings in the production of animal feed and biofuel. Algae provide a potential feedstock for biofuel and animal feed, and can also be grown in deserts. Should technological barriers be overcome, industrial algae production could provide 10 times as much feed protein as global soybean production, and meet global liquid fuel demand using an area of land just three times the size of Texas.[312] Farmed insects, which may be fed on waste biomass, can provide a protein source both for direct human consumption and for use in animal feed. They have a much smaller land footprint than conventional animal protein sources: early estimates suggest that the production of 1 gram of edible chicken protein requires two to three times as much land as does 1 gram of edible mealworm protein, while production of 1 gram of edible beef protein uses between eight and 10 times as much land.[313]

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307 Froggatt, A. and Wellesley, L. (2019), *Meat Analogues: Considerations for the EU*, Research Paper, London: Royal Institute of International Affairs, https://www.chathamhouse.org/2019/02/meat-analogues.
308 Alexander, P. et al. (2017), 'Could consumption of insects, cultured meat or imitation meat reduce global agricultural land use?', *Global Food Security*, 15, pp. 22–32, https://doi.org/10.1016/j.gfs.2017.04.001.
309 Tuomisto, H. L. and Teixeira de Mattos, M. J. (2011), 'Environmental Impacts of Cultured Meat Production', *Environmental Science & Technology*, 45(14), pp. 6117–23, https://doi.org/10.1021/es200130u.
310 Good Food Institute (2022), *2021 State of the Industry Report: Plant-based meat, seafood, eggs, and dairy*, https://gfi.org/wp-content/uploads/2022/04/2021-Plant-Based-State-of-the-Industry-Report-1.pdf; Good Food Institute (2022), *2021 State of the Industry Report: Cultivated meat and seafood*, https://gfi.org/wp-content/uploads/2022/04/2021-Cultivated-Meat-State-of-the-Industry-Report-1.pdf.
311 Total invested capital rose from $410 million in 2020 to $1.38 billion in 2021. For the more recent context, see Speed, M. (2023), 'Venture capital funds cool on plant-based meat start-ups', *Financial Times*, 4 July 2023, https://on.ft.com/3t2vsox.
312 Greene, C. et al. (2016), 'Marine Microalgae: Climate, Energy, and Food Security from the Sea', *Oceanography*, 29(4), https://doi.org/10.5670/oceanog.2016.91.
313 van Huis, A. and Oonincx, D. G. A. B. (2017), 'The environmental sustainability of insects as food and feed. A review', *Agronomy for Sustainable Development*, 37(5), p. 43, https://doi.org/10.1007/s13593-017-0452-8; van Huis, A. (2013), 'Potential of Insects as Food and Feed in Assuring Food Security', *Annual Review of Entomology*, 58(1), pp. 563–83, https://doi.org/10.1146/annurev-ento-120811-153704.

4.3 How plausible is a reduced land footprint for food production?

All available evidence suggests new strategies will not be deployed at the pace and scale required to avoid an increase in agricultural land demand and the further degradation of existing agricultural land.

All available evidence suggests new strategies will not be deployed at the pace and scale required to avoid an increase in agricultural land demand and the further degradation of existing agricultural land. Many of the most promising interventions in support of sustainable intensification and the decoupling of food production from land use have yet to be proved at scale.[314] The feasibility of each of the four strategies discussed above – sustainable intensification, dietary change, food loss and waste reduction, and decoupling food production from land use – is also highly dependent on the deployment of one or more of the other strategies in parallel. For example, existing techniques for boosting agricultural yields are unlikely to be enough to match demand growth,[315] so dietary shifts will also be needed to limit overall demand. At the same time, a shift to low- or no-meat diets will likely be difficult to realize without first closing the gap between current and potential crop yields, particularly for fruits and vegetables.[316] And higher yields for plant-based foods are only likely to be realized through increased freshwater use in irrigation.[317]

Significant uncertainties about regional patterns of uptake of these strategies also remain, as do questions as to where each approach (or combination of approaches) should best be deployed to achieve the maximum reduction in land use for food production while supporting global food and nutrition security. The viability of each of the strategies discussed in Section 4.2 depends on considerable shifts in institutional, societal and individual behaviours.[318] Financial, policy and

314 Fischer, R. A., Byerlee, D. and Edmeades, G. O. (2009), 'Can technology deliver on the yield challenge to 2050?', Rome: paper for the FAO Expert Meeting on How to Feed the World in 2050, 24–26 June 2009, https://ageconsearch.umn.edu/record/55481; Alexander et al. (2017), 'Could consumption of insects, cultured meat or imitation meat reduce global agricultural land use?'; Garnett, T. et al. (2013), 'Sustainable Intensification in Agriculture: Premises and Policies', *Science*, 341, pp. 33–34, https://doi.org/10.1126/science.1234485; Al-Chalabi, M. (2015), 'Vertical farming: Skyscraper sustainability?', *Sustainable Cities and Society*, 18, pp. 74–77, https://doi.org/10.1016/j.scs.2015.06.003.
315 Davis et al. (2016), 'Meeting future food demand with current agricultural resources'.
316 Ibid.
317 Springmann et al. (2018), 'Health and nutritional aspects of sustainable diet strategies and their association with environmental impacts: a global modelling analysis with country-level detail'; Davis et al. (2016), 'Meeting future food demand with current agricultural resources'.
318 Smith, P. (2013), 'Delivering food security without increasing pressure on land', *Global Food Security*, 2(1), pp. 18–23, https://doi.org/10.1016/j.gfs.2012.11.008; Parfitt, J., Barthel, M. and Macnaughton, S. (2010), 'Food waste within food supply chains: quantification and potential for change to 2050', *Philosophical Transactions of the Royal Society B: Biological Sciences*, 365, pp. 3065–81, https://doi.org/10.1098/rstb.2010.0126; Meijer, S. S. et al. (2015), 'The role of knowledge, attitudes and perceptions in the uptake of agricultural and agroforestry innovations among smallholder farmers in sub-Saharan Africa', *International Journal of Agricultural Sustainability*, 13(1), pp. 40–54, https://doi.org/10.1080/14735903.2014.912493; Mwangi, M. and Kariuki, S. (2015), 'Factors Determining Adoption of New Agricultural Technology by Smallholder Farmers in Developing Countries', *Journal of Economics and Sustainable Development*, 6(5), https://www.iiste.org/Journals/index.php/JEDS/article/view/20710/21632; Price, J. C. and Leviston, Z. (2014), 'Predicting pro-environmental agricultural practices: The social, psychological and contextual influences on land management', *Journal of Rural Studies*, 34, pp. 65–78, https://doi.org/10.1016/j.jrurstud.2013.10.001.

institutional constraints also threaten to slow these shifts and hamper widespread adoption, especially for technology-dependent solutions.[319]

Climate change is likely to increase the area of cultivable land in developed countries in high latitudes,[320] but a combination of trends – urban encroachment on croplands, growing demand for bioenergy production, increased reliance on carbon capture and storage – mean that the use of this land for food production is far from certain. On the other hand, in low-latitude countries where the area of cultivable land is projected to decrease with climate change, and where yields are expected to decline, the area of land under cultivation is forecast to increase substantially.[321] With or without the implementation of the strategies described above, many countries will increasingly look overseas for food production capacity, and land-rich countries where governance is poor will in turn likely see continued widespread land-use change.

319 Long, T. B., Blok, V. and Coninx, I. (2016), 'Barriers to the adoption and diffusion of technological innovations for climate-smart agriculture in Europe: evidence from the Netherlands, France, Switzerland and Italy', *Journal of Cleaner Production*, 112, pp. 9–21, https://doi.org/10.1016/j.jclepro.2015.06.044; Preston, F., Lehne, J. and Wellesley, L. (2019), *An Inclusive Circular Economy: Priorities for Developing Countries*, Research Paper, London: Royal Institute of International Affairs, https://www.chathamhouse.org/publication/inclusive-circular-economy-priorities-developing-countries; Rosenstock, T. S. et al. (2016), *The scientific basis of climate-smart agriculture: A systematic review protocol*, CCAFS Working Paper no. 138, Copenhagen: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), https://cgspace.cgiar.org/bitstream/handle/10568/70967/CCAFSWP138.pdf; Pretty, J. and Bharucha, Z. P. (2014), 'Sustainable intensification in agricultural systems', *Annals of Botany*, 114(8), pp. 1571–96, https://doi.org/10.1093/aob/mcu205; van Delden, S. H. et al. (2021), 'Current status and future challenges in implementing and upscaling vertical farming systems', *Nature Food*, 2(12), pp. 944–56, https://doi.org/10.1038/s43016-021-00402-w.
320 Olsson et al. (2019), 'Land Degradation', in Shukla et al. (eds) (2019), *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*.
321 Alexandratos, N. and Bruinsma, J. (2012), *World Agriculture Towards 2030/2050: The 2012 Revision*, ESA Working Paper No. 12-03, Rome: FAO, http://www.fao.org/3/a-ap106e.pdf.

05 Land and energy pressures

Decisions on land use in the energy sector must consider not only how to power the world of the future without significantly increasing the sector's land footprint, but also whether more expansive use of bioenergy is really feasible as a tool to mitigate climate change.

5.1 Introduction

The COVID-19 pandemic and subsequent fitful economic recovery, along with the impacts of Russia's war on Ukraine, have profoundly disrupted global energy markets. Both fossil fuels and low-carbon alternatives have been affected – and although hydrocarbon prices have eased since their peak in the aftermath of Russia's full-scale invasion of Ukraine in early 2022, both the pandemic and the war in Ukraine have underscored the vulnerability of many energy strategies to movements in energy markets.

Higher prices have put energy affordability and security at the forefront of national politics and, in some cases, have downgraded the political attention paid to emission-reduction plans and have even increased efforts to secure new sources of fossil fuels. Nonetheless, higher fossil fuel prices are likely to be the ultimate accelerant of measures to phase out dependency on hydrocarbons, and global renewable energy deployment is set to break all records in 2023. While it is too early to hypothesize about the long-term outcomes of recent changes in supply, demand and prices, decisions around future energy infrastructure will certainly have consequences for land use.

Two broad and opposing scenarios for the transition to green energy have emerged in the context of recent market upheavals. On the one hand, renewable energy optimists are contemplating a scenario in which peak demand for fossil fuels is reached earlier than expected, as the improving cost competitiveness of renewables in relation to fossil fuels drives an accelerated transition by countries seeking greater energy independence, and by energy companies investing windfall profits into low-carbon technologies.

On the other hand, some observers, witnessing new fossil fuel extraction and supply contracts being signed, anticipate that such patterns could become more widespread if hydrocarbon prices return to their recent very high levels (whether due to the war in Ukraine and international sanctions against Russia, or in response to political or market upheavals elsewhere, such as in the Middle East). The temptation would then increase for countries to exploit such options as a misguided 'quick fix' response to energy security or inflation concerns.

Direct land use for energy production is currently small in comparison with other land uses, accounting for approximately 2 per cent of the global land area.[322] However, anticipated changes in the global energy mix in response to the need to mitigate climate change have the potential to increase very significantly the land footprint of energy infrastructure.

Anticipated changes in the global energy mix in response to the need to mitigate climate change have the potential to increase very significantly the land footprint of energy infrastructure.

All forms of energy production require land. In some cases – including offshore operations such as wind farms and oil rigs, and onshore subterranean operations such as geothermal energy – the land footprint can be extremely small. Thermal power stations (coal, gas, nuclear and waste) and oil refineries also have small direct land footprints, but they require larger areas of land for their indirect extraction, processing and transportation requirements. Onshore wind and solar power footprints are made up of the principal installations, along with access roads and power transmission lines. The overall impact of such facilities varies according to where they are sited; in many cases, they can coexist with other land uses such as agriculture and established infrastructure. The land footprint of hydroelectric facilities depends on the area of flooded land, which varies significantly according to the size of the facility and the terrain.

Among all energy sources, the most significant land footprint is associated with bioenergy – whether generated from solid biomass, liquid biofuels or biogas. In addition to being grown specifically as a fuel source, bioenergy feedstocks can be derived from wastes and residues of industries with existing land footprints, such as timber production or agriculture; in these cases, the implications for land use are very different.

Given the urgent need for rapid acceleration of the energy transition to prevent the worst impacts of climate change, there are concerns that also need to be addressed as regards the competition for land that some new energy sources may create. As the energy densities of renewable energy sources are significantly lower than those of fossil fuels and nuclear power, supplying an equivalent amount of energy from renewables to that provided by hydrocarbons and nuclear requires proportionally more generators and, in the case of bioenergy, abundant feedstocks. The land-use pressures associated with these requirements will be compounded by the increased energy demand anticipated over the coming decades.

322 Fritsche, U. R. et al. (2017), *Energy and Land Use*, Global Land Outlook Working Paper, United Nations Convention to Combat Desertification (UNCCD), https://www.unccd.int/resources/publications/energy-and-land-use.

In 2017, the International Energy Agency (IEA) and the International Renewable Energy Agency (IRENA) presented the findings of a joint global energy scenario, named REmap (Renewable Energy Roadmap),[323] to the German presidency of the G20. REmap was a low-carbon technology pathway for an energy transition positioned as being 'compatible with limiting the rise in global mean temperature to 2°C by 2100 with a probability of 66 per cent, as a way of contributing to the "well below 2°C" target of the Paris Agreement'.[324]

Excessive reliance on bioenergy, with or without carbon capture and storage, would be the single biggest energy-sector driver of increased land use, both in forests and on agricultural lands.

This chapter considers the relative land footprints of different energy sources, using REmap as the basis for an indicative analysis of potential future tensions between land uses. Specifically, it explores the implications for land use of the assumptions in the REmap scenario, and considers the land-use pressures that might thus be associated with its realization. The IEA has since released an updated iteration of its analysis,[325] which now assumes an increased level of ambition for solar, wind and green hydrogen and therefore reduced reliance on bioenergy with carbon capture and storage (BECCS). This indicates potential to reduce the land footprint of the energy sector by further mobilizing investment in alternative renewables. However, the original REmap scenario – on which the analysis in this chapter focuses – remains an equally plausible illustration of the means and consequences of pursuing a more land-intensive approach to meeting the Paris targets.[326] This is especially pertinent if decarbonization is delayed in the near to medium term, and if solutions increasingly rely on negative emissions from BECCS during the 2040s. As this chapter shows, excessive reliance on bioenergy, with or without carbon capture and storage (CCS), would be the single biggest energy-sector driver of increased land use, both in forests and on agricultural lands.

5.2 Growth in energy demand and renewable energy supply

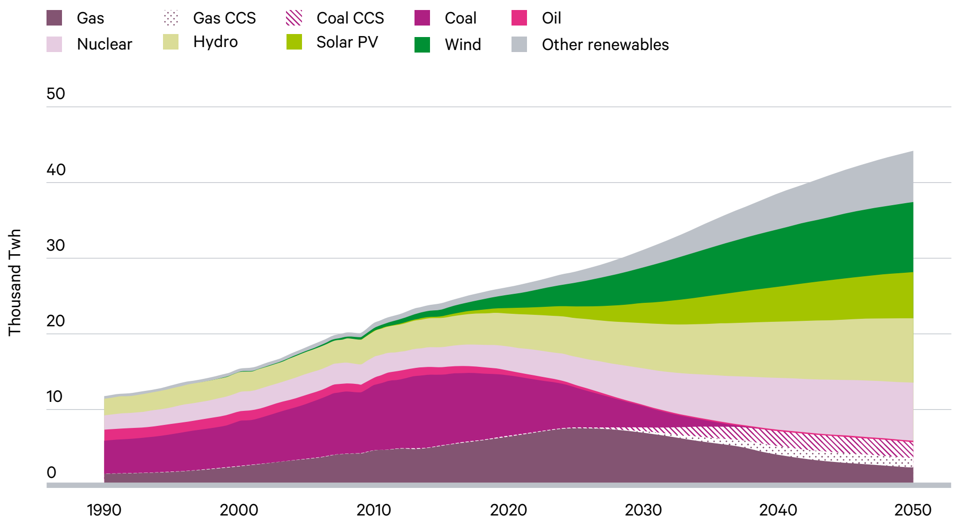
Growth in demand for energy depends on the mix of policies that governments adopt, and on the global economic impacts of events such as – most recently – Russia's war on Ukraine and the COVID-19 pandemic. In the IEA's Stated Policies Scenario,[327] global energy demand is projected to increase by more than 30 per cent from 2020 to 2040,[328] due to rising incomes and the addition of 1.3 billion people to the population. (This estimate does not account for any potential economic or demand changes resulting from the pandemic or from

323 International Renewable Energy Agency (IRENA) and International Energy Agency (IEA) (2017), *Perspectives for the Energy Transition: Investment Needs for a Low-Carbon Energy System*, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Mar/Perspectives_for_the_Energy_Transition_2017.pdf.
324 Ibid.
325 IEA (2021), *Net Zero by 2050: A Roadmap for the Global Energy Sector*, Paris: IEA, www.iea.org/reports/net-zero-by-2050.
326 There remain considerable uncertainties around future energy deployment mixes and the land area requirements of bioenergy and BECCS – see, for example, the different land-use change implications of IPCC 1.5°C-consistent scenarios in Figure 22. We therefore use the REmap energy scenario as a starting point to constrain the uncertainties for our analysis.
327 Previously known as the IEA's New Policies Scenarios; reflects the impact of existing policy frameworks and broader policy intentions that have been announced.
328 IEA (2019), *World Energy Outlook 2019*, Paris: IEA, https://www.iea.org/reports/world-energy-outlook-2019.

the Ukraine war.[329]) This increase in demand would be roughly twice as large were it not for projected improvements in energy efficiency. In contrast, in the IEA's Sustainable Development Scenario, overall demand in 2040 is kept at current levels by pursuing all economically viable avenues to improve efficiency. The REmap scenario investigated in this chapter also holds energy demand near current levels, but with a 2050 time horizon.

Fossil fuels remain dominant in today's energy mix, but the improving economics of renewable energy are changing the picture. In 2018, fossil fuels were used to meet 81 per cent of total primary energy demand, renewables 14 per cent and nuclear about 5 per cent.[330] The majority of renewables produce electricity, and in 2018 they accounted for 26 per cent of final electricity generation.[331]

Figure 26. Global electricity generation by source in the REmap 66 per cent 2°C scenario



Source: International Renewable Energy Agency (IRENA) and International Energy Agency (IEA) (2017), *Perspectives for the Energy Transition: Investment Needs for a Low-Carbon Energy System*, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Mar/Perspectives_for_the_Energy_Transition_2017.pdf.

One notable phenomenon, arguably a leading indicator of an accelerating low-carbon transition, is that most recent energy supply forecasts and scenarios have consistently *underestimated* the rate of deployment of renewables. Increased deployment rates have been accompanied by falling costs, improved technical viability, and thus greater public acceptance of renewable energy. As a result, the decades-old argument for a combination of renewables, fossil fuels, CCS and nuclear power is weakening. As IRENA emphasized in 2019: 'In most parts of the

329 The Stated Policies Scenario in the 2022 World Energy Outlook, launched after the calculations in this report were produced, projects a 24 per cent increase in global final energy consumption by 2040 relative to 2020, and a 30 per cent increase by 2050. IEA (2022), *World Energy Outlook 2022*, Paris: IEA, https://www.iea.org/reports/world-energy-outlook-2022.
330 IEA (2019), *Global Energy & CO_2 Status Report 2019*, Paris: IEA, https://www.iea.org/reports/global-energy-co2-status-report-2019/emissions.
331 Ibid.

world today, renewables are the lowest-cost source of new power generation.'[332] This trend can be expected to continue. An assessment of 100 per cent renewable energy scenarios and the criticisms of them concluded that 'the 100 per cent renewable energy scenarios proposed in the literature are not just feasible, but also viable'.[333]

The implications of this renewables transition for land use will vary significantly depending on the mix of renewables chosen. In the REmap scenario, wind power and solar photovoltaic (PV) generation become the largest technologies in terms of installed capacity, both roughly doubling their levels compared with the IEA's Stated Policies Scenario and generating 35 per cent of power by 2050 (Figure 26). Moreover, REmap envisages renewable sources providing around 65 per cent of global total primary energy supply – with solar PV, concentrated solar power (CSP), wind and hydropower providing around 36 per cent of the total renewable supply, and the remainder coming primarily from biomass.

5.3 Energy sources and their land footprints

5.3.1 Land-use intensity

Many studies have tried to quantify land use per unit of energy produced ('land-use intensity'); these assessments are summarized in Table 2. Two principal factors affect land-use intensity: operational climate conditions and the energy density of the energy source. Climate variability means that renewables produce energy at variable rates. This reduces the duration of power-producing periods and therefore increases the land required per unit of energy produced. As the energy densities of fossil fuels are significantly higher than those of renewables, and because the latter (other than geothermal power) cannot utilize subterranean resources, terrestrial renewables require more land to generate the same amount of energy.

As can be seen in Table 2, bioenergy crops require approximately 40–50 times more land than solar PV to produce an equivalent amount of energy. Searchinger et al. (2017) have estimated that on 73 per cent of the land on which solar PV is situated, over 100 times more usable energy per hectare is produced relative to bioenergy.[334] Notably, too, as discussed elsewhere in this chapter, wind and solar PV installations can coexist with agriculture and can also be built on land that is not suitable for agriculture. The same is not true of bioenergy, and while there are moves towards cultivation of bioenergy feedstocks on marginal land, the highest biomass yields are likely to originate on agricultural land. Hence, there is a far greater risk, relative to other renewables, of bioenergy directly competing for land that can otherwise be used for food production.

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332 IRENA (2019), *Renewable Power Generation Costs in 2018*, Abu Dhabi: IRENA, https://www.irena.org/publications/2019/May/Renewable-power-generation-costs-in-2018.
333 Brown, T. W. et al. (2018), 'Response to "Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems"', *Renewable and Sustainable Energy Reviews*, 92, pp. 834–47, https://doi.org/10.1016/j.rser.2018.04.113.
334 Searchinger, T. D., Beringer, T. and Strong, A. (2017), 'Does the world have low-carbon bioenergy potential from the dedicated use of land?', *Energy Policy*, 110, pp. 434–46, https://doi.org/10.1016/j.enpol.2017.08.016.

Table 2. Overview of different estimates of land-use intensity relating to a range of energy systems and fuels

Technology	Land-use intensity/footprint (ha/GWh)						
	US data (a)	US data (b)	EU data (c)	UNEP (d)	Fritsche et al. (e)	EU FOE (f)	Assumed for this report's analysis
Nuclear	0.01	0.01	0.10	–	0.01	–	NA
Gas	0.10	0.03	0.01	0.02	0.02	–	NA
Coal (open-cast)	0.82	0.02	0.04	1.50	0.50	–	NA
Onshore wind	0.13	0.10	0.07	0.03	0.10	–	0.10
Geothermal	0.51	–	0.25	0.03	0.25	–	0.25
Hydro	1.69	0.41	0.35	0.33	1.00	–	1.00
Solar PV	1.50	0.03	0.87	1.30	1.00	–	1.00
CSP	1.93	–	0.78	1.40	1.50	–	1.50
Batteries	–	–	–	–	–	–	17.78
Bioenergy crops to power	81.00	48.81	45.00	–	50.00	37.50	37.50
Forest biomass to power	–	–	–	–	–	107.90	107.90
Forest biomass to heat	–	–	–	–	–	32.37	32.37
Bioenergy crops to biofuel	34.31	47.40	–	–	–	30.51	30.51

Notes: Data include land use for spacing and from upstream life cycles (e.g. mining). '–' = no data, 'NA' = not applicable.
Sources: a) Trainor, A. M., McDonald, R. I. and Fargione, J. (2016), 'Energy Sprawl Is the Largest Driver of Land Use Change in United States', *PLoS ONE*, 11(9), p. e0162269, https://doi.org/10.1371/journal.pone.0162269; b) Fthenakis, V. and Kim, H. C. (2009), 'Land use and electricity generation: A life-cycle analysis', *Renewable and Sustainable Energy Reviews*, 13(6–7), pp. 1465–74, https://doi.org/10.1016/j.rser.2008.09.017; c) International Institute for Sustainability Analysis and Strategy (2017), 'Selected results from GEMIS 4.95: Electricity generation', http://iinas.org/tl_files/iinas/downloads/GEMIS/2017_GEMIS-results.xlsx (accessed 1 Jun. 2022); d) UNEP (2016), *Green energy choices: The benefits, risks and trade-offs of low-carbon technologies for electricity production*, Nairobi: United Nations Environment Programme; e) Fritsche, U. R. et al. (2017), 'Energy and Land Use', *Global Land Outlook Working Paper*, https://www.unccd.int/resources/publications/energy-and-land-use – estimate for unspecified region (i.e., generic); f) de Schutter, L. and Giljum, S. (2014), *A calculation of the EU Bioenergy land footprint*, Vienna: Wirtschafts Universität Wien, www.foeeurope.org/sites/default/files/agrofuels/2015/foee_bioenergy_land_footprint_may2014.pdf.

5.3.2 Fossil fuel and nuclear footprints

The land footprint[335] of fossil fuels is mainly associated with their extraction. Coal mining is the most land-intensive, particularly from open-cast pits. Coal mines also tend to have large impacts on existing water resources and surrounding land-use systems. In some countries, land reclamation is a common practice after a mine has been exhausted or otherwise decommissioned, although reclaimed mining land tends to have significantly lower levels of biodiversity and ecosystem services than land that has not been mined.

335 References in this section, except where noted: Fritsche et al. (2017), *Energy and Land Use*.

Oil and gas extraction, both onshore and offshore, usually involves smaller direct land-use footprints per unit of energy supply than coal. However, there can be additional land and environmental impacts from contamination – from leaking oil storage or pipelines, for instance. Oil and gas extraction is increasingly making use of enhanced recovery technologies such as hydraulic fracturing (fracking);[336] these processes increase the land footprint of extraction and generally have greater impacts on biodiversity, water systems and habitats.

3m
hectares of land in North America was devoted to oil and gas development from 2000 to 2012.

Although the land footprint per unit of energy for fossil fuels is small, the aggregate scale in absolute terms can be significant. In North America, approximately 3 million hectares (ha) of land (an area about the size of Belgium) was devoted to oil and gas development from 2000 to 2012.[337] In California alone, there are an estimated 105,000 active oil and gas wells (as of 2018); coupled with the associated roads, storage facilities, fuelling stations, oil refineries and pipelines, this infrastructure is estimated to occupy at least 670,000 ha, about 1.6 per cent of the state's land area.[338]

The direct land use from nuclear power is very small (see Table 2). However, the overall footprint expands considerably when the area of land required for mining uranium ores, waste storage and disposal is factored in. Nuclear accidents, of course, have the potential to affect much wider areas. The two exclusion zones created after the Chernobyl disaster in 1986 cover almost 480,000 ha, while the Fukushima exclusion zone in Japan is 31,000 ha in size.[339]

5.3.3 Renewables' direct land footprints

Solar and onshore wind power have high land-use intensities when compared with thermal power stations. This argument is sometimes used against the use of renewables. For example, according to the US Nuclear Energy Institute, solar power production uses up to 75 times more land than nuclear power does, while wind power uses up to 360 times more land.[340] A criticism of a 2018 proposal in the California state legislature to transition the state to 100 per cent renewable energy by 2045 claimed that it would 'require wrecking vast onshore and offshore territories with forests of wind turbines and sprawling solar projects'.[341]

However, such comparisons are misleading. They ignore the co-availability for other uses of the land on which renewables facilities are sited; these uses include agriculture (crops and animal pasture), forests and other ecosystem services. Within onshore wind farm boundaries, for example, approximately 90 per cent

336 Fracking is an oil well stimulation technique, conducted by the fracturing of geological bedrock formations using a pressurized liquid.
337 Allred, B. W. et al. (2015), 'Ecosystem services lost to oil and gas in North America', *Science*, 348, pp. 401–02, https://doi.org/10.1126/science.aaa4785.
338 Jacobson, M. Z., Delucch, M. A. and Enevoldsen, P. (2018), 'Using all renewables will require less land footprint than does the fossil fuel industry in California', 22 August 2018, http://web.stanford.edu/group/efmh/jacobson/Articles/I/18-08-LATimesRespBryce.pdf.
339 Area of the Fukushima exclusion zone as at May 2023. Reconstruction Agency (2023), 'Current Status of Reconstruction and Future Efforts', https://www.reconstruction.go.jp/english/topics/Progress_to_date/English_August_2023_genjoutorikumi-E.pdf.
340 Nuclear Energy Institute (2015), 'Land Needs for Wind, Solar Dwarf Nuclear Plant's Footprint', 9 July 2015, https://www.nei.org/news/2015/land-needs-for-wind-solar-dwarf-nuclear-plants.
341 Bryce, R. (2018), 'Op-Ed: All-renewable energy in California? Sorry, land-use calculations say it's not going to happen', *Los Angeles Times,* 21 August 2018, https://www.latimes.com/opinion/op-ed/la-oe-bryce-renewables-california-20180821-story.html.

of the land is not occupied by wind power equipment.[342] According to a US National Renewable Energy Laboratory (NREL) study, even though the total area per unit of energy for onshore wind ranges between 12 and 57 ha per megawatt (ha/MW) of output capacity (a typical new utility-scale wind turbine is about 2 MW), less than 0.5 ha/MW is disturbed permanently and less than 1.5 ha/MW is disturbed temporarily during construction.[343]

Utility-scale solar PV systems can also coexist with other forms of land use, particularly agriculture. Such 'agrivoltaic' systems have been widely installed in many locations over the last decade, with crops sited between solar arrays, underneath them (the shade provided by these arrays can improve productivity for some crops) or in combination with greenhouses. Solar thermal collectors for water or space heating are typically roof-mounted on individual buildings, as are small solar PV systems (250–400 W per panel), and such installations thus avoid any direct land use. In Germany, where there are over 2.2 million grid-connected PV systems (with an aggregate capacity of some 60 GW), rooftop installations make up 70 per cent of the total installed PV capacity.[344]

Another NREL assessment concluded that in terms of direct land-use requirements in the US, the capacity-weighted average for installed solar PV capacity is 3 ha/MW. In terms of actual electricity production, solar PV has an average total land-use requirement of 1.5 ha/GWh per year, and an average direct area requirement of 1.3 ha/GWh per year.[345] Based on this analysis, meeting current global electricity demand purely from utility-scale solar – however unlikely an ambition – would require the use of just 32 million ha, little more than the area of Poland. Adair Turner, the first chair of the UK's Committee on Climate Change,[346] has anticipated the potential land-use demand succinctly: even allowing for projected future population growth and increased demand for energy, 'estimated space requirements for solar energy sufficient to power the entire world are reassuringly trivial, at 0.5–1 per cent of global land area'.[347]

Of course, there are also indirect land-use impacts from the extraction of the materials used in the construction of renewable energy facilities, but for solar and wind these impacts are small. One US-focused study estimated the land use associated with mining for materials at 0.11 ha/MW for wind and 0.06 ha/MW for solar PV, compared with fuel production areas of 0.29, 0.52 and 0.58 ha/MW for coal, gas and nuclear power plants respectively.[348]

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342 Ledec, G. C., Rapp, K. W. and Aiello, R. G. (2011), *Greening the Wind: Environmental and Social Considerations for Wind Power Development*, Washington DC: World Bank, https://openknowledge.worldbank.org/handle/10986/2388; McDonald, R. I. et al. (2009), 'Energy Sprawl or Energy Efficiency: Climate Policy Impacts on Natural Habitat for the United States of America', *PLoS ONE*, 4(8), p. e6802, https://doi.org/10.1371/journal.pone.0006802.
343 Denholm, P., Hand, M., Jackson, M. and Ong, S. (2009), *Land-Use Requirements of Modern Wind Power Plants in the United States*, Golden: National Renewable Energy Laboratory, https://www.nrel.gov/docs/fy09osti/45834.pdf.
344 Fraunhofer ISE (2022), *Photovoltaics report*, Freiburg: Fraunhofer Institute for Solar Energy Systems, https://www.ise.fraunhofer.de/en/publications/studies/photovoltaics-report.html.
345 Ong, S. et al. (2013), *Land-Use Requirements for Solar Power Plants in the United States*, Golden: National Renewable Energy Laboratory, https://www.nrel.gov/docs/fy13osti/56290.pdf.
346 Subsequently renamed the Climate Change Committee, https://www.theccc.org.uk.
347 Turner, A. (2016), 'Who Has Space for Renewables?', Project Syndicate, 14 September 2016, https://www.project-syndicate.org/commentary/renewable-energy-land-requirements-by-adair-turner-2016-09.
348 Stevens, L. et al. (2017), *The Footprint of Energy: Land Use of U.S. Electricity Production*, Strata, June 2017, https://docs.wind-watch.org/US-footprints-Strata-2017.pdf.

Large-scale hydropower, which involves storing water in reservoirs behind dams, necessarily inundates land. This means that hydropower often has large localized land footprints as well as other impacts on upstream and downstream ecosystems. The direct land-use intensity of an individual hydropower system varies, depending on its size and the local topography: hydropower plants in flat areas tend to require much more land than those in hilly areas or canyons, where deeper reservoirs can hold greater volumes of water in smaller spaces. In contrast, the land footprints and biodiversity impacts of run-of-river hydropower plants, and of mini (<10-MW) or micro (<1-MW) hydropower systems integrated into water flows, are much smaller, as these do not require large reservoirs.

Dams have significant negative biodiversity impacts through destruction of habitats and obstruction of fish migration patterns.

A review of the area of land flooded by selected individual hydroelectric systems in countries on all continents found that the land intensity varied between 0.23 and 15.64 ha/GWh.[349] The largest such system in terms of power generated – the Itaipu dam on the border between Brazil and Paraguay – was found to have one of the smallest footprints per unit of energy, at 1.26 ha/GWh (on a total inundated area of 115,700 ha). However, additional calculations for other dams in South America not covered by the specific estimates above suggested far higher land-use intensities, of around 10–30 ha/GWh for large plants and 75–175 ha/GWh for smaller plants.[350] Dams also have significant negative biodiversity impacts through destruction of habitats and obstruction of fish migration patterns.

5.3.4 The emergence of large battery storage sites

Greater dependence on renewables will require greater flexibility of power systems[351] to account for increased daily variability in generation. One of many technologies with the potential to increase such flexibility is battery storage. The cost of battery production is falling sharply, and can be expected to continue doing so.

While large-scale battery storage is in its infancy, indications of its land footprint are beginning to emerge. Extrapolating from the efficiencies of the world's largest battery storage facility, in Florida, we estimate that providing enough battery storage for a single day's power supply globally would require about 1.3 million ha of land, a little less than the area of Montenegro.[352] Storage options other than batteries also exist – and more are likely to emerge. Currently the most used is pumped-hydro storage.

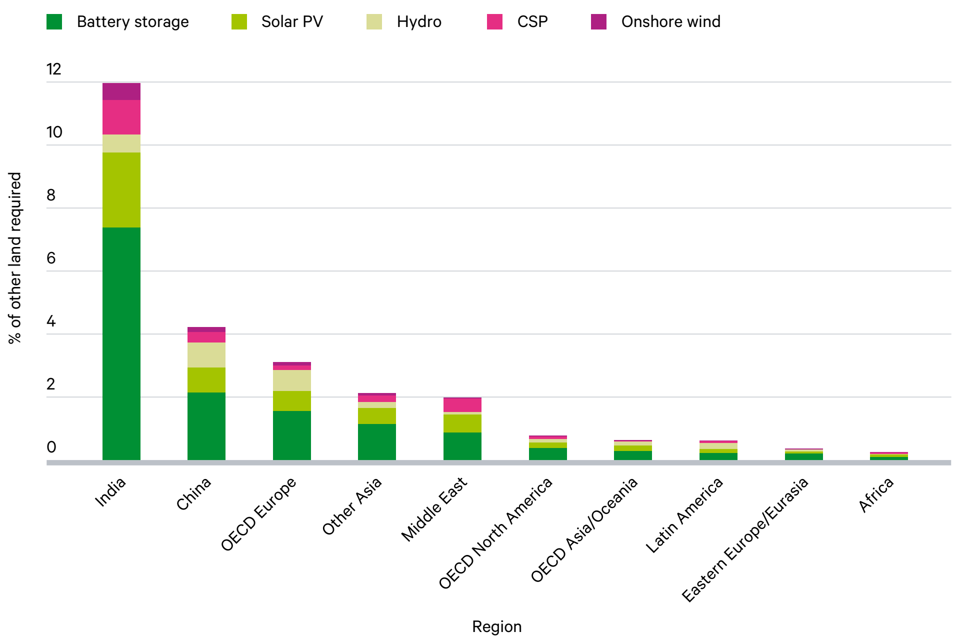
349 Fritsche et al. (2017), *Energy and Land Use*.
350 Ibid.
351 Froggatt, A. and Quiggin, D. (2018), *The Power of Flexibility: The Survival of Utilities During the Transformations of the Power Sector*, Research Paper, London: Royal Institute of International Affairs, https://www.chathamhouse.org/2018/08/power-flexibility.
352 The Manatee Energy Storage Center is a 409-MW/900-MWh battery storage facility in the US that was completed at the end of 2021. Said to be the world's largest, the facility covers 16 ha. Current total annual global electricity consumption is 26,614 TWh; daily demand is in the order of 72 TWh – which is 80,000 times larger than the electricity supply available from the Manatee facility. 80,000 multiplied by 16 ha is 1.28 million ha. Colthorpe, A. (2021), 'World's biggest solar-charged battery storage system unveiled in Florida', Energy Storage News, 15 December 2021, https://www.energy-storage.news/worlds-biggest-solar-charged-battery-storage-system-unveiled-in-florida.

5.4 Land requirement for renewables in 2050

Drawing on the REmap energy scenario and the land footprints of the major non-biomass renewable energy technologies listed in Table 2, we calculate the global land requirement of solar PV, CSP, onshore wind and hydropower in 2050 to be around 20 million ha; this estimated area increases to 41.9 million ha with the inclusion of battery storage.[353] This land footprint, including storage, is equivalent to 0.86 per cent of global agricultural land, or 1.01 per cent of the area defined as 'other' by the Food and Agriculture Organization of the United Nations (FAO).[354] Less than 3 per cent of this 'other' land is urban in all regions considered except Europe, where around 12 per cent of such land is urban.

As already noted, it has been estimated that 0.5–1 per cent of the global land area would be required for solar to power the entire world.[355] By way of comparison, under REmap we find that 0.32 per cent of the global land area would be required by renewables excluding biomass, keeping in mind that the REmap scenario envisages non-bioenergy renewables providing only around 23.4 per cent of total energy supply.

Figure 27. Proportion of regional 'other' land (FAO classification) required for non-bioenergy renewables and storage, under REmap in 2050



Source: Calculated from International Renewable Energy Agency (IRENA) and International Energy Agency (IEA) (2017), *Perspectives for the Energy Transition: Investment Needs for a Low-Carbon Energy System*, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Mar/Perspectives_for_the_Energy_Transition_2017.pdf.

353 Land use for batteries is calculated based on ensuring sufficient storage for a given generation of variable renewable supply. Quantifying battery land use under REmap in 2050, we have assumed that further to the use of green hydrogen as a storage vector, battery storage would need to be capable of time shifting 10 per cent of variable supply, with electric vehicles providing 40 per cent of storage capacity and stationary storage 60 per cent.
354 FAO (2022), 'FAOSTAT > Land Use', https://www.fao.org/faostat/en/#data/RL (accessed 1 Jun. 2022).
355 Turner (2016), 'Who Has Space for Renewables?'.

Working on the assumption that the majority of these renewables can be deployed on non-agricultural or non-forested land, Figure 27 illustrates the proportion of 'other' land (in FAO's classification), by region, required for non-bioenergy renewables and associated battery storage in 2050, in line with REmap projections. Battery storage significantly dominates the demand for land from renewable technologies. However, excluding India, in no single region does more than 5 per cent of 'other' land need to be turned over to the deployment of renewables. In India, 12 per cent of such land is required, principally because the country has a relatively small area of land classified as 'other' (16 per cent, compared with a global average of 31 per cent).

5.4.1 Bioenergy and BECCS

Biomass-based energy is the largest source of renewable energy globally. Bioenergy accounted for an estimated 9.5 per cent of global primary energy supply in 2018, while a third of the global population is estimated to rely on this source of energy to some extent.[356]

Increasingly in recent years, a range of biomass feedstocks have been used to provide heat, power and transport, often with the stated intention of also mitigating climate change. Together, these provided an estimated 5 per cent of global final energy consumption in 2017, or nearly half of the entire contribution of modern renewable energy.[357] Wood is currently the main biomass feedstock for heat and power, while the main biomass sources for transport are maize, sugar cane, palm oil, soybean oil and rapeseed oil.[358] Other feedstock sources include woody biomass grown specifically for energy (e.g. willow or poplar); herbaceous crops such as *Miscanthus* (elephant grass); and food crops, including oil crops such as oil palm, soybean and rapeseed. Bioenergy feedstocks can also include wastes and residues from other activities: for example, wood wastes from forest harvests or sawmills; agricultural residues, including field residues and process residues; and organic wastes, such as municipal solid waste. Efforts are also being made to develop so-called advanced biofuels, using wastes or algae for feedstocks.

The impacts of bioenergy on the climate and land use are complex. Modelling generally depends on counterfactuals (i.e. what would have happened to the land, forests or crops in the absence of use for bioenergy), the data on which are highly uncertain.[359] Under greenhouse gas reporting requirements in line with the United Nations Framework Convention on Climate Change (UNFCCC), biomass is considered carbon-neutral at the point of combustion. However, along the supply chain there will be emissions from harvesting, collection, processing and transport.

356 IEA (2020), 'Global primary energy, electricity generation, final consumption and CO_2 emissions by fuel, 2018', https://www.iea.org/data-and-statistics/charts/global-primary-energy-electricity-generation-final-consumption-and-CO2-emissions-by-fuel-2018.
357 REN21 (2019), *Renewables 2019 Global Status Report*, Renewable Energy Policy Network for the 21 Century, http://www.ren21.net/Portals/97/documents/GSR/REN21_GSR2011.pdf.
358 UFOP (2018), *Report on Global Market Supply 2017/2018*, Berlin: UFOP, https://www.ufop.de/files/3515/1515/2657/UFOP_Report_on_Global_Market_Supply_2017-2018.pdf.
359 For a detailed exploration of this topic, see Brack, D. (2017), *Woody Biomass for Power and Heat: Impacts on the Global Climate*, Research Paper, Royal Institute of International Affairs, https://www.chathamhouse.org/2017/02/woody-biomass-power-and-heat; European Academies Science Advisory Council (EASAC) (2017), *Multi-functionality and Sustainability in the European Union's Forests*, https://easac.eu/publications/details/multi-functionality-and-sustainability-in-the-european-unions-forests.

Further, assumptions about carbon neutrality disregard emissions from any initial land clearances or from any indirect land uses. Equally, they fail to account for significant losses of soil carbon during harvesting, and – particularly for trees – the time delay until the new trees are large enough to absorb carbon at the same rate as the harvested trees. On the carbon neutrality of bioenergy, the Intergovernmental Panel on Climate Change (IPCC) states: 'The approach of not including these emissions in the Energy Sector total should not be interpreted as a conclusion about the sustainability, or carbon neutrality of bioenergy.'[360] Bioenergy may also have negative impacts on biodiversity, habitats and water, and be associated with harmful levels of fertilizer and pesticide use.[361]

At present, the case for bioenergy looks stronger within the aviation, heavy goods vehicles and heat sectors, but its future is highly uncertain.

If wastes and residues are used as the bioenergy feedstocks, the calculation is significantly different. However, excessive extraction of residues can impair future plant growth and accelerate land degradation, principally because the decay of plant wastes and residues maintains soil health.[362]

Policy frameworks are slowly taking shape in response to the ongoing debate about the sustainability of bioenergy. The EU is beginning to phase out support for palm oil, a crop particularly associated with negative indirect land-use impacts on forests. In addition, the rapidly falling costs of non-bioenergy renewables are undermining the case for bioenergy. At present, the case for bioenergy looks stronger within the aviation, heavy goods vehicles and heat sectors, but its future is highly uncertain.[363]

More specifically, there is considerable debate around the value of BECCS, through which carbon emissions from bioenergy combustion are captured and permanently stored to create negative emissions. The problem is that emissions from the feedstock supply chain, and the corresponding potential 'carbon debt', could result in BECCS failing to deliver the negative emissions that are technically possible. The carbon debt can be defined as the amount of carbon stored within a tree, plus the emissions from the supply chain of the feedstock, that must be replaced by the next generation of growth before the capture and storage of emissions via a BECCS solution can be considered to have become carbon-negative.

The carbon payback period for a mature tree is likely to be at the upper end of the range of 44–104 years (calculated for a clear-cut forest).[364] But it could be even

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360 IPCC Task Force on National Greenhouse Gas Inventories (2022), 'Frequently Asked Questions (Q2–10)', https://www.ipcc-nggip.iges.or.jp/faq/faq.html.
361 Tudge, S. J., Purvis, A. and De Palma, A. (2021), 'The impacts of biofuel crops on local biodiversity: a global synthesis', *Biodiversity and Conservation*, 30(11), pp. 2863–83, https://doi.org/10.1007/s10531-021-02232-5; Hu, B. et al. (2020), 'Can bioenergy carbon capture and storage aggravate global water crisis?', *Science of The Total Environment*, 714, p. 136856, https://doi.org/10.1016/j.scitotenv.2020.136856.
362 Brack, D. and King, R. (2021), 'Managing Land-based CDR: BECCS, Forests and Carbon Sequestration', *Global Policy*, 12(S1), pp. 45–56, https://doi.org/10.1111/1758-5899.12827; IPCC (2019), *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*, Geneva: IPCC, https://www.ipcc.ch/srccl.
363 Reid, W. V., Ali, M. K. and Field, C. B. (2020), 'The future of bioenergy', *Global Change Biology*, 26(1), pp. 274–86, https://doi.org/10.1111/gcb.14883.
364 The carbon payback period is the time taken to achieve carbon parity, i.e. to balance the carbon debt with an equal amount of carbon sequestered during the regrowth of the harvested feedstock. Rolls, W. and Forster, P. M. (2020), 'Quantifying forest growth uncertainty on carbon payback times in a simple biomass carbon model', *Environmental Research Communications*, 2(4), p. 045001, https://doi.org/10.1088/2515-7620/ab7ff3; Sterman, J. D., Siegel, L. and Rooney-Varga, J. N. (2018), 'Does replacing coal with wood lower CO_2 emissions? Dynamic lifecycle analysis of wood bioenergy', *Environmental Research Letters*, 13(1), p. 015007, https://doi.org/10.1088/1748-9326/aaa512.

longer,[365] meaning that geological storage of carbon dioxide from mature trees should not be considered carbon-negative until the next generation of trees has grown for the full payback period.

One of the main advantages of BECCS is that while capturing and sequestering carbon dioxide, it produces energy. This dual value is the main reason why cost-optimizing decarbonization models select BECCS. However, there is a trade-off between its energy generation efficiency and carbon dioxide capture rate,[366] and there are indications that first-generation BECCS-to-power facilities will likely exhibit lower power generation efficiencies than those estimated in many of the integrated assessment models (IAMs) used by the IPCC to assess decarbonization pathways.[367] Post-combustion capture requires heat to release the carbon dioxide molecules from the solvent that absorbs the carbon dioxide. This 'energy penalty' has the consequence of reducing the efficiency with which a BECCS-to-power facility converts the embodied energy of biomass into electricity. As such, the capture rate and power efficiency of BECCS-to-power facilities are inversely proportional – the more carbon dioxide a BECCS facility captures, the less efficient it is at generating power, and vice-versa.

Not only is the energy output of BECCS crucial; so too is the energy input required to derive the output. 'Energy return on energy invested' (EROEI) is the ratio between the amount of usable energy produced and the amount of energy expended to obtain that usable energy. For BECCS-to-power systems, examples of energy inputs include the following: the drying of the biomass; other pelleting processes; energy used for transportation; and the energy penalty. An EROEI of 1 indicates the usable energy is equal to the amount of energy expended. As one 2018 paper highlighted: 'Implicit in these scenarios [IAMs] is the assumption that BECCS is a net producer of energy … [but] the net electricity balance of a UK-based BECCS facility can be either positive or negative.'[368]

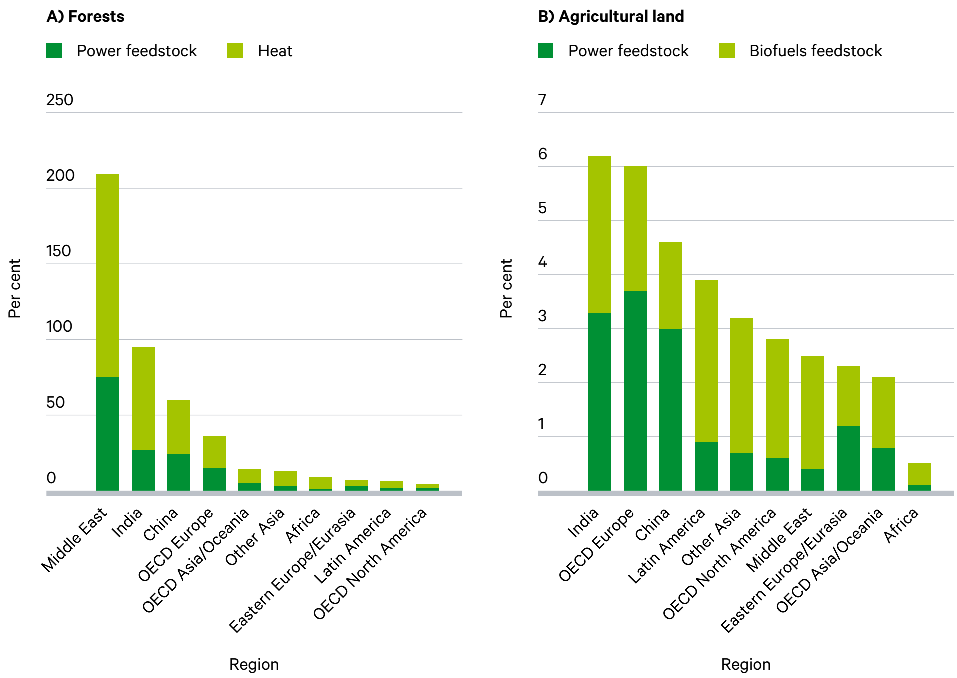
5.4.2 Bioenergy and BECCS land requirements in 2050: a modelling analysis

Beyond efficiency considerations, the other major question mark around the use of bioenergy and BECCS – as mentioned earlier – concerns the sheer amount of land needed for such solutions. The 2019 IPCC special report on climate change and land concluded that: 'Although estimates of potential are uncertain, there is *high confidence* that the most important factors determining future biomass supply are land availability and land productivity. These factors are in turn determined by competing uses of land and a myriad of environmental and economic considerations.'[369]

365 Holtsmark, B. (2010), *Use of wood fuels from boreal forests will create a biofuel carbon debt with long payback time*, Discussion Papers No. 637, Oslo: Statistics Norway, https://www.ssb.no/a/publikasjoner/pdf/DP/dp637.pdf.
366 The 'capture rate' is the proportion of carbon dioxide that the carbon capture and storage (CCS) equipment captures, relative to the amount released into the atmosphere, and is generally cited as being 90 per cent or more.
367 Quiggin, D. (2021), *BECCS deployment: The risks of policies forging ahead of the evidence*, Research Paper, London: Royal Institute of International Affairs, https://www.chathamhouse.org/2021/10/beccs-deployment.
368 Fajardy, M. and Mac Dowell, N. (2018), 'The energy return on investment of BECCS: is BECCS a threat to energy security?', *Energy & Environmental Science*, 11(6), pp. 1581–94, https://doi.org/10.1039/C7EE03610H.
369 IPCC (2019), *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*, Geneva: IPCC, p. 581, https://www.ipcc.ch/srccl.

Drawing on the bioenergy land footprints – across forests and agricultural land – for heating, power and biofuels (see Table 2), we estimate that the REmap scenario would require 520.5 million ha of forest (13 per cent of the world's total forest area) and 133.6 million ha of agricultural land (2.8 per cent of all agricultural land) to be turned over to bioenergy feedstock production by 2050.[370] Combined, these areas would be equivalent to 1.8 times the size of all European OECD countries' forest-covered and agricultural land, or slightly over twice India's entire land area. Note that these values are for unabated bioenergy only, prior to considering the *additional* land requirement of BECCS. FAO estimates that around 420 million ha of forests have been converted to other land uses globally since 1990.[371] All this suggests that pursuing the above-mentioned scale of bioenergy expansion between now and 2050 could result in forestry land-use changes surpassing those recorded over the last 30 years.

Figure 28. Proportion of forest and agricultural areas dedicated to bioenergy feedstocks, by region, under REmap energy scenario in 2050



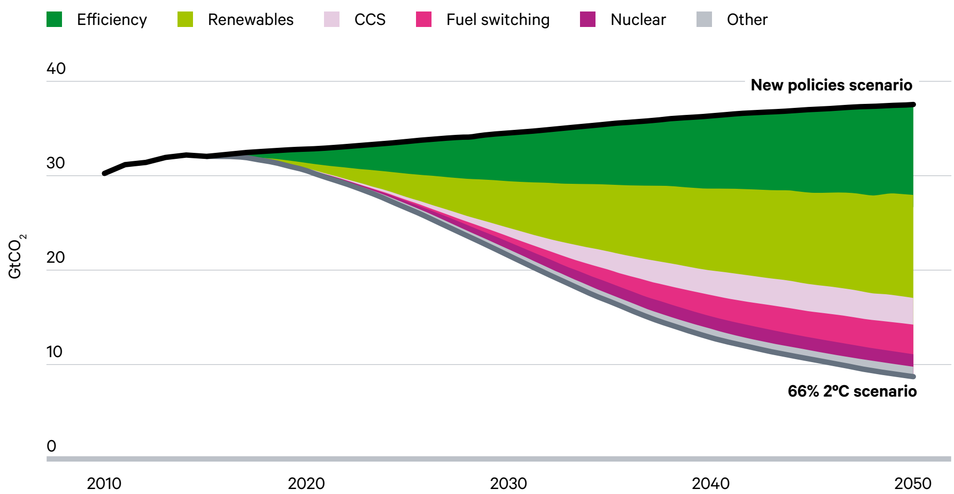
Sources: Calculated from International Renewable Energy Agency (IRENA) and International Energy Agency (IEA) (2017), *Perspectives for the Energy Transition: Investment Needs for a Low-Carbon Energy System*, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Mar/Perspectives_for_the_Energy_Transition_2017.pdf; and FAO (2022), 'FAOSTAT > Land Use', https://www.fao.org/faostat/en/#data/RL (accessed 1 Jun. 2022).

370 In order to derive regional land footprints for bioenergy feedstocks, assumptions on the power sector feedstock split between woody biomass and bio crops had to be made. Based on EU-specific data from de Schutter and Giljum (2014), approximately 52 per cent of power sector bioenergy feedstock was assumed to derive from forests, and 48 per cent from agriculture: de Schutter, L. and Giljum, S. (2014), *A calculation of the EU Bioenergy land footprint*, Vienna: Wirtschafts Universität Wien, www.foeeurope.org/sites/default/files/agrofuels/2015/foee_bioenergy_land_footprint_may2014.pdf. It is assumed the feedstocks for heating are entirely derived from forests, and for transport entirely from agricultural land, with the associated land footprints listed in Table 2.
371 FAO (2020), *State of the World's Forests 2020*, Rome: FAO, https://www.fao.org/state-of-forests/2020/en.

Assuming bioenergy feedstocks are sourced intra-regionally (illustrated in Figure 28a), the projected demand for feedstocks under REmap exceeds the available forestry resource in the Middle East. The same scenario also envisages that infeasibly (and undesirably) large proportions – over half the total – of forests in India and China would be required for bioenergy feedstocks. As such, the Middle East, India and China would need to import significant volumes of bioenergy. For agricultural land, all regions except Africa would need to dedicate between 2 and 6 per cent of farmland to the cultivation of bioenergy crops (Figure 28b).

But bioenergy will not only be required for heating, transport and power generation in 2050. Under REmap's assumptions, as with many IPCC decarbonization scenarios, BECCS is relied on to balance significant carbon budget deficits. While REmap explicitly states the need for BECCS, the IEA and IRENA do not quantify the scale of uptake needed. Extrapolating the REmap emissions curve trend in Figure 29 to the end of the century, we find that the energy sector alone will require negative emissions technologies (NETs) capable of absorbing 334.2 gigatonnes of carbon dioxide ($GtCO_2$) between now and 2100. This is based on REmap's self-defined energy sector carbon budget of 790 $GtCO_2$ (2015–2100).[372] In order to ascertain the proportion of BECCS required within any given period, we assume all NETs are provided by BECCS,[373] and spread the deployment of BECCS over time based on the S-curve illustrated in Figure 30a.

Figure 29. REmap global emissions abatement to 2050



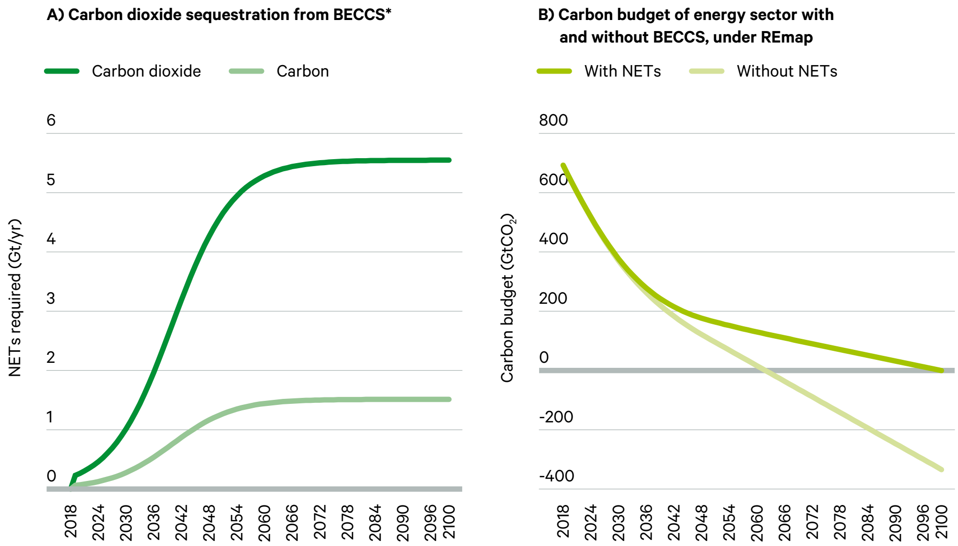
Source: International Renewable Energy Agency (IRENA) and International Energy Agency (IEA) (2017), *Perspectives for the Energy Transition: Investment Needs for a Low-Carbon Energy System*, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Mar/Perspectives_for_the_Energy_Transition_2017.pdf.

The requirement to sequester 1.51 gigatonnes of carbon (GtC) per year by the end of the 21st century, shown in Figure 30a, is less than half the 3.3 GtC per year requirement in one of the most prominent studies on the deployment of BECCS.[374]

372 And accounting for energy sector emissions between 2015 and 2020.
373 It should be noted that the potential sequestration contributions from a range of NETs are currently being explored by the scientific community. For the purposes of the calculations here, we assume that BECCS is the only NET available.
374 Smith, P. et al. (2016), 'Biophysical and economic limits to negative CO_2 emissions', *Nature Climate Change*, 6(1), pp. 42–50, https://doi.org/10.1038/nclimate2870.

There are two reasons for this. First, in this instance we are only considering *energy* sector emissions under the REmap scenario. While the energy sector is responsible for the largest proportion of carbon dioxide emissions, adding non-energy sector carbon budgets would increase the requirement for negative emissions, thus increasing the annual sequestration requirement at the end of the century.

Figure 30. BECCS deployment curve and energy sector carbon budget, with and without NETs



* Shown in both tonnes of CO_2 and equivalent tonnes of C, based on S-curve deployment; slope = 0.15, 50 per cent deployment by 2040 (mid-point of S-curve).
Source: Calculated from International Renewable Energy Agency (IRENA) and International Energy Agency (IEA) (2017), *Perspectives for the Energy Transition: Investment Needs for a Low-Carbon Energy System*, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Mar/Perspectives_for_the_Energy_Transition_2017.pdf.

Second, the scale of negative emissions achievable at the end of this century is dependent on the rate of BECCS deployment. Our REmap-based calculations require the energy sector carbon budget to remain neutral throughout the century; the darker green line in Figure 30b always remains above zero, rather than displaying a negative carbon budget during part of the century. If a temporary carbon budget overshoot were to be adopted, however, BECCS deployment could follow a slower trajectory over the coming decades but would need to be scaled up rapidly in the latter decades, thus increasing the annual requirement at the end of the century. This would entail significantly more risk, principally because the carbon budget for a 66 per cent chance of limiting global heating to 2°C would be expended with the uncertain expectation of achieving net negative emissions at a later point.

5.4.2.1 Where will feedstocks come from?

Given the potential scale of BECCS deployment and the land required for feedstocks, a key question concerns where these feedstocks might be situated. With the global annual atmospheric carbon absorption requirement set at

1.51 GtC (Figure 30a), we investigated regional requirements for BECCS. This entailed geographically allocating the deployment of BECCS. We based our calculations for this on work by Kato and Yamagata (2014),[375] who use 'a top-down analysis of required yields and a bottom-up evaluation of BECCS potential using a process-based global crop model'. Our allocation is based on a resource assessment (assuming BECCS deployment uses feedstocks from the same region), rather than on national responsibilities according to each country's emissions. Based on this assessment, China, North America, India and European OECD countries would need to deploy the greatest proportion of BECCS (Table 3).

Table 3. Requirement of BECCS to balance energy sector carbon budget, under REmap, in $MtCO_2$ per year

	Regional BECCS deployment as % of global BECCS requirement	**BECCS CO_2 sequestration rate ($MtCO_2$ per year)**		
		2030	**2040**	**2050**
OECD North America	14	138	379	620
OECD Asia/Oceania	5	48	130	213
OECD Europe	11	108	297	486
Eastern Europe/Eurasia	7	75	206	337
India	12	121	331	542
China	31	318	870	1,423
Other Asia	7	73	201	328
Latin America	6	57	156	255
Middle East	3	28	76	123
Africa	5	46	127	208
Total	**100**	**1,012**	**2,774**	**4,536**

Sources: Calculated from International Renewable Energy Agency (IRENA) and International Energy Agency (IEA) (2017), *Perspectives for the Energy Transition: Investment Needs for a Low-Carbon Energy System*, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Mar/Perspectives_for_the_Energy_Transition_2017.pdf; and FAO (2022), 'FAOSTAT > Land Use', https://www.fao.org/faostat/en/#data/RL (accessed 1 Jun. 2022); and Kato and Yamagata (2014), 'BECCS capability of dedicated bioenergy crops under a future land-use scenario targeting net negative carbon emissions'.

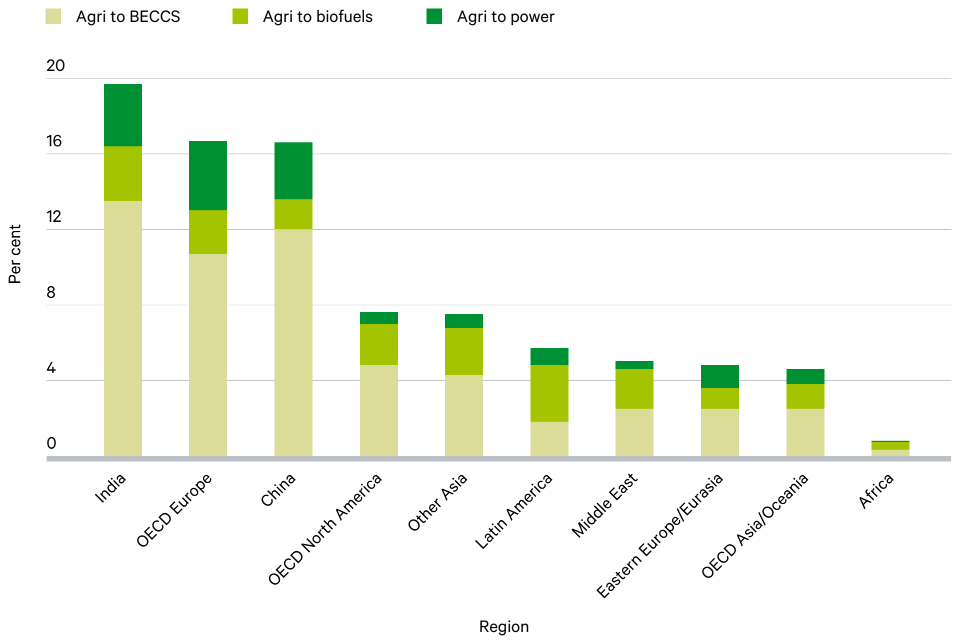
With the regional deployment of BECCS defined, the technology's land-use requirements can then be explored. Here, we draw on work by Smith et al. (2016), who define the land-use footprint of BECCS feedstocks as 380–700 million ha for an end-of-century sequestration rate of 3.3 GtC a year.[376] Their estimate is based

375 Kato, E. and Yamagata, Y. (2014), 'BECCS capability of dedicated bioenergy crops under a future land-use scenario targeting net negative carbon emissions', *Earth's Future*, 2(9), pp. 421–39, https://doi.org/10.1002/2014EF000249.
376 Smith et al. (2016), 'Biophysical and economic limits to negative CO_2 emissions'.

on the assumed use of feedstocks of 'high-productivity dedicated energy crops (willow and poplar short rotation coppice and *Miscanthus*)', roughly equivalent to those assessed by Kato and Yamagata (2014).[377] On this basis, we limit the land available to BECCS to that suitable to the growing of bioenergy crops – namely agricultural land – and take the mid-point in the Smith et al. (2016) range, resulting in a land footprint of 0.0446 ha per tonne of carbon dioxide.

All regions except Africa would need to dedicate 4 per cent or more of their agricultural land to the growing of bioenergy crops; the figure is as high as 16–20 per cent for India, OECD Europe and China once BECCS requirements are accounted for (Figure 31). Globally, the BECCS-associated agricultural land requirement (202 million ha) is equivalent to 112 per cent of India's total agricultural land. If the land required for power and biofuel feedstocks is included in the calculation, the global agricultural land area dedicated to bioenergy crops swells to 336 million ha – equivalent to 180 per cent of India's agricultural land area.

Figure 31. Proportion of agricultural area dedicated to BECCS feedstocks by region, under REmap energy scenario in 2050



Note: This figure builds on Figure 28b showing the agricultural land required for bioenergy feedstocks.
Sources: Calculated from International Renewable Energy Agency (IRENA) and International Energy Agency (IEA) (2017), *Perspectives for the Energy Transition: Investment Needs for a Low-Carbon Energy System*, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Mar/Perspectives_for_the_Energy_Transition_2017.pdf; and FAO (2022), 'FAOSTAT > Land Use', https://www.fao.org/faostat/en/#data/RL (accessed 1 Jun. 2022).

Our calculations are based on REmap's 2050 time horizon, and assume BECCS deployment reaches half the level required to balance the energy sector's carbon budget by 2040. Following the deployment curve of Figure 30a, 247.5 million ha would

377 Kato and Yamagata (2014), 'BECCS capability of dedicated bioenergy crops under a future land-use scenario targeting net negative carbon emissions'.

be required at the end of century. If, however, deployment is delayed and greater emphasis is placed on BECCS deployment in the latter half of the century, we would expect the land area needed for BECCS at the end of century to be nearly three times greater, at 683 million ha, on the basis of 50 per cent deployment by 2080.

If all the 336 million ha of agricultural land required for BECCS and unabated bioenergy were to consist of cropland, this would equate to almost 21.5 per cent of total global cropland.

By comparison, the most recent IPCC Working Group III mitigation report estimates that by 2050 the technical potential of bioenergy, constrained by food security and environmental considerations, will be 5–50 exajoules (EJ) a year for residues and 50–250 EJ a year for dedicated biomass production.[378] Across all the illustrative mitigation pathways (IMPs) within the IPCC's Sixth Assessment Report (AR6) that are likely to limit warming to 2°C or below, BECCS deployment reaches 2.75 (0.52–9.45) $GtCO_2$ per year in 2050.[379] Combined with unabated bioenergy, deployment on this scale requires 199 (56–482) million ha of cropland, equivalent to almost 13 per cent of global cropland area. Furthermore, the vast majority of bioenergy is assumed to be derived from cropland. Under our investigation of REmap, if all the 336 million ha of agricultural land required for BECCS and unabated bioenergy were to consist of cropland, this would equate to almost 21.5 per cent of current total global cropland.

Box 11. Betting on BECCS?

Beyond the land-use requirements involved, large-scale deployment of bioenergy with carbon capture and storage (BECCS) poses several other significant challenges:

A large implementation gap
Carbon capture and storage (CCS) technologies – required for both BECCS and direct air carbon capture and storage (DACCS) – are nascent and unproven at scale. They have so far been limited to small-scale demonstration projects, with few others in the pipeline. Currently, fewer than 20 CCS projects are in existence worldwide, with a cumulative annual capture capacity of 0.0315 $GtCO_2$, of which only 0.0037 $GtCO_2$ is in geological storage.[380]

Feedstock governance
Feedstock expansion for BECCS is expected to occur primarily in tropical countries with high biodiversity value, weak forest governance and chequered histories of land-use planning.[381] This presents risks of harmful land-use change and conversion of natural forests. Producing the volumes of feedstock required for a 'BECCS-only' solution would almost certainly result in ecological catastrophe, contributing to a vicious circle of agricultural expansion and intensification that would erode ecosystem services

378 IPCC (2022), *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge and New York: Cambridge University Press, https://doi.org/10.1787/72a9e331-en.
379 Pathak, M. et al. (2022), 'Technical Summary', in Shukla, P. R. et al. (eds) (2022), *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge and New York: Cambridge University Press, https://doi.org/10.1017/978100 9157926.002.
380 Fajardy, M., Köberle, A., Mac Dowell, N. and Fantuzzi, A. (2019), *BECCS deployment: a reality check*, Grantham Institute Briefing paper, 28, https://www.imperial.ac.uk/media/imperial-college/grantham-institute/public/publications/briefing-papers/BECCS-deployment---a-reality-check.pdf.
381 Brack, D. and King, R. (2020), *Net Zero and Beyond: What Role for Bioenergy with Carbon Capture and Storage?*, Research Paper, London: Royal Institute of International Affairs, https://www.chathamhouse.org/2020/01/net-zero-and-beyond-what-role-bioenergy-carbon-capture-and-storage; Beringer, T., Lucht, W. and Schaphoff, S. (2011), 'Bioenergy production potential of global biomass plantations under environmental and agricultural constraints', *Global Change Biology Bioenergy*, 3, pp. 299–312, https://doi.org/10.1111/j.1757-1707.2010.01088.x.

and contribute to climate change. Although smart interventions at different scales can help optimize the ecosystem services provided by land and reduce competition for land, it is doubtful whether these goals can be achieved in many of the countries where feedstock production is likely to occur, due to lower levels of development and governance.[382] Unlike first-generation biofuels (e.g. maize, sugar cane, sugar beet and rapeseed), woody bioenergy and other short-rotation second-generation crops do not necessarily compete directly with food crops.[383] However, at the scale envisioned there would inevitably be some contestation for use of appropriate lands, and there would be a significant risk of generating indirect emissions as agriculture expanded into forests to accommodate the growing land area assigned to bioenergy crops. One estimate suggests that if the 10–25 per cent of existing croplands most suited to producing bioenergy feedstocks were repurposed for this use, then agricultural calorie production might be reduced by 43–73 per cent.[384] Closing yield gaps on the remainder of the agricultural land, or switching to more intensive forms of production, would be unlikely to meet the caloric needs of a global population expected to number 9.7 billion in 2050.[385]

Carbon neutrality
As mentioned previously, there remain questions about the carbon balance – and hence the fundamental carbon sequestration potential – of BECCS on a large scale. Under many circumstances BECCS may not actually result in net negative emissions: the efficiencies assumed by some IAMs need to be stress-tested. The carbon removal potential and break-even time needed for a BECCS system to become carbon-negative differ greatly from one project to another, depending on the feedstocks involved, the supply-chain emissions (including those from indirect land-use change) produced, and whether the system is optimized for energy production or negative emissions. For example, it can take between one and 50 years for a project to break even. Given the geographies of existing energy systems – i.e. the locations of geological storage sites for carbon dioxide, and the locations of potential feedstocks – it is estimated that just the logistics of collating and transporting bioenergy on the scale envisioned could account for up to half of global primary energy consumption.[386]

While some BECCS pathways may be feasible locally, there are clearly limitations at the global scale.[387] Given the prominence of BECCS among negative emissions technologies, key governance priorities must include the following: the implementation of full carbon accounting through complex value chains; the establishment of efficiency standards for water, land, carbon dioxide and energy; the monitoring of break-even times; and attaching an economic cost to undesirable side-effects.

382 Bailey, R. and King, R. (2018), 'Betting on BECCS? Exploring Land-Based Negative Emissions Technologies', Chatham House Sustainability Accelerator, 17 May 2018, https://accelerator.chathamhouse.org/article/betting-on-beccs-exploring-land-based-negative-emissions-technologies.
383 Fuss, S. et al. (2016), 'Research priorities for negative emissions', *Environmental Research Letters*, 11(11), p. 115007, https://doi.org/10.1088/1748-9326/11/11/115007.
384 Boysen, L. R. et al. (2017), 'The limits to global-warming mitigation by terrestrial carbon removal', *Earth's Future*, 5(5), pp. 463–74, https://doi.org/10.1002/2016EF000469.
385 Ibid.
386 Anderson, K. and Peters, G. (2016), 'The trouble with negative emissions', *Science*, 354, pp. 182–83, https://doi.org/10.1126/science.aah4567.
387 Ibid.

5.5 Challenges and conclusions

There remains significant uncertainty over energy sector decarbonization pathways. This is in large part due to the many competing low-carbon technology options. The uncertainty is compounded by the large number of additional technologies currently under development. Some of these may make significant contributions to mitigating climate change, while others are likely to be distractions that impede progress on the time-critical imperative of lowering emissions today.

The uncertainties in energy decarbonization pathways translate into equivalent uncertainties around future land uses, as the land footprint of each technology varies significantly.

However, one clear conclusion can be drawn from the modelling presented in this chapter: excessive reliance on bioenergy, with or without CCS, would be the single biggest energy-sector driver of increased land use, both in forests and on agricultural lands. Indeed, this conclusion could be reached simply on the basis of the land-use intensity values for bioenergy (Table 2), which are orders of magnitude larger than those for other renewables.

Clearly these land requirements for bioenergy, if met, would have devastating impacts on biodiversity, habitats, water availability and the livelihoods of agricultural workers. The implications for the global population would also be immense; for example, the potential impacts on food production and food prices are hard to conceive.

Fortunately, other, proven low-carbon technologies with significantly lower land intensities now exist, and their costs are falling sharply. Solar and wind power are often now cheaper than fossil fuels; they can be deployed on non-agricultural or non-forest land; and they can be integrated harmoniously with some types of agricultural land uses. Not only is the availability of land not a limiting factor in their deployment, but their smaller footprints could significantly reduce future competition for land among different land uses. Moreover, the faster these technologies are deployed, the less the world will need to rely on BECCS and other NETs to reduce carbon budget debts.

In this context, it would appear prudent to minimize reliance on bioenergy and BECCS in any energy sector decarbonization pathway. This is not to argue that bioenergy has no future. Power from bioenergy has the advantage of being 'dispatchable', in that it can be deployed in a way that responds dynamically to varying demand for power – although there are other technologies that can do the same, and storage may obviate this need over time. Alternatives to bioenergy for heat are not as well commercialized as those for power. The final mix will vary according to technological developments and the national strategies deployed, but solar thermal, electric heat pumps, hydrogen and, especially, efficiency investments will all compete with bioenergy.

06 The land crunch

Humanity's demands on land are only set to increase, and the prioritization of any one category of essential land use will encroach on the availability of land for other vital uses. Difficult policy trade-offs are inevitable as the emerging land 'crunch' hits harder.

6.1 Challenges around the finite supply of land

As established in the preceding chapters, the demand for land – for climate and environmental regulation, and for food and for energy crops in particular – is growing. Many of these demands require high-quality, productive lands and rich soils, meaning different land uses are increasingly in competition with one another. At the same time, the planet's capacity to meet existing demand for land and land-derived resources, let alone increased demand in the future, is being depleted by climate change, urbanization, biodiversity loss, demographic changes and other pressures.

We describe this mismatch between supply and demand as a 'land crunch'. To a significant extent, the land crunch is a real and present problem for humanity already (see Box 12), but as this chapter elaborates, the pressures associated with the land crunch could increase dramatically – potentially to the point of unmanageability – in the coming decades without comprehensive action to reconcile demand with the more or less finite supply of land.

As a starting point for assessing these tensions, it is worth exploring in broad terms how lands may be reallocated to accommodate rising demand, how much additional land each type of demand could conceivably require, and how the balance of land uses might change accordingly. Since agriculture is a primary driver of land-use change and is implicated in both the food and energy sectors, it makes sense to start with the land available for farming. Estimates of the areas potentially suitable for crops (including bioenergy crops) but not currently under cultivation vary widely. Models relying on global-scale climate, soil and terrain data typically suggest figures of around 1.6 to 1.9 billion hectares (ha) – an area roughly the size of Russia, and greater than the current extent of all global croplands. But these are likely overestimates. They fail to take account of the social and ecological utility of the potentially suitable lands included in such assessments, or of the opportunity costs agriculture presents for other land uses.[388]

Detailed analyses of regions often assumed to hold promise for cultivation frequently show that once biodiversity, carbon and socio-economic constraints are fully accounted for, significantly less land is suitable for conversion.

Perhaps more realistically, estimates that factor in the constraints and trade-offs associated with land conversion suggest that around 0.45–0.60 billion ha (still 1.5 to two times the size of India's land area) are potentially available for farming.[389] These lands, characterized by a mixture of grasses, shrubs and trees (receiving enough rainfall to permit crop production but lacking dense tree cover),[390] are found mainly in Latin America's *cerrados* and grasslands, Africa's savannahs and shrublands, and the abandoned farmlands of the former Soviet Union.[391] The vast majority lie in just five countries: Argentina, Brazil, the Democratic Republic of the Congo (DRC), Mozambique and Russia.[392]

Not all of this more modest area can truly be considered potentially viable cropland. Detailed analyses of regions often assumed to hold promise for cultivation frequently show that once biodiversity, carbon and socio-economic constraints are fully accounted for, significantly less land is suitable for conversion.[393] For example, the carbon content and biodiversity values of savannahs are often vastly underestimated.[394] Wet woodland savannahs can be as biodiverse as tropical forests.[395] Only 2 per cent of Africa's wet savannahs could realistically be converted into a low-carbon source of maize, while only 11 per cent could serve as farmland for the low-carbon cultivation of soybeans.[396] Land conversion could, moreover, have serious repercussions for such areas' human inhabitants, potentially displacing them and triggering social or political unrest. Many communities live symbiotically with their surrounding landscape – frequently using the land for low-impact agro-pastoralism, small-scale livestock grazing, wild game hunting and traditional cultural activities.[397]

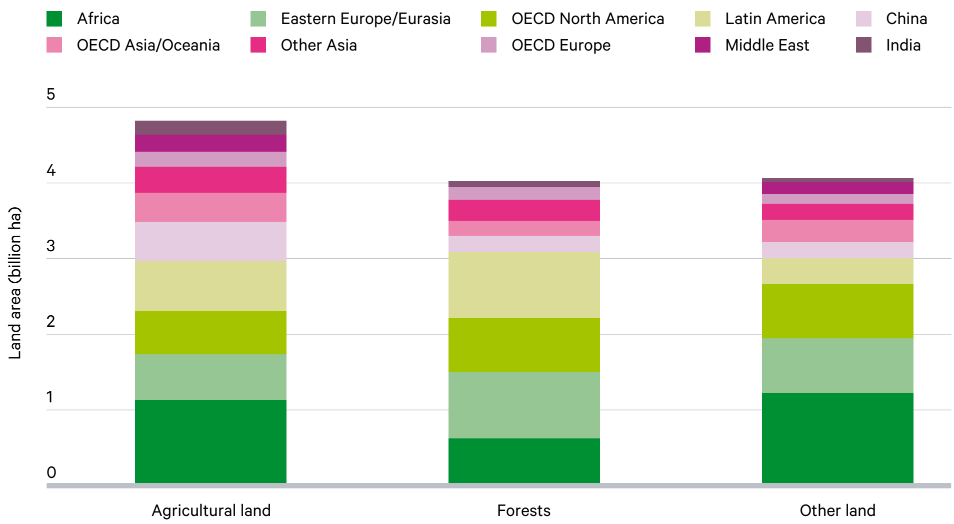
Given these constraints, any future expansion of humanity's land footprint for provisioning, regulating services and settlement might be best sought on what can be termed 'degraded' lands. However, this proposition is not as simple as it may at first appear.[398] There is little to no consensus on what qualifies as 'degraded' land,

388 Lambin, E. F. et al. (2013), 'Estimating the world's potentially available cropland using a bottom-up approach', *Global Environmental Change*, 23(5), pp. 892–901, https://doi.org/10.1016/j.gloenvcha.2013.05.005.
389 Ibid.
390 Hanson, C. and Searchinger, T. (2015), *Ensuring Crop Expansion is Limited to Lands with Low Environmental Opportunity Costs*, Creating a Sustainable Food Future Working Papers, 10, Washington, DC: World Resources Institute, https://www.wri.org/research/ensuring-crop-expansion-limited-lands-low-environmental-opportunity-costs; Estes, L. D. et al. (2016), 'Reconciling agriculture, carbon and biodiversity in a savannah transformation frontier', *Philosophical Transactions of the Royal Society B: Biological Sciences*, 371(1703), p. 20150316, https://doi.org/10.1098/rstb.2015.0316.
391 Lambin, E. F. and Meyfroidt, P. (2011), 'Global land use change, economic globalization, and the looming land scarcity', *Proceedings of the National Academy of Sciences*, 108(9), pp. 3465–72, https://doi.org/10.1073/pnas.1100480108.
392 Lambin et al. (2013), 'Estimating the world's potentially available cropland using a bottom-up approach'.
393 Ibid.; Hanson and Searchinger (2015) also show that considering savannahs and grazing lands as always appropriate for cropland expansion has led to overestimates of the amount of land available: Hanson and Searchinger (2015), *Ensuring Crop Expansion is Limited to Lands with Low Environmental Opportunity Costs*.
394 Estes et al. (2016), 'Reconciling agriculture, carbon and biodiversity in a savannah transformation frontier'.
395 Ibid.
396 'Low-carbon' is taken to mean releasing one-third less carbon per tonne of crop than the global average carbon loss per tonne of crop. Searchinger, T. D. et al. (2015), 'High carbon and biodiversity costs from converting Africa's wet savannahs to cropland', *Nature Climate Change*, 5(5), pp. 481–86, https://doi.org/10.1038/nclimate2584.
397 Lambin and Meyfroidt (2011), 'Global land use change, economic globalization, and the looming land scarcity'.
398 Hanson and Searchinger (2015), *Ensuring Crop Expansion is Limited to Lands with Low Environmental Opportunity Costs*.

and the label is often very broad and inconsistently used:[399] estimates of the amount of degraded lands and their locations vary widely, from less than 1 billion ha to over 6 billion ha.[400] And, just as with semi-natural lands converted for crop expansion, degraded lands are often not vacant, instead providing important socio-economic and ecosystem functions.[401] In short, whatever its true extent and geographical distribution, this land type will not be able to satisfy all of the competing demands on it. Depending on the nature and intensity of the anticipated new land use, converting degraded lands may simply accelerate that degradation, or require vast quantities of resources to be imported from elsewhere to sustain activity beyond the land's natural carrying capacity. Conversely, appropriate and proactive stewardship could help arrest and reverse the degradation process and realize the land's productive potential.

As illustrated in Figure 32, 4.8 billion ha of land worldwide is used for agriculture. (And as noted in Chapter 2, this accounts for about 35 per cent of the surface area of all countries, with land used for crops making up about a third of that share and grazing land two-thirds.) A further 4 billion ha (30 per cent of the extent of all countries) is forested, of which 2.8 billion ha is managed in some way and roughly 300 million ha planted.

Figure 32. Land areas and type by region



Source: FAO (2022), 'FAOSTAT > Land Use', https://www.fao.org/faostat/en/#data/RL (accessed 1 Jun. 2022).

399 For a brief discussion of different use cases, see World Resources Institute (undated), 'What is degraded land?', https://www.wri.org/forests/what-is-degraded-land.
400 Gibbs, H. K. and Salmon, J. M. (2015), 'Mapping the world's degraded lands', *Applied Geography*, 57, pp. 12–21, https://doi.org/10.1016/j.apgeog.2014.11.024.
401 Hanson and Searchinger (2015), *Ensuring Crop Expansion is Limited to Lands with Low Environmental Opportunity Costs*.

Of the total plant biomass growth each year,[402] humans take approximately 25–33 per cent for food, fibres and energy.[403] Partly as a result of more people on the planet, but mainly because people are richer now on average than in the past, human demand continues to grow. More demand results in more human appropriation of land, for example:

- Global energy demand is projected to increase by more than 30 per cent from 2020 to 2040,[404] driven by rising incomes and population growth – the global population is expected to rise by 1.3 billion by 2040 (Chapter 5).[405]
- Increasing reliance within energy decarbonization pathways on bioenergy to supply future energy demand could result in 520.5 million ha of forests, along with 133.6 million ha of agricultural lands, being dedicated to bioenergy feedstocks by 2050 (Chapter 5).
- Current annual water withdrawals of approximately 4,600 cubic kilometres (km^3) are considered close to maximum sustainable levels, yet are projected to increase by about 30 per cent by 2030[406] – around 4 billion people already experience some degree of annual water scarcity.[407] The majority (70 per cent) of water used globally is for agriculture, mostly for irrigation.[408]
- Food supply may need to increase by 47–60 per cent by 2050.[409] This might require an expansion of agricultural area, as crop yields have not been increasing consistently in step with demand growth.[410] Different models within the academic literature are based on different assumptions, but most models project an expansion of cropland, typically in the range of 10–26 per cent.[411] Without further innovation to increase yields, the area of cropland would need to increase by 42 per cent and the area of pasture by 15 per cent to meet currently projected demand[412] (see Chapter 4 for more on the challenges around sustainable intensification of farming).

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402 Biomass growth is the result of carbon dioxide sequestered during photosynthesis less the carbon dioxide released during respiration from metabolizing sugars and starches for energy. Technically this is known as 'net primary production' (NPP) and also serves as measure of net carbon sequestration.
403 Haberl, H., Erb, K.-H. and Krausmann, F. (2014), 'Human Appropriation of Net Primary Production: Patterns, Trends, and Planetary Boundaries', *Annual Review of Environment and Resources*, 39(1), pp. 363–91, https://doi.org/10.1146/annurev-environ-121912-094620.
404 International Energy Agency (IEA) (2019), *World Energy Outlook 2019*, Paris: IEA, https://www.iea.org/reports/world-energy-outlook-2019.
405 Calculated from United Nations Department of Economic and Social Affairs, Population Division (2022), 'Data Portal > Total population by sex', https://population.un.org/dataportal/data/indicators/49/locations/900/start/2020/end/2040/table/pivotbylocation (accessed 1 Jun. 2022).
406 Boretti, A. and Rosa, L. (2019), 'Reassessing the projections of the World Water Development Report', *npj Clean Water,* 2(15), https://doi.org/10.1038/s41545-019-0039-9.
407 Mekonnen, M. M. and Hoekstra, A. Y. (2016), 'Four billion people facing severe water scarcity', *Science Advances*, 2(2), https://doi.org/10.1126/sciadv.1500323; Wada, Y. and Bierkens, M. F. P. (2014), 'Sustainability of global water use: past reconstruction and future projections', *Environmental Research Letters*, 9(10), p. 104003, https://doi.org/10.1088/1748-9326/9/10/104003.
408 Boretti and Rosa (2019), 'Reassessing the projections of the World Water Development Report'.
409 Alexandratos, N. and Bruinsma, J. (2012), *World Agriculture Towards 2030/2050: The 2012 Revision*, ESA Working Paper No. 12-03, Rome: FAO, http://www.fao.org/3/a-ap106e.pdf; Gouel, C. and Guimbard, H. (2019), 'Nutrition Transition and the Structure of Global Food Demand', *American Journal of Agricultural Economics*, 101(2), pp. 383–403, https://doi.org/10.1093/ajae/aay030.
410 Ray, D. K., Mueller, N. D., West, P. C. and Foley, J. A. (2013), 'Yield Trends Are Insufficient to Double Global Crop Production by 2050', *PLoS ONE*, 8(6), p. e66428, https://doi.org/10.1371/journal.pone.0066428; Bajželj, B. et al. (2014), 'Importance of food-demand management for climate mitigation', *Nature Climate Change*, 4(10), pp. 924–29, https://doi.org/10.1038/nclimate2353.
411 Schmitz, C. et al. (2014), 'Land-use change trajectories up to 2050: insights from a global agro-economic model comparison', *Agricultural Economics*, 45(1), pp. 69–84, https://doi.org/10.1111/agec.12090.
412 Bajželj et al. (2014), 'Importance of food-demand management for climate mitigation'.

— Meeting the goals of the United Nations Framework Convention on Climate Change (UNFCCC)'s 2015 Paris Agreement, including keeping anthropogenic global warming to well below 2°C relative to pre-industrial levels, implies a very tight carbon budget that is likely to be exhausted in the next decade. Unless much greater decarbonization ambition is achieved quickly, and that ambition implemented, excess emissions will need to be offset via carbon dioxide removal (CDR), which will require the deployment of negative emissions technologies (NETs) at scale[413] (see Chapter 3). The longer it takes to meet the target of net zero emissions, the greater the need will be for NETs. If the achievement of net zero emissions is delayed until 2060, a 1.5°C degree pathway may require up to 800 million ha of land for bioenergy with carbon capture and storage (BECCS).[414] This is equivalent to 56 per cent of the world's arable land area, or about 2.7 times the land area of India. A less ambitious 2°C pathway would still need 380–700 million ha of land. In the absence of BECCS, a comparably large area would be required for afforestation and reforestation.[415]

At the same time as demand is growing for services from land, agricultural land is being lost to urban and infrastructural expansion and sea-level rise.

At the same time as demand is growing for services from land, agricultural land is being lost to urban and infrastructural expansion and sea-level rise. In 21 European countries alone, an average of 634,000 ha of 'land-take' occurred each year between 1990 and 2006.[416] On a global basis, by 2030, urban expansion may have taken land that, in 2000, produced 3–4 per cent of global crop yields.[417] This partly the reflects the fact that, for historical reasons, many major settlements are sited on farmland, so their expansion inevitably impacts local agricultural productivity. In addition, rising sea levels threaten to reduce the available agricultural land in coastal areas; and, as coastal populations are forced to move elsewhere, land availability inland may be further impacted.[418] (This is a particular problem given that coastal areas often both have the most fertile land and are heavily populated.) With unchecked climate change and no adaptation, global average temperature rise could reach 4°C and lead to a sea-level rise of 2 metres by 2100 – in this case, as much as 179 million ha of land might be lost globally, displacing up to 187 million people this century.[419] Such an area would be equivalent to about 13 per cent of today's global arable land.

In addition to the potential for loss of farmland to urbanization and sea-level rise, the direct impacts of climate change (e.g. through changing temperatures, precipitation, pests, disease, loss of biodiversity) and land degradation from unsustainable land management (e.g. soil degradation, loss of biodiversity) are likely to reduce the provisioning capacity of many ecosystem services on which

413 Smith, P. et al. (2016), 'Biophysical and economic limits to negative CO_2 emissions', *Nature Climate Change*, 6(1), pp. 42–50, https://doi.org/10.1038/nclimate2870.
414 IEA (2016), *World Energy Outlook 2016*, Paris: IEA, https://www.iea.org/reports/world-energy-outlook-2016.
415 Smith et al. (2016), 'Biophysical and economic limits to negative CO_2 emissions'.
416 Gardi, C. et al. (2015), 'Land take and food security: assessment of land take on the agricultural production in Europe', *Journal of Environmental Planning and Management*, 58(5), pp. 898–912, https://doi.org/10.1080/09640568.2014.899490.
417 Bren d'Amour, C. et al. (2017), 'Future urban land expansion and implications for global croplands', *Proceedings of the National Academy of Sciences*, 114(34), pp. 8939–44, https://doi.org/10.1073/pnas.1606036114.
418 Hauer, M. E. (2017), 'Migration induced by sea-level rise could reshape the US population landscape', *Nature Climate Change*, 7(5), pp. 321–25, https://doi.org/10.1038/nclimate3271.
419 Nicholls, R. J. et al. (2011), 'Sea-level rise and its possible impacts given a "beyond 4°C world" in the twenty-first century', *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 369(1934), pp. 161–81, https://doi.org/10.1098/rsta.2010.0291.

people depend. Less land availability, with less ecosystem service capacity, will intensify competition for the remaining land even if demand for the services from it were to remain unchanged.[420]

As discussed above, however, demand is unlikely to stay at today's levels: growing populations and affluence will drive demand higher. So while the overall availability of high-quality land is increasingly constrained, there is strong potential for growth in demand for the services from land – in turn intensifying current land crunch pressures (Box 12).

6.2 Land scarcity – assessing the data

Building on the analysis of energy and land use in Chapter 5, the following section offers an approximate quantification of the scale of competition for land under six different scenarios. These are based on a combination of our own modelling of land use associated with the REmap energy sector decarbonization scenario introduced in Chapter 5, and a range of scenarios from the literature that consider potential changes to food supply and demand practices.

Our modelling makes simplifying assumptions, but it starts from the perspective of compliance with the Paris Agreement, as reflected in the use of REmap as the basis for our initial land-use calculations. As mentioned previously, REmap was developed by the International Energy Agency (IEA) and the International Renewable Energy Agency (IRENA). It is a 'high-ambition' 2050 scenario compatible with humanity having a 66 per cent chance of keeping the average global temperature rise to 2°C by 2100.[421] In Chapter 5, we estimated how much land would be needed for renewables, including bioenergy production (and carbon capture), given likely trajectories for the replacement of fossil fuels under REmap. Taking this land use as a starting point, here we additionally consider some implications for agricultural land – both under business-as-usual (BAU) assumptions about the food system (see also Chapter 4), and under scenarios in which diets and agricultural practices transition towards greater sustainability requiring less land.

Our six scenarios are labelled S0, S1, S2, S3, M1 and M2. At one end of the sustainability spectrum, S0 is premised on business-as-usual food systems and can be thought of as 'REmap + BAU agri-food'. Scenarios S1–S3 and M1–M2 build on work by Bajželj et al. (2014) and Alexander et al. (2017) respectively.[422] Coupled with our REmap-based land-use calculations, these five scenarios consider the 2050 land-sparing potential of the following changes: sustainable intensification of agriculture (S1); sustainable intensification of agriculture, plus a reduction in food waste (S2); sustainable intensification of agriculture,

420 Shukla, P. R. et al (eds) (2019), *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*, Geneva: Intergovernmental Panel on Climate Change (IPCC), https://www.ipcc.ch/srccl.
421 International Renewable Energy Agency (IRENA) and International Energy Agency IEA (2017), *Perspectives for the Energy Transition: Investment Needs for a Low-Carbon Energy System*, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Mar/Perspectives_for_the_Energy_Transition_2017.pdf.
422 Bajželj, B. et al. (2014), 'Importance of food-demand management for climate mitigation'; and Alexander, P. et al. (2017), 'Could consumption of insects, cultured meat or imitation meat reduce global agricultural land use?', *Global Food Security*, 15, pp. 22–32, https://doi.org/10.1016/j.gfs.2017.04.001.

plus food waste reduction and the global adoption of healthy diets (S3); and the partial replacement of animal products with cultured meat (M1) and plant-based 'imitation' meats (M2).

Our analysis shows that under current trends (S0) substantial growth in demand for land can be expected between now and 2050, in turn intensifying existing land crunch pressures (Box 12). The increase in the total land area required by humanity reflects a projected over-reliance on bioenergy and significant demand for agricultural land for non-bioenergy crops and livestock; this has implications for forests, food production and carbon sequestration, and necessitates a vast expansion in agriculture (Figure 33 and Figure 34). The key findings for S0 are as follows:

— Overall, the agricultural land footprint expands and primary forest cover shrinks. These two factors, combined, result in the aggregate land area requirement for forests and agriculture increasing from 8.8 billion ha to 9.9 billion ha.

— Allowing for the maximum suitable area of other lands to be converted to agriculture, and for 0.35 billion ha of deforestation for agriculture,[423] this would still result in a large projected agricultural land deficit in 2050 of 0.573 billion ha (Figure 34).

— Without significant shifts in agricultural and dietary trends, 23.1 per cent more agricultural land would be needed for non-bioenergy crops and livestock, with an additional 2.8 per cent of agricultural land required for non-BECCS bioenergy feedstocks. Furthermore, the land needed for CDR through BECCS would amount to about 202 million ha in 2050[424] – a requirement equivalent to an additional 4.2 per cent of agricultural land. Combined, all agricultural bioenergy feedstocks would require 21.4 per cent of the current global cropland area. In aggregate, the increase in bioenergy, crop and livestock agricultural demand would imply agricultural land expanding by 30.1 per cent, or by around 1.45 billion ha. This would clearly have significant implications for biodiversity, water availability and other ecosystem services.

— Non-BECCS woody biomass feedstock production will require around 13 per cent of the global forest area, with an additional 9 per cent of forests being converted to agriculture. Worryingly, the level of forestry land-use change between now and 2050, just in relation to bioenergy feedstocks, could surpass that recorded over the last 30 years.

In short, the S0 'REmap + BAU' scenario indicates that increasing demand for agricultural land for food production, combined with increasing demand for bioenergy feedstock production, results in heavy encroachments into forest regions and rapid expansion of agricultural land areas.

If we leave unchallenged the arguable over-reliance on bioenergy within the REmap scenario, we next need to consider whether sustainably intensifying farming practices,[425] reducing food waste and promoting healthier diets can ease the land crunch associated with business-as-usual conditions.

423 The deforestation estimate is derived from Bajželj et al. (2014), 'Importance of food-demand management for climate mitigation'.
424 By 2100, the land area required may be 248–683 million ha, depending on the timing of deployment at scale over the coming decades. See Chapter 5 for more details.
425 See Chapter 4 for a discussion of 'sustainable intensification' and technologies associated with this term.

Box 12. The realities of a 'land crunch': present and future

The mismatch between the demand for land-derived goods and services and the availability of land to provide those resources, as explored through the scenarios in this chapter, can concisely be described as a 'land crunch'. The term not only implies increased competition for land, but also that efforts to keep pace with demand frequently come with substantial trade-offs, including many adverse impacts and the potential for cascading environmental risks. For example, the conversion of primary forest to agricultural use is often a consequence of demand for productive land outstripping supply.

Just as humanity is already facing a climate crisis that is likely to intensify in the decades ahead, the 'land crunch' is, in many respects, a current reality as well as a future prospect. Even if demand for the goods and services from land remains unchanged from today's levels, the declining availability and productivity of realistically useable land will intensify competition for the remaining land.

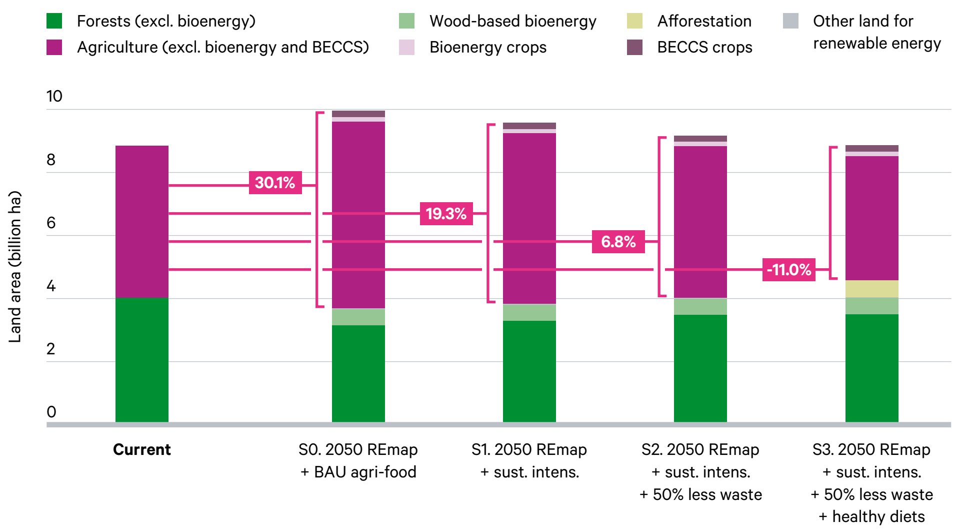
But as the analysis in this chapter suggests, under current market trends – and without suitable interventions – demand for land is highly likely to *increase* from today's levels. For example, by mid-century the world is likely to see substantial deficits in agricultural land, potentially equivalent in size to roughly twice India's land area. The problem will be compounded by declining land quality, meaning that more land will be required to produce a given unit of output, in turn degrading more and more land. Rising demand for land is also likely to lead to further losses in primary forest cover, potentially exceeding total losses over the past 30 years. If not addressed, the numerous factors that converge to create additional demand will exacerbate land crunch issues considerably, meaning the pressures and challenges could become insurmountable.

Uncertainties in land resource quality and quantity, along with the adverse impacts of the land crunch, together make a compelling case for taking a precautionary approach to land use. As the scenarios in this chapter show, changing the size and composition of demand for land-derived food and energy could substantially reduce the magnitude and impacts of the land crunch and deliver net benefits for all. However, positive outcomes of this type are not a given; achieving them will require concerted, proactive and suitably ambitious policy design and implementation.

Although competition for land and the resources it provides has been a common theme throughout human history, what sets apart today's intensifying land crunch is the *global* nature of current land-use pressures and resource flows, as well as the global dimension to the collective responses most likely to prove effective. Rising prosperity and the growth of the global population also, of course, create demand pressures that are unprecedented.

The need to address the land crunch is all the more urgent because of the current and expected impacts of climate change and biodiversity loss. These impacts not only affect the quality and availability of land – and how it can be used – but also amplify the risks that cascade from a tightening land crunch.

Figure 33. Change in global land use to 2050 modelled under the REmap energy scenario, combined with a BAU agri-food scenario (S0), compared with three additive agri-food scenarios (S1–S3)



Note: The three agri-food scenarios are: (S1) a shift towards 'sustainable intensification' of agriculture; (S2) a shift towards sustainable intensification of agriculture, combined with a 50 per cent reduction in food waste; and (S3) a shift towards sustainable intensification of agriculture, combined with a 50 per cent reduction in food waste and changes in diet. Light pink percentage labels refer to all agricultural land-use change relative to the current situation.
Sources: Chatham House modelling calculations; Smith, P. et al. (2016), 'Biophysical and economic limits to negative CO_2 emissions', *Nature Climate Change*, 6(1), pp. 42–50, https://doi.org/10.1038/nclimate2870; Bajželj, B. et al. (2014), 'Importance of food-demand management for climate mitigation', *Nature Climate Change*, 4(10), pp. 924–29, https://doi.org/10.1038/nclimate2353; FAO (2022), 'FAOSTAT > Land Use', https://www.fao.org/faostat/en/#data/RL (accessed 1 Jun. 2022); IRENA and IEA (2017), *Perspectives For The Energy Transition: Investment Needs for a Low-Carbon Energy System*, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Mar/Perspectives_for_the_Energy_Transition_2017.pdf.

Our next scenario, S1 (also see Figure 33), envisions yields increasing by 50 per cent, and approaching the maximum potential achievable through 'sustainable intensification' and new technologies such as breeding improvements and precision agriculture. S1 would see the expansion of agricultural land falling from 30.1 per cent above current levels under S0 to 19.3 per cent above current levels – the consequent 0.93 billion ha increase in agricultural land would be roughly equivalent to the total land area of the US.

The next two scenarios, also illustrated in Figure 33, respectively overlay a 50 per cent reduction in food waste (S2) and additionally switching to diets broadly in line with national dietary guidelines (in amount and composition) (S3) on to the sustainable intensification scenario (S1). In the first instance – reducing food waste by 50 per cent (S2) – agricultural land would only need to expand by 6.8 per cent by 2050. With the addition of healthier diets (S3), the land area used for agriculture actually shrinks by 11 per cent relative to the current situation, potentially allowing for afforestation of 0.532 billion ha. As such, the requirements for managed agricultural land in the future could be less than they are today, even including the likely requirements for bioenergy and BECCS feedstocks under the REmap energy scenario.

Given that the REmap energy scenario implies the need for large volumes of bioenergy feedstocks (as do many IPCC scenarios), our modelling indicates that energy and food production will increasingly compete for agricultural land as well as forests. As such, Figure 34 illustrates the changing composition of global land use, comparing the business-as-usual S0 scenario to the ambitious S3 agri-food scenario.

Under the business-as-usual agri-food scenario, production of crops and livestock expands agricultural land use by 1.11 billion ha, with 0.35 billion ha of forests converted to agriculture.

As Figure 34 illustrates, under the business-as-usual agri-food scenario (S0), production of crops and livestock expands agricultural land use by 1.11 billion ha, with 0.35 billion ha of forests converted to agriculture. A remaining 0.76 billion ha would need to come from expansion on to non-forested land (FAO classifies this as ‘other’ land – see Chapter 2).[426] However, as previously noted, estimates suggest only around 0.45–0.6 billion ha of this type of land area (‘other’ land) is suitable for such conversion.[427] Assuming a central estimate of 0.525 billion ha, this results in an agricultural land deficit of 0.237 billion ha. This deficit increases by a further 0.336 billion ha due to the need to produce agricultural bioenergy feedstocks, resulting in an overall agricultural land deficit of 0.573 billion ha.

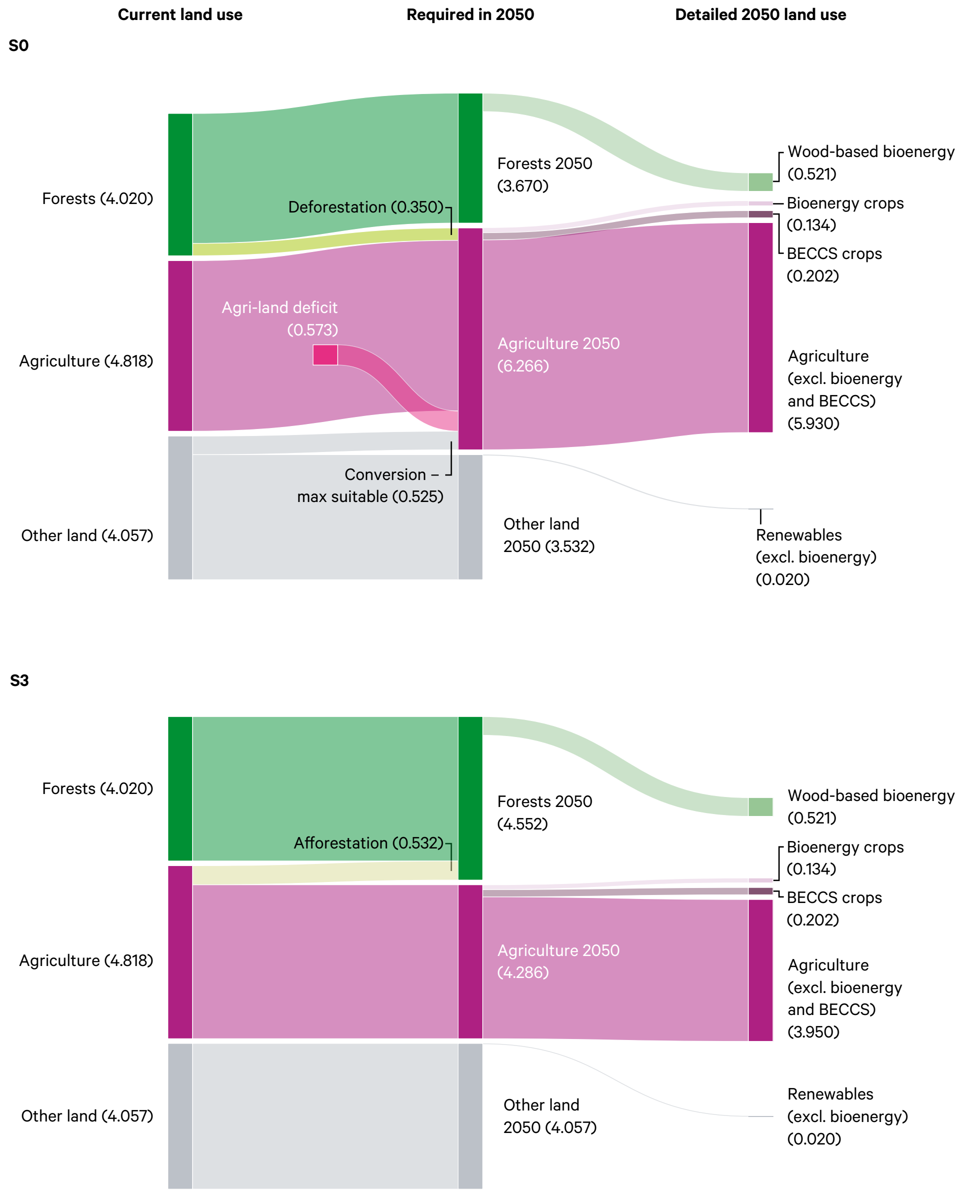
We have made no assessment of whether this 0.573 billion ha land deficit would require additional deforestation (beyond the 0.35 billion ha of forests converted to agriculture). However, once the limit for converting ‘other land’ is reached, it is likely that addressing the overall 0.573 billion ha deficit would indeed lead to additional deforestation. As such, it is conceivable that 0.923 billion ha of forests could be clear-felled for conversion to agriculture, with an additional 0.52 billion ha under heavy management to produce woody biomass, in aggregate representing 36 per cent of today’s global forest area.

By contrast, the ambitious agri-food scenario (S3) illustrated in Figure 34 allows for 0.532 billion ha of afforestation. More realistically, it is likely that a middle ground will need to be found through a combination of reducing reliance on bioenergy feedstocks, arriving at more achievable levels of sustainable intensification, shifting diets and reducing food waste.

There is a stark difference in land-use changes between allowing the agri-food system to progress under business-as-usual market forces (S0) and intervening to ensure land tensions are avoided (S3). Based on the calculations detailed here, without active and difficult-to-achieve interventions, the 2050 agricultural land deficit is likely to be equivalent to 1.9 times India’s land area, and the loss of primary forest cover could exceed the losses of the previous three decades. Such changes would have devastating impacts on biodiversity and all manner of ecosystem services, and would cause huge upward pressures on food prices. It is hard to envisage such a future not leading to irreversible consequences exceeding multiple planetary boundaries.

426 FAO’s ‘other’ land-use category includes built-up and related land, barren land and other wooded land. See Chapter 2 for further details.
427 Lambin et al. (2013), ‘Estimating the world’s potentially available cropland using a bottom-up approach’.

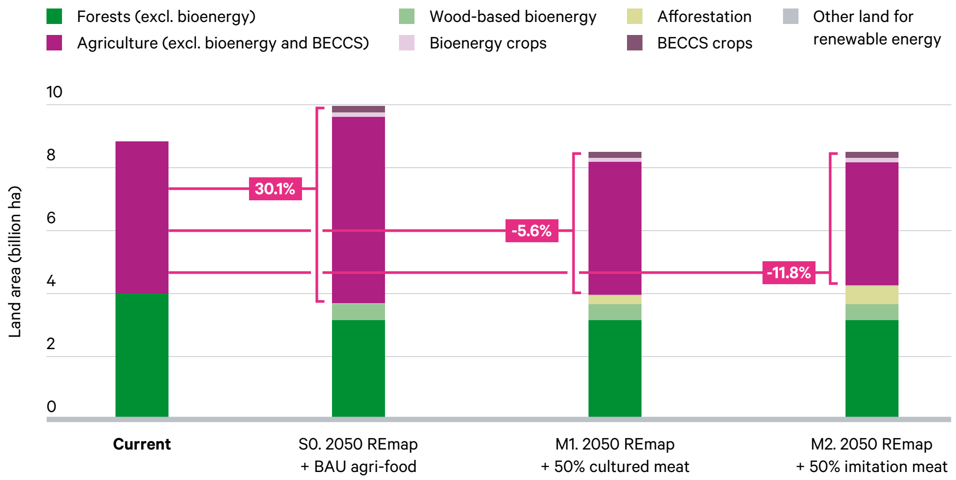
Figure 34. Allocation of land types in 2050 agri-food scenarios: BAU (S0) compared with ambitious scenario (S3) of sustainable intensification + 50 per cent less food waste + healthy diets



Note: REmap scenario held static; all values in billion ha.
Sources: Chatham House modelling calculations; Smith, P. et al. (2016), 'Biophysical and economic limits to negative CO_2 emissions', *Nature Climate Change*, 6(1), pp. 42–50, https://doi.org/10.1038/nclimate2870; Bajželj, B. et al. (2014), 'Importance of food-demand management for climate mitigation', *Nature Climate Change*, 4(10), pp. 924–29, https://doi.org/10.1038/nclimate2353; FAO (2022), 'FAOSTAT > Land Use', https://www.fao.org/faostat/en/#data/RL (accessed 1 Jun. 2022); IRENA and IEA (2017), *Perspectives For The Energy Transition: Investment Needs for a Low-Carbon Energy System*, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Mar/Perspectives_for_the_Energy_Transition_2017.pdf.

Conversely, S3 – while clearly a preferable outcome to S0 – is not a blueprint for reducing pressures on land. Similar outcomes could potentially be achieved by decoupling dietary demand from land demand, notably through the adoption of diets based on alternative proteins[428] such as cultured meat (i.e. grown from stem cells) or plant-based 'imitation' meat.[429] Figure 35 illustrates that a 50 per cent cultured-meat scenario[430] – which we label M1 – would reduce the required agricultural land area by 5.6 per cent relative to today, potentially allowing for 0.27 billion ha of afforestation. The M2 scenario – in which 50 per cent of animal product consumption is replaced by the consumption of imitation meat – reduces the required agricultural land area further, by 11.8 per cent relative to the current situation, potentially allowing for 0.57 billion ha of afforestation.

Figure 35. Change in global land use by 2050 modelled under the REmap energy scenario, combined with a BAU agri-food scenario (S0), compared with two meat substitution scenarios (M1 and M2)



Note: Light pink percentage labels refer to all agricultural land-use change relative to the current situation.
Sources: Chatham House modelling calculations; Smith, P. et al. (2016), 'Biophysical and economic limits to negative CO_2 emissions', *Nature Climate Change*, 6(1), pp. 42–50, https://doi.org/10.1038/nclimate2870; Alexander, P. et al. (2017), 'Could consumption of insects, cultured meat or imitation meat reduce global agricultural land use?', *Global Food Security*, 15, pp. 22–32, https://doi.org/10.1016/j.gfs.2017.04.001; FAO (2022), 'FAOSTAT > Land Use', https://www.fao.org/faostat/en/#data/RL (accessed 1 Jun. 2022); IRENA and IEA (2017), *Perspectives For The Energy Transition: Investment Needs for a Low-Carbon Energy System*, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Mar/Perspectives_for_the_Energy_Transition_2017.pdf.

These results are broadly consistent with other recent attempts to examine the same question using alternative approaches. For example, Bajželj et al. (2014) examine scenarios for the future of the food system and conclude that only with sustainable agricultural intensification, waste reduction and dietary change can climate change be mitigated, principally through reducing land pressure.[431] Similarly, Springmann et al. (2018) modelled the extent to which the food system can feed future populations nutritiously without breaking planetary boundaries

428 Alexander et al. (2017), 'Could consumption of insects, cultured meat or imitation meat reduce global agricultural land use?'.
429 For more information regarding the meat substitutes scenarios, see Chapter 4, drawing on Alexander et al. (2017), 'Could consumption of insects, cultured meat or imitation meat reduce global agricultural land use?'.
430 By this, we mean a scenario in which 50 per cent of current animal products are replaced with cultured meat.
431 Bajželj et al. (2014), 'Importance of food-demand management for climate mitigation'.

(including climate and nutrient cycles), and concluded that this would only be possible with the adoption of sustainable intensification, waste reduction and dietary change.[432]

Even given the somewhat hazy picture of global land availability, matching demand for land to the most appropriate sources and locations of supply is not a straightforward problem to be resolved algorithmically. And of course, crucially, power, politics and trading relationships complicate the resource availability picture considerably. Chapters 7–9 of this report tackle these issues.

6.3 Making space for nature

The scenarios presented above indicate that land crunch pressures are likely to intensify, especially if the use of bioenergy for energy sector decarbonization and CDR via BECCS expands aggressively. This situation will be made worse if not accompanied by demand-side changes in dietary habits and reductions in food waste. Relying on sustainable intensification alone to raise crop yields closer to their theoretical limits does not fully ease this tension, and such an approach in turn would create additional environmental impacts of its own, for example affecting air quality and water availability.

Land crunch pressures are likely to intensify, especially if the use of bioenergy for energy sector decarbonization and CDR via BECCS expands aggressively.

However, perhaps the biggest loser from the pressures from the demand for land will be biodiversity. A potential requirement for up to 30 per cent more agricultural land (some 1.45 billion ha), depending on the scenarios for sustainable intensification, will likely result in a cascading series of risks to habitats, biodiversity, and regulating and supporting ecosystem services (see Chapter 2, Table 1). The intense competition for land will increase the prices of land-based products and services. It will incentivize the intensification of agriculture, with the associated inputs, land homogenization and degradation all contributing to the erosion of biodiversity. Land with the highest nature value (such as primary tropical forests) will also be at increasing risk of being brought into production.

The importance of biodiversity and ecosystem service loss on a global scale has been underscored by major studies such as the 2019 report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES).[433] Stronger calls to address the issue are emerging from society more widely, echoing messages espoused by civil society movements internationally. The scale of the losses involved, and the increasing recognition that biodiversity is a huge part of nature's contribution to human health and well-being, mean that biodiversity is moving from a 'nice to have' attribute to a 'must have' in policy debates, with many scientists and organizations calling for rewilding and natural solutions to allow space for nature.[434]

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432 Springmann, M. et al. (2018), 'Options for keeping the food system within environmental limits', *Nature*, 562(7728), pp. 519–25, https://doi.org/10.1038/s41586-018-0594-0.
433 Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) (2019), *Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*, Bonn: IPBES Secretariat, https://doi.org/10.5281/zenodo.3831673.
434 Thunberg, G. et al. (2022), 'A natural solution to the climate disaster', *Guardian*, 3 April 2019, https://www.theguardian.com/environment/2019/apr/03/a-natural-solution-to-the-climate-disaster.

The land crunch investigated in this chapter – and through the report more widely – clearly shows that the balance between space for nature, maintaining biodiversity, food production and energy production will require increasingly difficult trade-offs and ambitious action as pressures on land intensify. Determining the optimal balance is not a simple matter, but decisions cannot be delayed: changes to energy infrastructure, farming practices and societal behaviour, along with norms relating to diets and food waste, will take decades to be realized on the scale required. The urgency of these decisions – along with the particular opportunity afforded by near-term policy moments – is highlighted in Box 13.

Box 13. The urgency of now – summary of progress on the three 'Rio conventions'

The next few years are crucial for setting the tone and ambition for environmental action, and for helping to chart a path towards more sustainable land use. However, with political bandwidth and fiscal capacity still constrained by the after-effects of the pandemic and cost-of-living and resource security concerns, substantial difficulties remain to be overcome.

In the near term, a series of important environmental negotiations and intergovernmental meetings are continuing that will together shape the international sustainability agenda for the coming decades. Climate change, biodiversity loss, land degradation and food insecurity are inseparable challenges that must be addressed together. Strategy in all four areas must be reflected in a holistic and integrated set of targets, informed by science, that will drive action towards achieving the Sustainable Development Goals.

2020 was supposed to be the 'super year' for the environment, with several pivotal summits set to refocus global commitments on climate change and biodiversity. However, the COVID-19 pandemic forced the postponement of many scheduled international forums, including the major UN conferences of the parties (COPs) to the three 'Rio conventions' – on climate change (UNFCCC[435]), desertification (UNCCD[436]) and biodiversity (CBD[437]). With the last of these eventually concluding in late 2022, clarity on the principles that countries are committing to has finally begun to emerge.

Despite the lost time, the necessary rescheduling of these summits offered a couple of benefits. First, there was more opportunity, arguably not fully realized, to forge stronger linkages between the agendas of the three COPs, and to develop a dialogue that builds between each conference to establish shared nature-based solutions. These factors will be crucial if land is to meet the multiple demands on it. Second, perhaps more tangibly, the delays to the Glasgow climate summit (COP26) allowed the US, under the administration of President Joe Biden, to re-engage more fully and reverse its withdrawal from the Paris Agreement that had taken effect in the final weeks of the Donald Trump presidency.[438]

435 United Nations Framework Convention on Climate Change.
436 United Nations Convention to Combat Desertification.
437 Convention on Biological Diversity.
438 The US is, notably, not a party to the CBD nor likely to become one under any administration in the near term.

Climate – UNFCCC

The UN-led climate talks, COP26, rescheduled to November 2021, were regarded as a crucial moment for climate diplomacy, marking the first milestone since the COP21 Paris Agreement in 2015 committed countries to 'ratcheting up' their climate pledges – nationally determined contributions (NDCs) – every five years. On this front, governments fell short: although over 120 parties submitted new or updated NDCs, the new targets only narrow the gap to 1.5°C by 15–17 per cent and are, if fully implemented (and even this is far from certain), projected to result in warming of 2.4°C by the end of the century. If humanity is to limit warming to 1.5°C above pre-industrial levels,[439] additional greenhouse gas emissions reductions over and above these NDC pledges will be needed before 2030. The required size of these additional cuts equates to reducing emissions by the equivalent of two years of current annual global emissions. To limit warming to 2°C, the equivalent reductions needed would equate to one year's total emissions.[440]

The Glasgow Climate Pact – the main political outcome of COP26 – asked governments to revisit and strengthen their NDCs by the following COP to bring these in line with the Paris Agreement's temperature goal and to develop, also before the end of 2022, long-term strategies to transition to net zero emissions.[441] Only 34 of 194 parties revised their NDCs in the timeframe, although this did include major economies such as Australia, Indonesia and Mexico, and only 11 long-term strategies were submitted, bringing the total to 54. This resulted in the outcome document from COP27, hosted by Egypt, having to reiterate the previous requests to countries that had not acted on their NDCs or strategies to do so by COP28 in the United Arab Emirates at the end of 2023.

COP26 did secure a couple of significant plurilateral commitments relevant to land – although achieving the important end-of-decade ambitions embodied in these commitments will require immediate step-changes in action. The key points of these commitments are as follows:

— The Glasgow Leaders' Declaration on Forests and Land Use represents a pledge from 141 countries, home to 91 per cent of the world's forests, to halt and reverse forest loss and land degradation by 2030 'while delivering sustainable development and promoting an inclusive rural transformation'.[442]

— Over 100 countries signed up to the Global Methane Pledge to reduce global methane emissions by 30 per cent by 2030. The signatories include six of the world's top 10 methane emitters – Argentina, Brazil, the EU, Indonesia, Pakistan and the US – and collectively cover countries responsible for nearly half of global methane emissions.[443]

439 Both 1.5°C and 2°C are relevant temperature targets: the 2015 Paris Agreement refers to an aim of 'holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change'.
440 Åberg, A. et al. (2021), *COP26: What happened, what does this mean, and what happens next?*, Briefing, London: Royal Institute of International Affairs, https://www.chathamhouse.org/2021/11/cop26-what-happened-what-does-mean-and-what-happens-next.
441 Ibid.
442 UN Climate Change Conference (COP26) (2021), 'Glasgow Leaders' Declaration on Forests and Land Use', 2 November 2021, https://ukcop26.org/glasgow-leaders-declaration-on-forests-and-land-use.
443 Global Methane Pledge (2022), 'Global Methane Pledge', https://www.globalmethanepledge.org.

The subsequent COP27 was a lower-key affair, billed as the 'implementation COP'. However, as with emissions pledges, it resulted in similar procrastination on mobilizing adaptation financing from developed countries, and on defining a Global Goal on Adaptation. It did, however, establish a breakthrough agreement on funding for the severe 'loss and damage' consequences of climate change and, for the first time, included a reference to nature-based solutions in the main political outcome document. This encouraged parties to consider nature-based solutions or ecosystem-based approaches for mitigation and adaptation actions while ensuring relevant social and environmental safeguards. However, efforts to explicitly link nature and climate in the main outcome document were unsuccessful.[444]

Desertification – UNCCD
Parties to the Rio convention most often overlooked – on desertification (UNCCD) – gathered for their 15th session (COP15) in Abidjan, Côte d'Ivoire, in May 2022. Parties committed to accelerating the restoration of 1 billion ha of degraded land by 2030, supported by enhanced data gathering and monitoring and by the establishment of a new partnership model for large-scale integrated landscape investment programmes. Action was also announced on drought resilience, and there was a symbolic but important commitment to ensuring greater synergies among the three Rio conventions, including through national-level implementation of the treaties through nature-based solutions and target-setting.[445]

Biodiversity – CBD
The UN Convention on Biological Diversity (CBD) summit, COP15, was also disrupted by COVID-19 and split into two meetings – the initial online session was held in the autumn of 2021, but substantive in-person negotiations had to wait until the end of 2022, when they took place in Montreal, Canada, instead of in Kunming, China, as originally intended (though China retained the COP presidency). The summit came at a critical juncture following the release of a landmark IPBES report which indicates that nature is declining globally at alarming and unprecedented rates. Many of the Aichi Biodiversity Targets (which had been guiding international efforts up to 2020) have not been achieved.[446] With the expiration of these targets and associated international agreements, COP15 represented an important opportunity to establish a replacement framework and supporting mechanisms that can halt and reverse biodiversity loss, in line with the CBD 2050 vision of 'living in harmony with nature'.

Despite a faltering process leading up to the conference, parties agreed a new post-2020 global biodiversity framework (GBF), the 'Kunming-Montreal Global Biodiversity Framework'. The new framework commits parties to a set of goals and targets to end biodiversity loss. Target 3 has received particular attention for its potential to galvanize

444 Alayza, N. et al. (2022), 'COP27: Key Takeaways and What's Next', World Resources Institute, 8 December 2022, https://www.wri.org/insights/cop27-key-outcomes-un-climate-talks-sharm-el-sheikh.
445 UNCCD (2022), 'United global call to act on land degradation and drought concludes major UN meeting in Côte d'Ivoire', 20 May 2022, https://www.unccd.int/news-stories/press-releases/united-global-call-act-land-degradation-and-drought-concludes-major-un.
446 IPBES (2019), *Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*.

action, and has been compared, in this regard, with the Paris Agreement's clear call to limit the global average temperature increase to 1.5°C. Commonly referred to as '30×30', it calls on countries to ensure that at least 30 per cent of terrestrial, inland water, and coastal and marine areas are conserved by 2030. The GBF also aims to mobilize at least $200 billion of nature funding per year by 2030 from all sources – domestic, international, public and private – including at least $30 billion per year in international finance flows from developed countries to developing countries.[447]

The GBF is a landmark agreement, albeit one that is non-binding, and the following years will be critical in ensuring the necessary steps are taken to implement and finance the agenda. It will also be important to ensure that such steps support progress against the agendas of the other two Rio conventions.

Outlook for future action on the Rio conventions

While some progress has been made since the pandemic disrupted timelines, rapidly increasing momentum on all these agendas in the coming years will be crucial for building trust between countries, and between citizens and governments. It will also be crucial for determining if the various 2030 targets under the Rio conventions, as well as the UNFCCC's 1.5°C climate commitment, can be realized.

Unfortunately, progress is being stymied as governments focus on contemporary economic and security concerns, which are constraining bandwidth for international engagement and progressive national policymaking on environmental issues. If commitments at these summits are not backed up by immediate actions to fulfil them, there is a real risk that they will become empty promises that fail to deliver the urgently required path corrections. Early in the COVID-19 pandemic, there was some optimism that ambitious recovery plans could galvanize collective action and create more sustainable and resilient approaches to economic development. The rhetoric of 'building back better' signalled the potential for green stimulus packages that could assist with driving ambition and realizing long-term environmental goals. There is scant evidence, however, that such opportunities are being seized and the lessons from the pandemic learned. Nevertheless, with the war in Ukraine driving activity to address energy and food security concerns, there may yet be accelerated action to improve energy efficiency, scale up renewable energy use, and reshape demand in ways that could meaningfully 'bend the curve' – enabling land-based sectors to provide stronger protection for nature, climate and health.

447 CBD (2022), 'COP15: Nations adopt four goals, 23 targets for 2030 in landmark UN biodiversity agreement', press release, 19 December 2022, https://www.cbd.int/article/cop15-cbd-press-release-final-19dec2022.

6.4 Conclusions

Land is essentially finite in area: conversion of land types to meet changing demands generally requires significant trade-offs, often with highly damaging consequences. While there are other pressures on land beyond those examined in detail in Chapters 3–6 of this report,[448] the greatest and most expansive pressures in the future will, in aggregate, overwhelmingly come from agriculture, bioenergy, and the need to preserve land and habitats for regulating and supporting ecosystem services (see Chapter 2, Table 1).

The modelling presented in Chapters 5 and 6 has shown that existing land crunch issues will be exacerbated by the twin problems of rising demand for food and over-reliance on bioenergy feedstocks for energy decarbonization – placing unmanageable strains on agricultural land, even if forests and other types of land are converted to new uses. Without ambitious changes in agri-food practices (on both the supply and demand sides), and a shift away from prospective reliance on bioenergy towards the use of less land-intensive renewables, the planetary pressures and impacts on society could rapidly become insurmountable.

Significant as these challenges are on a purely global accounting basis, they are even more vexing once power and politics are considered. Land is distributed unevenly, both in terms of its quality and quantity. Many inequities also affect access to land, and capacities and incentives to manage it. As a result, land optimization and governance will always be intensely political.

As pressures on the availability of land increase, the possession or control of land could convey strategic leverage much as ownership of oil and gas reserves did in the latter half of the 20th century. National security strategies will become increasingly preoccupied with access to land and land-based commodities; the problematic implications of such approaches are well documented throughout history.

Chapters 7–9 will now consider the growing strategic importance of land, examine how different countries' land-derived assets are increasingly enmeshed in geopolitical relationships, and chart a way forward for sustainable global land stewardship in the face of a deepening land crunch.

448 Including pressures from extractive industries, urbanization, infrastructure, sea-level rise and climate degradation.

07 Measuring land wealth

What is land 'wealth'? Many factors, from the quantity and quality of land to governance and climate risk resilience, contribute to each country's ability to benefit from its land asset base. Our new Land Wealth Index presents a country-by-country assessment, illustrating how globally important resources are distributed between nations.

As suggested by the trends and pressures described in the preceding chapters, high-quality land that is effective at providing environmental regulatory and supportive functions, and that offers humanity essential resources and cultural value, is becoming increasingly scarce. The problem is global in scale: both because many countries individually face a deepening land crunch, and because the aggregate pressures have serious implications for humanity's efforts to remain within planetary boundaries.

Unsustainable patterns of food provision, energy generation, freshwater use, resource extraction, human settlement and infrastructure construction are – along with climate change – undermining the ability of terrestrial resources to continue to deliver ecosystem services (including climate and environmental regulation). Classic 'frontier expansion', exemplified historically by human migration into wilderness or underpopulated areas, is less and less viable as an option for finding additional unappropriated land. Few genuine frontiers remain; and where they do, the ecological and environmental costs of expanding humanity's footprint on to them are generally unjustifiable if fully accounted for. Some barren lands may be able to provide additional resource capacity for certain purposes (such as solar arrays, to give one example), but areas of unequivocally 'spare' land are increasingly rare. In sum, there remains a fundamental tension between diminishing terrestrial resource availability, increasingly unsustainable demand and escalating environmental risks.

These factors indicate that land is becoming increasingly strategically important. Access to, ownership of and control over land and land-derived resources will become ever more significant throughout this century – and will matter to actors at all levels, from intergovernmental and multinational to community and individual. There is a clear challenge here for management of the global commons. Safeguarding natural capital held by sovereign states, companies or individual landowners, but in which all of humanity has an interest, will require robust regulation and cooperative engagement in international governance mechanisms, coupled with decisive action at local levels. (Recommendations are set out in full in Chapter 9.)

Countries will increasingly be confronted with the reality that degraded ecosystems will reduce their own resilience to severe and frequent environmental shocks.

Nation states will continue to rely on their land asset bases to fulfil economic and development ambitions, and will often seek to profit from extraterritorial demand for land-derived goods and services as the means to do so (for example, through exports of food and natural resources). Yet at the same time, such countries will increasingly be confronted with the reality that degraded ecosystems will reduce their own resilience to severe and frequent environmental shocks. Conversely, many countries facing resource insecurity will seek to expand their access to others' land-based resources to ensure their own security and prosperity. They may attempt to do this either through cooperative action or unilaterally using economic coercion – or, in extremis, military force. Whether the drivers of land appropriation are domestic or international, without effective legislation and enforcement, people who are already struggling to survive on marginal lands, or whose land tenure is insecure, will increasingly find their livelihoods constrained, controlled or buffeted by the interests of actors with greater economic and political power.

In this chapter, we focus primarily on the strategic value of land from the perspective of the nation state. Of course, many decisions about land use, preservation and restoration are made within a given country's borders by a broad range of public, private and individual actors, often reflecting highly unequal power and ownership distributions. But nation states are the agents with the ultimate levers of control within these borders, and are the principal interlocutors in global governance arrangements.

To highlight where countries' comparative advantages and disadvantages lie in terms of land availability and quality, and how these and related factors intersect with geopolitical and economic relationships, we have created an indicative 'land wealth index'. This new resource (introduced in Section 7.2) is based on a range of indicators that effectively quantify the relative 'value' of and risks to each country's land-based resources. As such, the index also provides a means of considering potential land-related risk hotspots that require urgent global action, or over which international tensions may play out. In addition, the index – along with the selective geopolitical typologies it loosely informs (also described in this chapter) – has an important role in informing the analysis of the interactions between land wealth and geopolitical and economic power in Chapter 8.

7.1 An evolving picture

Land wealth is not just a function of current environmental conditions and management practices in any given country. It is also historically contingent: the delineation and contestation of national borders, and how previous inhabitants have shaped the land, are central determinants of the extent and nature of countries' land resources. In West Africa, to give just one example, Nigeria and Niger share a 1,500-km border drawn by Britain and France during the partitioning of Africa by European colonizers. While Nigeria has a long coastline, extensive arable land and major reserves of oil and gas, Niger is arid and landlocked, although it does have significant mineral resources. Another example of land wealth reflecting very different formative forces is the UK. Its international borders in part reflect historical political geography on the island of Ireland, but are otherwise largely defined by the physical geography of the British Isles. The UK's landscape – especially the extent of its forests – has been significantly reshaped since farming was introduced from the European continent in the late Stone Age,[449] through the Bronze Age (when the forest area was reduced by half), and then by successive occupying powers and land users to present-day agriculturalists, industrialists, dwellers and planning committees.

Considerable disparities can be observed in what might be considered each country's land wealth, reflecting the consequences not just of physical and political geography, but of history and economics. At the same time, significant international trade in 'virtual' or embodied land and fresh water – through markets in food, forest products, natural fibres, biofuels and even electricity[450] – is crucial in redistributing land wealth between countries. These same trade flows, along with the direct acquisition of lands, are also used to appropriate and exploit land wealth.

Given the mounting and geographically heterogeneous pressures on land – together with inequities in national land-based resources, disparities in governance capabilities, and common but differentiated responsibilities for managing globally important resources – it is worth examining where land wealth exists, how it is changing, and the factors that might determine national land-use choices in the future. To do so, we have developed the Chatham House Land Wealth Index (LWI).

7.2 The Chatham House Land Wealth Index

The Chatham House Land Wealth Index (LWI), created for this report, offers a country-by-country picture of land wealth worldwide, reflecting the extent and essential characteristics of the productive and environment-supporting lands of 163 countries. It is a composite metric offering a working assessment of the relative 'wealth' of each country according to its land. The information it provides is designed to help researchers and policymakers better understand how global land interdependencies are evolving, how strategic responses by different nations

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449 Natural History Museum (2019), 'Ancient DNA shows migrants introduced farming to Britain from Europe', 15 April 2019, https://www.nhm.ac.uk/press-office/press-releases/ancient-dna-shows-migrants-introduced-farming-to-britain-from-eu.html.
450 If generated by, or in place of, land- or water-intensive means.

might develop in the context of broader geopolitical relationships, and which countries may be regarded as the conventional and perhaps unconventional 'land superpowers' of the future (see Section 7.4.1).

Assessing land wealth is, of course, a complex undertaking: such an assessment needs to capture the varied uses and functions of land for all countries considered. The LWI brings together 16 quantitative indicators, grouped under five intuitive domains, to encapsulate the factors affecting each country's land asset base. These domains cover the quantity of land, recent trends, future risks, governance and economic capacity, and direct and indirect population pressures. The measures included are not exhaustive, and are certainly open to critique, but they do have the utility of being broad-ranging and of capturing values not typically included in economic assessments: for example, the holistic conception of wealth used in the LWI recognizes the ecological and societal value of land as well as its market potential.

The LWI is not intended as a definitive 'league table' of land wealth. Rather, in presenting the index, we aim to provide an intuitive sense of how globally important resources are distributed between nations, along with a data-driven indication of countries' susceptibility or resilience to land-related pressures in the widest sense. The aim is to encourage discussion about how countries may soon increasingly compete on the basis of their land resources, and where global cooperation is required to mitigate national or supranational exploitation of lands and avert potential future problems such as food shortages or conflict.

As such, perhaps the key aspect of the LWI is the light it sheds on the *qualitative* dimensions of land wealth. What this means, in simple terms, is that although absolute land area is a significant determinant of a country's land wealth, it is far from the only factor. Huge countries such as the US, Russia, Australia, China, Brazil and Canada all, unsurprisingly, feature in the top 10 places in the LWI (see Table 5). But a smaller country can also rank highly if it has high-quality land or manages its land well, among other variables. A good example is Germany, which ranks fifth in the index despite being the 64th largest country by area.

At the same time, the LWI underscores the essential truth that having a lot of land is not, on its own, a guarantee of land wealth – especially if that land is degraded, poorly governed or both. Algeria and the Democratic Republic of the Congo (DRC), in their own different ways, illustrate the point. These two countries rank 95th and 56th in the index respectively, despite being the 10th and 11th largest countries in the world. Neither scores well on measures of governance capacity, with Algeria's position in the index also reflecting the inherent challenges associated with a predominantly desert landscape. The DRC, in contrast, is one of the most carbon- and biodiversity-rich countries, possessing high-quality lands that are important beyond its borders for mitigating and providing resilience to global environmental change. However, the country's rapid projected population growth and high vulnerability to land exploitation, combined with the governance pressures mentioned above, bring down its overall ranking. India also ranks far lower, at 45th, than it would in a table reflecting size alone (i.e. seventh), with poor soil quality a factor across much of the country.

7.2.1 Land Wealth Index indicators

Quantity indicators

A primary determinant of each country's land wealth is its quantity of land available for productive use, or for use in regulating and supporting vital ecosystems and Earth system processes. Five metrics are included here: quantity of cropland; quantity of natural and semi-natural vegetation; quantity of carbon stored in living forests; quantity of carbon sequestered by vegetation each year (also referred to as 'net primary production' – NPP); and additional capacity available for 'population-satisfying' food production[451] (also known as 'biophysical redundancy'). Larger countries typically score better on these measures because they have more physical space. However, countries with vast expanses of land that is unproductive or low in ecological value, where environmental conditions are harsh, or where population and development pressures are constraining the potential of vegetation, will not rank as highly.

Degradation and utilization trend indicators

Some countries may have plentiful, high-quality land, but these assets may still be insecure if land wealth is being eroded by changing environmental conditions, or squandered in pursuit of immediate economic gain (as exemplified by the huge wildfires in the Brazilian Amazon in 2019 and 2022). The 'trends' category of indicators captures some of these dynamics, pointing to areas of concern that may require international interventions to safeguard the future of land resources. Four metrics are included: the proportion of species habitat that has been lost since 2001; the proportion of tree cover that has been lost over a similar period; the proportion of land that has recently been decreasing in productivity; and recent changes to the proportion of the country's population that could have its food intake requirements satisfied by land's additional capacity (i.e. changes to biophysical redundancy). It should be noted that if a country's lands were already degraded at the start of this period, and if their condition has not significantly worsened since then, or has improved, then the country will still score well by these measures, irrespective of the absolute condition of those assets (as seen, for example, with biophysical redundancy in Djibouti or tree cover in Egypt).

Risk indicators

While the amount of land available is critically important, so too are its quality and vulnerability to environmental threats. The four indicators in this domain address the following questions about the vulnerability, exposure and resilience of each country's terrestrial assets: How good are the soils? How well protected is the biodiversity? How severe are the current water risks? How severely exposed is the land to future climate threats? Countries that score highly in this domain (i.e. meaning that the risks are relatively low) may not be conventionally perceived as land superpowers; nor may they produce vast quantities of marketable ecosystem services. However, such countries are likely to become increasingly

451 In other words, this is a country's unexploited potential to produce additional food calories relative to its population's food energy requirements.

important globally in regulating and building resilience to environmental change. This may suggest that they warrant greater international attention and support to preserve their vital asset bases.

Governance and economic capacity indicators

The two indicators in this domain do not directly relate to each country's land-based resources. Instead, they point to how well equipped each country is to manage its land, in terms of both the competence of governance and the economic resources available. We measure governance using a composite index that takes the average of the Worldwide Governance Indicators (WGI)[452] for each country (reflecting government effectiveness, control of corruption, political stability and absence of violence/terrorism, regulatory quality, rule of law, and voice and accountability). Economic capacity is proxied by gross national income (GNI) per head. None of these measures is land-specific, so they provide only a broad signal of the enabling environment in which effective land management may occur. Low-capacity countries with significant land-based resources may require international support or changes to incentives so that they are able to safeguard ecosystem services provided to the global community from within their borders (a good example is Venezuela; see Section 7.4.2). Equally, greater international scrutiny of dominant economic powers may be needed to guard against hegemonic appropriation of land in furtherance of such countries' own resource security agendas.

Population indicators

A few of the indicators in other domains (GNI per head, biophysical redundancy and, to a limited degree, climate exposure[453]) incorporate direct consideration of national population dynamics. Many of the other indicators are, at least in part, affected by the direct and indirect land footprints of populations. Direct footprints relate to the proportion of land appropriated for people to live on. Indirect footprints refer to the land area and terrestrial resources given over to provisioning for those people – such as producing and extracting food, water and commodities. An indirect footprint is, to varying degrees, international, whereas a direct footprint is entirely territorial. While current population pressures are reflected in the other indicator values, future population dynamics are sufficiently material to nations' land wealth prospects to warrant explicit representation. As a simple proxy, the LWI incorporates a measure of each country's projected population change between 2019 and 2050.

7.2.2 Methodology: deriving a composite assessment

As an initial step in developing the LWI, we excluded all countries with a land area of less than 0.5 million hectares (ha) from the analysis, as many data were missing across multiple indicators for countries of this size. Despite meeting the threshold for land area, a small number of other countries, economies and territories (listed in the note to Table 5) were also excluded on grounds of insufficient data. This

452 Worldwide Governance Indicators, https://info.worldbank.org/governance/wgi.
453 Climate exposure includes population change as one of the food sub-indicators.

resulted in 163 countries being included in the assessment.[454] We then conducted a principal component analysis (PCA) to produce a composite index value across all indicators and domains.

PCA is a statistical technique used for describing variation among diverse variables across the smallest number of dimensions that the variation in the data requires. This approach has the advantages of reducing the dimensionality of the data, and of providing a more objective means of deriving a composite score than subjectively weighting the (subjective) domain values: no matter which domain the indicator is assigned to, all indicators are considered collectively. This is important because one indicator may share information with others and thus not be treated as statistically independent (e.g. measures of forest carbon content, NPP and soil carbon content reflect similar aspects of a 'higher-level' variable associated with land productivity). The use of PCA ensures that the relationships between indicators are described in the smallest set of statistically independent 'components' or axes that capture their joint relationships.[455] PCA is based on correlation analysis, so our initial step in populating the LWI and calculating index values was to transform the data appropriately to reduce any skew, and to ensure the results were robust in terms of outliers and the distribution of data.

Our analysis identified five principal components (columns C1 to C5 in Table 4) that collectively described 72 per cent of the variance in the dataset of multiple indicators. From these, we extracted a single LWI score for each country. (This score was the sum, across the five components, of each of the component scores multiplied by the variance explained by that component.) Each of the five components is strongly associated with a small number of the primary indicators, and so it is possible to see how the variables group together statistically. Component 1 (C1) captures 22 per cent of the variance and is most strongly associated with NPP,[456] the amount of vegetation, carbon stored in forests, and the area of cropland – we have labelled it 'amount and quality of land'. All component labels are short-form rather than comprehensive descriptions of the phenomena with which they are most strongly associated. For the avoidance of doubt, this in no way affects the underlying relationship between the component and each individual indicator. Table 4 shows the full strength of each relationship (by cell colour) and the overall weighting of each component (see the row labelled 'variance'). Component 2 (C2, 'development status' – 18 per cent of the variance) is most strongly associated with governance indicators (WGI and GNI per head) and to a lesser degree is inversely associated with the projected rate of population growth. Component 3 (C3, 'changing environmental

454 The LWI's country list is based on the World Bank's list of countries and economies: https://data.worldbank.org/country. As the underlying datasets vary to some degree in their inclusion or exclusion of different countries and territories, and in their treatment of nations' outlying territories as part of the country or as separate entities, these anomalies have been considered pragmatically on a case-by-case basis. Generally, overseas territories are not of significant enough size to make a material difference to country indicator values in the LWI. See Table 5 and its note for full details.

455 For example, suppose PCA is conducted for a dataset compiled of physical measurements of hundreds of people: arm length, leg length, head circumference, chest, waist, hip size and foot size. The first component, explaining most of the variation in the data, would capture how the variables are related to a person's size (longer arms and longer legs are correlated with taller people). The second component would capture the impact of body shape (larger hips are correlated with larger waists and chests). The third would likely capture the effect of sex on the other variables (because sex-related differences in shape are smaller than height- or body-shape-related differences).

456 The negative correlation between C1 and NPP shown in the heatmap reflects the fact that the initial transformation of the NPP data series was to take the cubic root of the raw values. This is the only instance in which the transformation inverted the relationship.

risks' – 13 per cent) is associated with trends in loss of tree cover and habitat, less strongly with water risks, and inversely with biodiversity protection and climate exposure. Component 4 (C4, 'land resources and their change' – 10 per cent) is most associated with biophysical redundancy and its rate of change, and to a lesser extent is inversely related to water risks. Component 5 (C5, 'soil quality and its change' – 9 per cent) is inversely associated with degrading land productivity, positively associated with soil quality (soil organic carbon – SOC), and to a lesser extent exhibits an inverse relationship with population growth.

Table 4. Chatham House Land Wealth Index – principal components

		C1: Amount and quality of land	C2: Development status	C3: Changing environmental risks	C4: Land resources and their change	C5: Soil quality and its change	Communality*
	Variance	22%	18%	13%	10%	9%	72%
Domain	**Indicator**						
Quantity	Cropland	0.85	-0.19	0.05	-0.02	0.14	77%
	Natural and semi-natural vegetated land	0.93	-0.04	-0.02	0.07	-0.04	87%
	Carbon stock in living forest biomass	0.86	0.06	-0.28	0.19	0.12	87%
	Net primary production	-0.93	-0.06	0.14	0.01	0.04	88%
	Biophysical redundancy	0.27	-0.08	-0.12	0.73	0.15	65%
Degradation and utilization trends	Species habitat loss	-0.06	0.08	0.73	0.25	-0.25	66%
	Tree cover loss	-0.10	0.01	0.80	-0.11	0.09	68%
	Land productivity declines	-0.08	-0.05	0.02	-0.28	-0.85	81%
	Biophysical redundancy change	-0.16	-0.13	0.31	0.66	0.03	57%
Risk	Carbon content in the topsoil	0.12	0.46	-0.28	0.04	0.54	60%
	Biodiversity and habitat protection	0.13	0.41	-0.41	0.39	0.05	50%
	Water risk	-0.07	-0.32	0.48	-0.54	-0.20	67%
	Climate exposure	0.34	-0.42	-0.41	0.03	-0.27	54%
Governance and economic capacity	Governance	-0.06	0.89	-0.14	0.09	0.06	82%
	Economic capacity	-0.05	0.91	0.10	-0.10	-0.04	84%
Population	Population change, 2019–50	0.07	-0.69	-0.16	0.18	-0.47	76%

* The proportion of each variable's variance that can be explained by the components.
Key: Main heatmap – colour gradient reflects strength of relationship between indicators (rows) and components (columns), ranging from -1 (red) for a perfect inverse relationship to 1 (green) for a perfect positive relationship; top variance row and last communality column – higher values have darker shading.
Source: Authors' calculations.

As a final step, the component and overall LWI scores for each country were normalized, with the raw scores rebased to values between 0 and 100, to allow for more intuitive interpretation.

In general, a high LWI score tends to be associated most strongly with an abundance of cropland, large areas of naturally and semi-naturally vegetated land, and high volumes of forest carbon. High-scoring countries typically have also experienced low rates of land productivity decline and habitat loss since the turn of the century, although habitat losses among the lowest-ranking countries have been less severe than among mid-ranking countries. Volumes of annual carbon uptake by vegetation (i.e. NPP) and the density of carbon content in the topsoil (a measure of soil quality) have weaker relationships to aggregate LWI scores. Forward-looking measures of the severity of countries' exposure to climate hazards over the remainder of the 21st century are not good predictors of LWI scores. However, there is an inverse association between LWI performance and projected population growth rates. Countries with strong governance indicators (correlated with income per head) also tend to achieve high LWI scores.

7.2.3 Limitations of the Land Wealth Index

In addition to the points set out above, the principal limitations of this simplified composite index are its subjective reductionism of highly complex land systems; its uneven temporal coverage (since many of the constituent datasets are collected relatively infrequently) and lack of time series; and its embodiment of inherent weaknesses in the underlying indicators. The structure of the LWI seeks to control for these limitations and redundancy between indicators to the extent possible, but shortcomings remain. To reiterate, the intention is to frame our analysis and to foster debate, not to provide a definitive 'league table' of countries' relative or absolute land wealth or their (potential) successes and failures in managing this wealth; to do so is inevitably subjective and beyond authoritative quantification.

Table 5. Chatham House Land Wealth Index and component scores

LWI rank	Country	Land Wealth Index	C1: Amount and quality of land	C2: Development status	C3: Changing environmental risks	C4: Land resources and their change	C5: Soil quality and its change
1	United States	100	100	80	63	75	41
2	Russia	97	100	62	64	62	73
3	Australia	93	94	85	63	81	15
4	China	88	95	54	67	47	75
5	Germany	87	58	92	64	69	71
6	Poland	85	54	76	63	84	81
7	France	83	68	85	61	71	53
8	Kazakhstan	82	74	52	93	61	47
9	Brazil	81	98	60	45	68	50
10	Canada	81	97	100	39	22	54
11	Spain	78	59	81	65	75	50

LWI rank	Country	Land Wealth Index	C1: Amount and quality of land	C2: Development status	C3: Changing environmental risks	C4: Land resources and their change	C5: Soil quality and its change
12	Venezuela	77	75	51	66	76	57
13	Colombia	76	78	57	53	67	68
14	Italy	75	57	75	66	73	55
15	Japan	75	62	83	56	63	57
16	Belarus	74	46	53	61	84	100
17	United Kingdom	74	50	89	54	76	58
18	Botswana	73	56	73	74	92	19
19	Georgia	73	39	55	83	82	78
20	Iran	72	56	43	99	53	65
21	Austria	72	37	86	59	85	66
22	Argentina	72	83	62	55	70	31
23	Romania	72	53	62	62	80	71
24	Czechia	72	36	79	61	81	79
25	Mexico	71	80	52	58	57	60
26	Finland	69	47	90	37	75	77
27	Bulgaria	69	40	64	64	84	76
28	Mongolia	69	57	52	79	54	70
29	Switzerland	69	28	93	66	76	63
30	Norway	69	45	97	56	72	41
31	Bolivia	68	72	47	55	83	50
32	Peru	68	77	55	60	48	56
33	Lithuania	67	33	73	56	87	79
34	Croatia	67	35	70	61	91	69
35	Ukraine	67	60	44	64	70	74
36	Guyana	66	50	61	66	67	68
37	Slovakia	66	31	72	59	90	75
38	Türkiye	66	65	42	74	53	69
39	Sweden	66	53	91	39	60	64
40	Hungary	65	35	71	57	84	71
41	Kyrgyzstan	64	40	34	100	61	75
42	New Zealand	64	50	94	43	76	37
43	Papua New Guinea	64	66	36	70	74	52
44	Azerbaijan	64	37	39	87	70	80
45	India	63	86	32	65	39	62
46	Greece	63	42	69	64	75	56
47	Gabon	62	55	49	62	90	43

LWI rank	Country	Land Wealth Index	C1: Amount and quality of land	C2: Development status	C3: Changing environmental risks	C4: Land resources and their change	C5: Soil quality and its change
48	Latvia	62	32	75	45	88	80
49	Estonia	62	28	78	44	84	87
50	Serbia	61	37	54	69	63	88
51	Bosnia and Herzegovina	61	32	45	74	78	88
52	South Africa	61	69	55	60	69	30
53	Ireland	61	31	90	52	81	51
54	Slovenia	61	23	78	57	83	76
55	Zambia	60	68	33	48	94	49
56	Democratic Republic of the Congo	58	82	9	53	79	62
57	Netherlands	58	26	86	54	61	77
58	Armenia	58	23	48	79	68	90
59	Belgium	58	25	78	55	85	62
60	Angola	57	75	25	60	83	33
61	Central African Republic	56	59	19	63	96	50
62	Chile	56	63	81	51	29	45
63	Indonesia	55	84	48	36	34	69
64	Cuba	55	46	49	62	68	63
65	Sudan	55	66	15	79	62	53
66	Thailand	55	62	53	50	54	58
67	Congo, Rep.	55	59	28	56	87	54
68	Tanzania	55	74	34	48	80	35
69	Suriname	54	41	65	56	64	62
70	South Korea	54	42	63	62	55	60
71	Cameroon	53	61	28	57	85	46
72	Namibia	53	50	54	57	87	27
73	Pakistan	53	57	19	83	43	75
74	Nepal	53	48	32	74	63	64
75	Morocco	53	45	45	69	60	62
76	Mozambique	53	66	27	55	89	35
77	Ethiopia	53	68	27	63	70	40
78	Denmark	52	26	91	47	80	41
79	Uruguay	52	42	71	39	82	47
80	Panama	52	38	60	50	82	56
81	Bhutan	50	29	58	63	80	54
82	Costa Rica	49	31	65	50	69	68

LWI rank	Country	Land Wealth Index	C1: Amount and quality of land	C2: Development status	C3: Changing environmental risks	C4: Land resources and their change	C5: Soil quality and its change
83	Nigeria	49	64	30	56	74	39
84	Portugal	49	35	81	43	71	45
85	North Macedonia	49	21	51	64	68	86
86	Montenegro	47	16	63	54	77	82
87	Brunei	47	9	76	45	86	79
88	Ecuador	47	57	50	48	54	51
89	Afghanistan	46	49	0	96	43	77
90	Iceland	46	15	99	56	76	22
91	North Korea	45	36	34	59	77	67
92	Myanmar	44	69	28	46	51	58
93	Kenya	44	59	33	53	71	36
94	Tajikistan	44	31	21	87	60	69
95	Algeria	43	40	32	67	54	71
96	Albania	43	24	52	57	69	73
97	Moldova	43	20	44	64	65	84
98	Uzbekistan	41	39	28	84	38	64
99	Ghana	41	45	37	43	83	50
100	Egypt	40	24	33	78	75	49
101	Senegal	39	41	30	49	85	50
102	Zimbabwe	39	54	27	50	84	29
103	Turkmenistan	38	33	33	86	44	47
104	Mauritania	38	28	16	71	81	62
105	Dominican Republic	38	31	43	51	67	64
106	Libya	37	27	32	87	55	45
107	Philippines	36	57	38	43	36	63
108	Guinea	36	41	23	39	94	57
109	Mali	36	47	11	53	83	52
110	Lesotho	33	15	27	78	73	59
111	Benin	33	35	29	44	94	43
112	Cyprus	32	8	74	53	58	54
113	Chad	32	51	11	49	75	47
114	Bahamas	32	17	82	58	65	6
115	Tunisia	31	25	43	64	49	55
116	Sri Lanka	31	35	51	49	52	45
117	Burkina Faso	31	42	20	48	79	47
118	Israel	31	10	68	64	50	46

LWI rank	Country	Land Wealth Index	C1: Amount and quality of land	C2: Development status	C3: Changing environmental risks	C4: Land resources and their change	C5: Soil quality and its change
119	Oman	30	17	53	79	57	22
120	Côte d'Ivoire	30	49	27	27	78	55
121	Iraq	30	31	25	75	73	22
122	Togo	30	25	22	55	85	58
123	Bangladesh	30	39	27	52	43	75
124	Laos	30	45	35	26	69	61
125	Syria	29	30	33	70	54	39
126	Equatorial Guinea	29	23	41	43	100	32
127	Malawi	28	34	22	42	89	49
128	Cambodia	28	40	34	30	74	55
129	Fiji	27	27	64	58	52	16
130	Paraguay	27	50	43	17	68	47
131	United Arab Emirates	27	15	71	65	49	19
132	Somalia	26	49	13	52	68	33
133	Yemen	26	31	29	75	45	35
134	Jordan	26	9	43	75	49	55
135	Timor-Leste	25	25	31	66	61	38
136	Rwanda	25	22	33	43	63	74
137	Jamaica	24	19	50	49	37	75
138	Uganda	24	46	26	37	64	41
139	Sierra Leone	23	30	20	36	87	57
140	El Salvador	23	21	50	48	46	58
141	Honduras	23	35	37	25	57	70
142	Vanuatu	22	22	56	60	68	0
143	Saudi Arabia	21	38	65	66	0	19
144	Eswatini	20	15	23	53	71	66
145	Lebanon	20	13	49	62	21	72
146	Nicaragua	20	35	29	17	60	81
147	Malaysia	19	56	59	0	9	78
148	Belize	18	18	48	23	78	53
149	Eritrea	17	35	24	62	48	25
150	Madagascar	16	58	8	18	60	56
151	Trinidad and Tobago	16	18	77	40	17	45
152	Vietnam	14	59	48	14	8	52
153	Kuwait	14	2	69	62	57	4
154	Liberia	14	35	9	29	78	55

LWI rank	Country	Land Wealth Index	C1: Amount and quality of land	C2: Development status	C3: Changing environmental risks	C4: Land resources and their change	C5: Soil quality and its change
155	Gambia	14	13	14	49	81	55
156	Qatar	13	0	64	62	47	23
157	Guinea-Bissau	13	21	14	30	90	57
158	Burundi	12	20	3	53	76	51
159	Niger	11	41	6	40	69	31
160	Solomon Islands	10	21	26	42	52	55
161	Guatemala	7	34	32	9	41	73
162	Haiti	3	14	9	48	37	77
163	Djibouti	0	3	38	66	47	8

Notes: All values are scaled 0–100 based on minimum (dark pink) and maximum (dark green) values per column. Index values are displayed as integers but ranking reflects the full decimal values. The first shaded column on the left shows each country's aggregate Land Wealth Index (LWI) value. The subsequent columns to the right show the values for each component used to derive the aggregate LWI value. The individual components represent a distillation of the full set of 16 indicators used to produce the index following the principal component analysis described in Section 7.2.2.

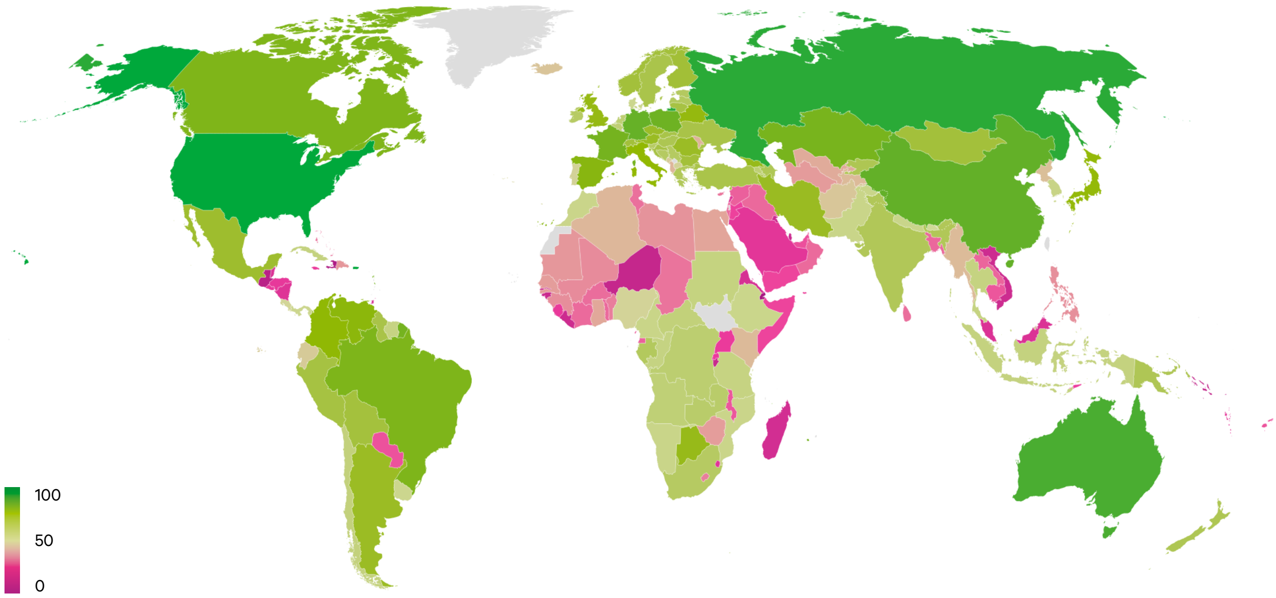
The final country list is based on the World Bank's list of countries and economies: https://data.worldbank.org/country. As the underlying datasets vary to some degree in their inclusion or exclusion of different countries, and in their treatment of nations' outlying territories as part of the country or as separate entities, these anomalies have been considered pragmatically on a case-by-case basis. Generally, overseas territories are not of significant enough size to make a material difference to country indicator values in the LWI. A number of countries, economies and other territories are excluded from the LWI on grounds of insufficient comparable data or absence from the available datasets, despite their meeting the threshold for land area. These are: Greenland, New Caledonia, Puerto Rico, South Sudan, Taiwan, and the West Bank and Gaza. The selection of countries in the LWI reflects limitations and assumptions in the datasets available, and does not imply any judgment or opinion on the part of the authors or Chatham House on the political status or borders of any country or geographical entity.

Sources: Authors' calculations, based on (by domain): **Quantity indicators** – OECD (2019), FAO (2019), Peng, D. et al. (2017), Fader, M. et al. (2016); **Degradation and utilization trend indicators** – Yale Center for Environmental Law & Policy (2018), EU Joint Research Centre (2019), Fader, M. et al. (2016); **Risk indicators** – FAO (2019), Yale Center for Environmental Law & Policy (2018), World Resources Institute (2019), University of Notre Dame (2019); **Governance and economic capacity indicators** – World Bank (2018), World Bank (2019); **Population indicators** – United Nations Department of Economic and Social Affairs, Population Division (2017). See Appendix (p. 217) for the full set of references.

7.3 Land wealth overview

The scores and rankings produced by the LWI assessment are set out in Table 5, and presented graphically in Figure 36 (composite scores) and Figure 37 (component scores). In broad terms, we can observe a positive correlation between a country's productive land resources (NPP, cropping area, forest cover for carbon storage) and its composite land wealth score. Larger countries with productive land resources (e.g. the US, Russia, Australia and China) score highest, and smaller countries (Solomon Islands, Guatemala, Haiti and Djibouti) score lowest.

Figure 36. Chatham House Land Wealth Index by country

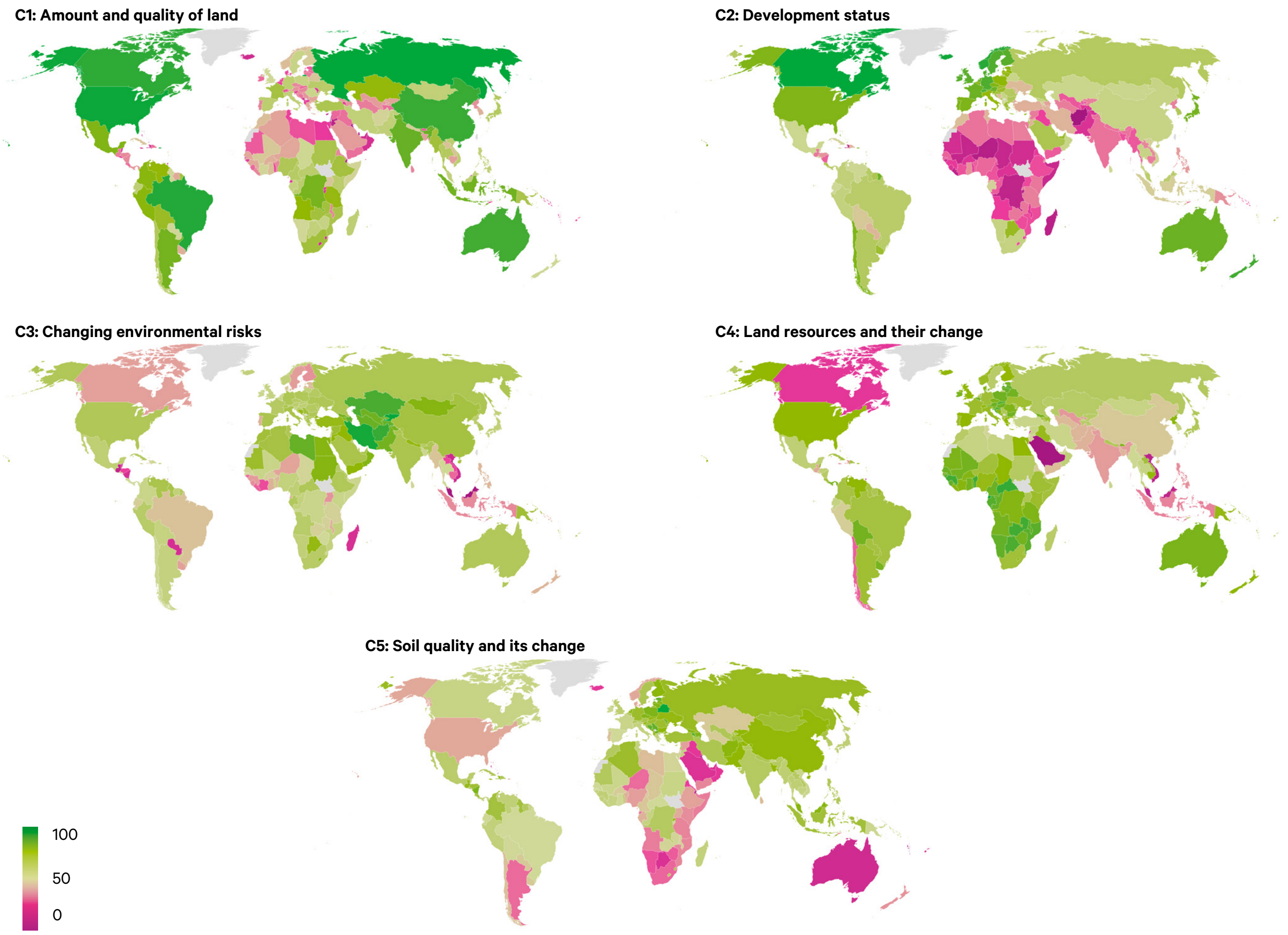


Source: Authors' analysis.

Having a large land area gives a country the opportunity to use land for a variety of functions, and means that land is less likely to be overwhelmed or become highly degraded too quickly. Countries with large areas of productive land, especially those with lower population densities, are or have the potential to be 'land superpowers', able to use land productively for domestic purposes and to export 'virtual land' embodied in products and ecosystem services from which other countries benefit. Canada and Brazil, among others, fit into the first category (see 'Land superpowers', Section 7.4.1), Kazakhstan and Bolivia into the second ('Potential land elites', Section 7.4.2).

Conversely, countries with small land asset bases may be hard hit by increasing competition between the goods and services being demanded from their land; many such countries, it should be noted, are below the 0.5 million ha threshold set for inclusion in the LWI. City states such as Singapore (land area 72,000 ha), as well as many other small island states, do not have adequate farmland to support their populations. This makes these countries heavily reliant on virtual land imports to achieve food security.

Figure 37. Countries' land wealth by each of the five featured PCA components



Note: PCA = principal component analysis.
Source: Authors' analysis.

However, land area is clearly not the only determining factor in a country's composite land wealth score. Many larger countries with poor-quality land (especially if this land is required to support a large population) are broadly as vulnerable as small countries to climate and environmental threats, and/or to disruptions in access to virtual land. Without ameliorative action, such countries are likely to be among the primary casualties of increased competition for land (see Chapters 6 and 8). Saudi Arabia, for instance, which is largely arid, ranks 143rd in the index and scores poorly on 'quantity' domain indicators despite being the 12th largest country in the world. Equally, countries that are politically unstable or have weak governance and limited economic capacity are among the lowest-ranking in the LWI – this reflects their limited capacity to govern and make productive use of their available land assets. Many African countries score poorly against indicators in this domain, with Botswana, Namibia and South Africa being notable exceptions outside northern Africa. Niger, highly exposed to climate change, is the 21st largest country in the world, but occupies the fifth lowest position in the LWI on account of its low-quality soils, limited biodiversity and constrained economic and governance capacities. The African continent beyond northern Africa is also the region in which projected population growth is most likely to generate additional future pressures on land resources. Niger's population is expected to almost treble by 2050, and the populations of 20 other African countries – including Nigeria, the DRC and Tanzania – are expected to more than double.[457] Sizeable countries with large quantities of high-quality land resources may also find their asset bases weakening and/or exposed to future risks. For example, Brazil scores in the bottom quarter of countries within the 'trends' domain as a result of recent losses in species habitat and tree cover, increased demand for land and decreasing land productivity.

7.3.1 Regional land wealth patterns

Figure 37 reveals some broad regional patterns in how the LWI components contribute to countries' land wealth (bearing in mind both that the component labels used in the figure and in the commentary below are shorthand for the components' relationships to the underlying indicators, as shown in Table 4, and that the following discussion is necessarily generalized and masks considerable intra-continental and intra-regional heterogeneity).

North American countries are among the most land-wealthy, and score generally well in terms of amount and quality of land (not least on account of their size) but less well on changing environmental risks and soil quality changes. There is a marked difference between these countries in terms of the 'land resources and their change' component, which largely reflects the state of and changes to biophysical redundancy: the US performs much better than Canada, and Mexico has an intermediate value.

South American countries generally score well on the 'land resources and their change' component (Chile is a notable exception), and all but the smallest fare well in terms of amount and quality of land. There is more of a spread of middling values in terms of development status and soil quality measures.

European countries generally perform reasonably evenly (and well) in terms of development status and land resource change, and are similarly consistent, though slightly worse-performing, on environmental risk measures; Portugal and some Nordic countries do less well on this measure, however.

Africa is among the best-performing regions for land resources and their change, highlighting the continent's importance to the global land bank. However, this, combined with being one of the worst-performing regions in terms of development status, means that many African countries are vulnerable, or potentially vulnerable, to actors looking to exploit their land resources. Central Africa fares better than much of the rest of the continent in terms of amount and quality of land. North African and Sahelian countries are among the worst-performing countries by this measure; but in terms of soil quality and its change, southern African and Horn of Africa countries score lower.

457 United Nations Department of Economic and Social Affairs, Population Division (2022), 'Data Portal > Total population by sex', https://population.un.org/dataportal/home (accessed 1 Aug. 2022).

Asian countries, other than those in Southeast Asia, score fairly well on measures of changing environmental risk (largely reflecting relatively modest losses in tree cover and habitat), although in the case of some countries in Central and Western Asia this may reflect relatively low baseline values. The region as a whole does less well on land resources and their change; however, Mongolia and some other countries in Northern Asia score better in this regard.

Many countries in Oceania are too small to be included in the analysis. Of those assessed, Australia notably exhibits an extreme range of values: it is among the best-performing countries in terms of amount and quality of land, but among the worst-performing in terms of soil quality and its change. New Zealand tends to perform similarly to its larger and distant neighbour, but is less extreme on the above two measures and fares less well in terms of changing environmental risks. Papua New Guinea performs better in terms of changing environmental risks than either Australia or New Zealand, and also scores more highly on soil quality and its change (although it is still only in the middle among all countries for this component).

7.3.2 Inequalities between neighbours or near neighbours

While there are clear regional dimensions to land wealth, it is also instructive to compare the contributory factors among countries sharing broadly similar biomes within the same region. In East Africa, for example, Kenya ranks 45 places higher than its neighbour Uganda, despite the two countries having similar cropland, NPP and governance scores, and despite Uganda experiencing lower water risk and less productivity decline. Kenya's appreciably higher ranking is largely accounted for by its greater quantities of natural and semi-natural land and forest carbon, together with lower projected population growth for the land to support.

In South Asia, the obvious size disparity between India and Bangladesh – the latter is only around 4.5 per cent the size of the former – contributes to Bangladesh appearing almost 80 places lower on the LWI. Differences between the two countries' rankings in terms of quantities of natural lands and carbon sinks are more significant than the differences between their cropland area rankings: both countries have more cropland than their LWI rankings would suggest. Beyond this, Bangladesh has suffered less habitat loss per hectare and, in aggregate, has much better soil quality than India, which encompasses the large arid regions of Rajasthan in the northwest.

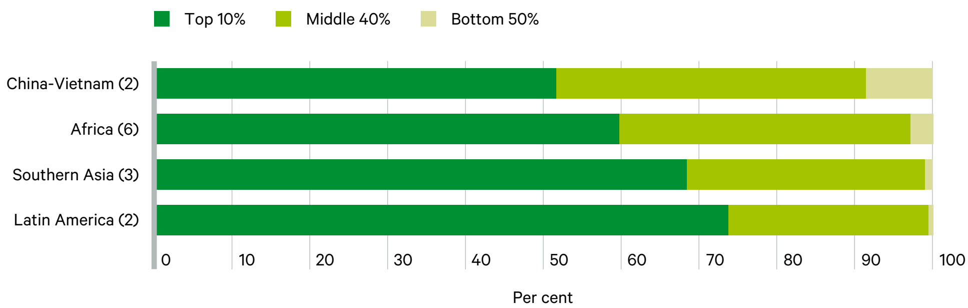
Russia and Ukraine score similarly on many indicators, and the global significance of the Black Sea 'breadbasket' region has been starkly illustrated under conditions of war. Yet Russia ranks 33 positions higher than Ukraine, largely on account of its more expansive crop and vegetated areas, greater carbon stocks and flows, and lower water risk.

The Central Asian countries of Kazakhstan and Uzbekistan are separated by 90 places on the LWI (Uzbekistan being the lower-ranking of the two), despite both suffering from the devastating shrinkage of the Aral Sea and both being water-scarce (Kazakhstan to a lesser degree). In the case of Uzbekistan, a 2022 World Bank country study observed that much of the country's economic potential is lost through inefficient use of natural resources: 'Water and energy are used wastefully, and the neglect of land management threatens livelihoods and future sources of growth.'[458] Kazakhstan, although heavily reliant on extractive industries, has extensive crop and natural lands with high carbon sequestration potential. Its land productivity is declining, but it has suffered less recent deforestation and species habitat loss than its neighbour.

Turning to two largely arid countries in the Middle East, Iran ranks over 100 places higher than its neighbour Iraq, despite performing only moderately better in terms of most quality, vulnerability and capacity indicators. The primary determining factors are Iran's much lower projected population pressures and its greater vegetation and NPP values compared with those for Iraq. Iran's percentile score of 99 (and Iraq's of 75) for the 'changing environmental risks' component reflects this component's strong association with some of the trend indicators (Table 4) that signal relative changes since the early 2000s. Since these reflect changes rather than absolute levels, countries with resources that were already degraded in the early 2000s and that have not subsequently deteriorated much further, or that have seen even modest improvements, will score well against these measures. Thus, Iran performs much better on habitat and tree losses (relative indicators) than it does on soil quality and biodiversity (absolute indicators).

In the Americas, the large and largely forested nations of Brazil and Canada score similarly highly on the overall LWI and provide an interesting set of contrasts. The main distinguishing features are Canada's much greater governance capacity – Brazil is below the expected level for its LWI ranking – and Brazil's more extensive croplands but, partly as a result, its poorer performance in terms of recent species habitat loss and soil carbon content.

Figure 38. Intra-country agricultural land inequalities: distribution of land value among landowners and landless agricultural households



Source: Calculated from Bauluz, L., Govind, Y. and Novokmet, F. (2020), *Global Land Inequality*, WID.world Working Paper 2020/10, https://wid.world/document/global-land-inequality-world-inequality-lab-wp-2020-10.

Even within countries with substantial land wealth, there are of course significant intranational inequities in access to and control over these resources, adversely affecting growth and development. (There is a clear positive correlation between equality of land distributions and subsequent growth in gross domestic product –

458 World Bank (2022), *Toward a Prosperous and Inclusive Future: The Second Systematic Country Diagnostic for Uzbekistan*, Washington, DC: World Bank Group, p. 8, http://documents.worldbank.org/curated/en/933471650320792872/Toward-a-Prosperous-and-Inclusive-Future-The-Second-Systematic-Country-Diagnostic-for-Uzbekistan.

GDP – per head.[459]) As a simple illustration, Figure 38 shows, for 13 countries, the share of land value that accrues to different segments of income distribution among land-owning and landless agricultural households.[460] Although this is limited to analysis of agricultural land and considers only market values, it clearly demonstrates widespread inequalities, with the top 10 per cent of agricultural households capturing on average more than 60 per cent of the value of agricultural land. If land wealth is to be better and more equitably distributed within countries, this will require issues around security of tenure to be addressed. It will also require all stakeholders, including marginalized and indigenous communities, to be involved in decision-making concerning land use (see Chapter 2, Box 2).

7.3.3 Land wealth and environmental risks

To put into context countries' terrestrial resources and their ability to govern them, we compared land wealth as measured by the LWI with each country's greenhouse gas emissions and natural disaster risk (the latter as captured by the WorldRiskIndex,[461] which measures exposure to natural hazards and societal vulnerability to those hazards, based on countries' likelihood of suffering harm, their adaptation capacity and their short-term coping capacity). There is little correlation between land wealth and exposure to natural hazards: countries with significant exposure to natural disaster risks are distributed throughout the LWI, though none is among the truly land-wealthy. However, as recent experiences with catastrophic forest fires in Brazil, the US and Canada have demonstrated, land-wealthy countries are certainly not immune to such risks.

As recent experiences with catastrophic forest fires in Brazil, the US and Canada have demonstrated, land-wealthy countries are certainly not immune to natural disaster risks.

There is a stronger, inverse relationship between land wealth and societal vulnerability (both the LWI and the WorldRiskIndex include governance and capacity metrics). Notable outliers with much lower societal vulnerabilities than their land wealth would suggest include the arid Gulf countries of Qatar, Kuwait, the United Arab Emirates (UAE) and Saudi Arabia, all of which have little land wealth but considerable ability to adapt to, cope with and avoid suffering from natural disasters, on account of their high levels of economic development. Conversely, Angola, the Central African Republic, the DRC and Papua New Guinea are much more vulnerable than might be expected given their respective land wealth scores. For these countries and others like them, there is a strong imperative to ensure sufficient capacity is built to adapt to environmental risks through responses that utilize land assets sustainably rather than undermining them.

In the authors' assessment, there is some indication that countries with the highest rates of greenhouse gas emissions growth between 1990 and 2014 are also those with relatively low exposure to climate risks. This raises the troubling possibility that some countries with actively growing emissions, particularly through forest conversion, are unconcerned about the climate change it creates because their short-term economic interests outweigh their perceptions of climate risks that

459 World Bank (2005), *World Development Report 2006: Equity and Development*, Washington, DC: World Bank, https://doi.org/10.1596/978-0-8213-6249-5.
460 Bauluz, L., Govind, Y. and Novokmet, F. (2020), *Global Land Inequality*, WID.world Working Paper 2020/10, https://wid.world/document/global-land-inequality-world-inequality-lab-wp-2020-10.
461 Bündnis Entwicklung Hilft (2021), *The WorldRiskReport*, Berlin: Bündnis Entwicklung Hilft, https://weltrisikobericht.de/download/2723.

will disproportionately affect other, more vulnerable, countries. This highlights the challenges of 'negative externalities', where costs are borne by third parties rather than the polluter. Unless addressed through legislation, market mechanisms, other incentives or regulation, environmental irresponsibility may persist at others' expense (see recommendations in Chapter 9).

7.4 Land wealth and international relations

As alluded to earlier, each country's land wealth is not just of concern to itself. Land wealth is increasingly significant in shaping the political, economic, security and trade relationships between countries, as well as their dealings with one another in environmental forums. As such, the LWI is intended to give an idea of how countries might be motivated, or best placed, to act in the future on the basis of their land wealth, and what this could mean for international relations and land-use pressures between now and the middle of the century.

Considering how land wealth overlays and interacts with other international dynamics, in the sections below we describe five potential (and non-exhaustive) country typologies that are relevant to emerging trends warranting increased international scrutiny and action. We have labelled these typologies as follows: 'land superpowers', 'potential land elites', 'threatened land-wealthy countries', 'land-poor geopolitical elites' and 'land-poor developing countries'. These typologies reflect some of the more noteworthy intersections between land wealth and broader economic, political and other international relations dynamics, and indicate the likely impacts of geopolitical and economic power on a country's future land wealth and vice-versa. To be clear, no rigid correlation exists between a country's LWI ranking and its typology. The typologies are not intended to serve as contiguous or mutually exclusive categories from the top to the bottom of the LWI. While each typology is a composite of land wealth on the one hand and geopolitical and economic power on the other, the LWI itself informs only the former component. It does not capture the latter, which is informed by factors associated with more traditional understandings of the international order – such as size of the economy and membership of economically and politically influential groupings.

For example, countries towards the top of the LWI will generally be land superpowers or potential land elites on account of their significant land-based resources, but their designation as one or other of these two typologies will also reflect their economic and political power, which is not captured by the LWI. A potential land elite, for example, may have a higher overall land wealth score than a land superpower, but would not be classed as a land superpower because it has less political clout or economic influence. In Europe, for instance, Poland may be thought of as a potential land elite, whereas France may be regarded as a land superpower despite ranking one place lower than Poland in the LWI; most notably, this is because France's biophysical redundancy is much lower.

Additionally, some countries have features associated with more than one typology: for example, there may be some overlap between land superpowers and threatened land-wealthy countries if a superpower's abundant terrestrial resources and associated influence could be materially threatened by future environmental change. A good example is China, which we classify primarily as a land superpower. However, its high risk of water scarcity means that in some respects the country also falls into the 'threatened land-wealthy' category.

At the other end of the scale, countries classified as land-poor geopolitical elites or land-poor developing countries will generally appear lower in the LWI since, despite vastly different geopolitical economies, they have in common a paucity (although differing profiles) of land wealth. A small but rich country might have the ability to acquire or access land-derived resources overseas to compensate for a lack of native resources. Qatar, for example, ranks alongside Guinea-Bissau in the LWI and scores lowest of all 163 countries featured in the LWI for amount and quality of land, yet on a per capita basis it is one of the world's richest countries. In our framework, it is categorized as a land-poor geopolitical elite. This leaves it far better placed to avoid or manage resource constraints than the land-poor developing countries that occupy most of the lowest positions around it in the index. More generally, there is a troubling risk of a new scramble for resources, in which countries with significant geopolitical heft will wield their soft power and economic influence to exploit other countries' lands.

The typologies are, moreover, not intended to be definitive for every country; rather, they are indicative of differences in characteristics. In other words, the typologies are designed to highlight interesting patterns and commonalities rather than provide a comprehensive system of categorization covering every country. We have emphasized the ends of the land wealth and international influence spectrums to discuss some of the more interesting convergences between these two dimensions, but other categories covering more moderate land wealth and levels of influence are equally conceivable. Furthermore, as the typologies that we discuss are contestable and only partially reflective of countries' LWI scores, we have deliberately not assigned countries to typologies in Table 5 – even if it is understandably tempting to do so. Some countries featured in the index fall outside the five typologies discussed in the report; this is particularly the case for countries with middling land wealth or geopolitical/economic power profiles. More important than the exact boundaries of these categories are the geopolitical and resource management dynamics they bring into focus.

The following sections describe each typology. Using the five typologies as a reference point, the geopolitical implications of countries' motivations or capacity to act in the future, on the basis of their land wealth, are discussed in further detail in Chapter 8.

7.4.1 Land superpowers

It is perhaps not surprising that, under the LWI assessment, the US, Russia, Australia, China, Brazil and Canada all feature among the top 10 land-wealthy countries. These are large countries with significant areas of vegetated and cropping lands, able to store and absorb large volumes of carbon. They also have substantial economic and governance resources. More generally, the world's biggest economic powers tend to have significant land wealth: all the G7 countries rank in the top

17 positions in the LWI; and 13 of the G20 countries are in the top 25.[462] Such countries, which combine significant land wealth with substantial political and economic strength, can broadly be considered as 'land superpowers'.

While geopolitical and economic influence are not wholly determined by land wealth, they can certainly be bolstered by it. Nonetheless, the role that land has played in the accrual of countries' economic wealth varies considerably across the traditional global economic powerhouses. For example, the US's economic growth was initially founded on the expansion of agricultural productivity. Conversely, although agricultural land constituted the majority of Britain's wealth in the 18th and early 19th centuries, this share was rapidly supplanted by ownership of assets from overseas through colonial expansion and the Industrial Revolution. Today, neither domestic agricultural land nor investments overseas contribute greatly to the UK's economic standing.[463] Nonetheless, this standing, combined with a high land wealth ranking (17th), results in the UK's classification as a land superpower. Its LWI score reflects a poor performance in terms of tree cover losses, and a middling ranking on forest carbon and land productivity trends, but is boosted by the country's biophysical redundancy trends, current soil carbon content, habitat protections, relatively limited climate exposures and strong governance.

An abundance of natural resources can often result in more difficult and stunted development pathways – the 'natural resource curse' – rather than acting as an effective catalyst.

Just as it was for the US and the UK, broad-based agricultural productivity growth is certainly a common prerequisite for kick-starting economic development, but it typically plays a diminishing role thereafter.[464] More generally, an abundance of natural resources can often result in more difficult and stunted development pathways – the 'natural resource curse' – rather than acting as an effective catalyst (although this certainly isn't always the case, as exemplified by the more positive trajectories of Botswana, Chile and Malaysia[465]). Equally, in some cases, economic development is not linked to land wealth; land-limited countries such as Singapore (which, as already noted, does not meet the size threshold for inclusion in the LWI) have generated enormous 'landless' wealth by creating value through manufacturing and services trade.[466] Other key components of land wealth, such as good governance and strong institutions, do appear to have more widespread importance in catalysing and maintaining economic success, but so too do factors unrepresented in the LWI, such as investments in human capital that manifest in technological progress and innovation.[467]

462 The exceptions are Türkiye (38), India (45), South Africa (52), Indonesia (63), South Korea (70) and, notably, Saudi Arabia (143). The European Union is the 20th member; Spain, which attends the G20 as a permanent guest, is 11th in the LWI.
463 Picketty, T. (transl. Goldhammer, A.) (2014), *Capital in the Twenty-First Century*, Cambridge, MA and London: The Belknap Press of Harvard University Press. In the 10-year period 2012–21, the value added by agriculture, forestry and fishing contributed an average of 0.6 per cent to the UK's gross domestic product (GDP). The UK's gross national income (GNI) was, over the same period, an average of 1.5 per cent less than its GDP, reflecting net outflows from domestic activity rather than net inflows from foreign sources. Calculated from World Bank (2022), 'World Development Indicators', https://databank.worldbank.org/source/world-development-indicators (accessed 1 Aug. 2022).
464 Whitfield, L. (2012), 'How Countries Become Rich and Reduce Poverty: A Review of Heterodox Explanations of Economic Development', *Development Policy Review*, 30 (3), pp. 239–60, https://doi.org/10.1111/j.1467-7679.2012.00575.x.
465 Stevens, P., Lahn, G. and Kooroshy, J. (2015), *The Resource Curse Revisited*, Research Paper, London: Royal Institute of International Affairs, https://www.chathamhouse.org/2015/08/resource-curse-revisited.
466 Timmer, C. P. (2006), *How Countries Get Rich*, Washington, DC: Center for Global Development, https://www.cgdev.org/publication/how-countries-get-rich.
467 Ibid.

Although land wealth may not always be a causal factor in positioning certain countries among the global economic elite, land superpowers' combination of economic and land resources means they have considerable ability to exercise and invest their land wealth as they see fit. They are well positioned to capture further value through exporting 'virtual' land – embodied in traded products or ecosystem services – and can exert influence in international forums governing the globally important resources they control.

Russia's geopolitical and economic standing has been severely degraded by its war on Ukraine: although Russia remains a permanent member of the UN Security Council and is unlikely to be ejected from the G20 (as it was previously from the then G8), the international response to its aggression means it has fewer opportunities to constructively engage and trade as before. Nonetheless, the reality that Russia typically accounts for around a fifth of all global wheat exports is just one example of the worldwide significance of its land-based resources, and the country remains a land superpower. The potential geopolitical land-use consequences of Russia's war on Ukraine are discussed further in Chapter 8 (Box 15).

7.4.2 Potential land elites

Since land resources are becoming strategically more important as growth in consumption of goods and services (the result of expanding populations and incomes) pushes the planet towards the boundaries of sustainability, then plausibly some countries with significant land assets will be increasingly well positioned to join a reshaped global geopolitical elite. Those we identify as 'potential land elites' are typically large countries with significant areas of vegetated and cropping lands, able to store and absorb large volumes of carbon. They tend to have less substantial economic and governance resources and less geopolitical influence than land superpowers. In Central and Eastern Europe and Central Asia, for instance, Poland, Kazakhstan, Belarus, Georgia, Romania and Lithuania all score highly in the LWI and are classified (either exclusively or primarily) as potential land elites. In the Americas, Venezuela, Colombia, Bolivia and Peru are in the top quintile of the LWI, along with the region's land superpowers of Brazil and Argentina.

The factors contributing to each of these countries' land wealth vary, but, with the notable exceptions of Georgia and Lithuania, all have plentiful natural vegetation, representing the productivity of the land. Some, in common with many of the land superpowers, have experienced significant tree cover loss since the turn of the century. Kazakhstan and Georgia have lower-quality soils and have experienced more biodiversity decline than many of the other potential land elites. Botswana is the highest-ranked African country on account of its abundant natural and semi-natural vegetated land, its limited habitat and tree losses, and its established biodiversity protection measures. However, its land productivity and the carbon content of its soils are poor, suggesting little room for 'business as usual' agricultural expansion, and this may be of concern given its expected rate of population growth to 2050.[468] If, however, under a system in which countries are economically and politically

468 Botswana's population is projected to increase by 25 per cent between 2019 and 2050. Calculated from United Nations Department of Economic and Social Affairs, Population Division (2022), 'Data Portal > Total population by sex', https://population.un.org/dataportal/data/indicators/49/locations/900,72/start/2015/end/2050/table/pivotbylocation (accessed 1 Aug. 2022).

rewarded for biodiversity protection and land restoration, Botswana is empowered to manage the threats to its existing land wealth, then it could be well placed to join established land elites rather than see further degradation of its resources.

Notably, too, the comparative advantages and opportunities enjoyed by potential land elites will vary in terms of how these factors might be asserted or leveraged internationally. Much will depend not only on the physical availability of high-quality lands in such countries – as well as on governance and economic capabilities – but also, critically, on the international context, as examined in Chapter 8. Countries with significant biophysical redundancy that also score highly on measures of land quality and risk exposure may increasingly be able to project power and gain wealth through their ability to export virtual land embodied in expanded agricultural production. Essentially, what this means is that they will have more freedom to trade land-derived goods and services by virtue of being under relatively less pressure to restrict the use of local lands to production of food for their own populations.

Those that score more poorly on degradation and risk exposure indicators may be better served by increasing their emphasis on nature-based solutions and other restorative measures to increase carbon sequestration and ecosystem richness, assuming durable market mechanisms or other strong incentives evolve to provide income for doing this. In the past, such functions have not been widely monetized or used in trade, and so have not necessarily galvanized much international attention or helped countries to attain geopolitical influence. However, as international carbon markets mature and payments for ecosystem services (PES – see Chapter 3) become more widespread – as may now be accelerated by the adoption of the Kunming-Montreal Global Biodiversity Framework at the UN Biodiversity Conference (COP15) in December 2022[469] – the value of restored lands is increasingly being recognized in economic terms. Countries that are motivated to draw on such mechanisms may gain greater international importance as a result.

7.4.3 Threatened land-wealthy countries

Just as the factors contributing to land wealth vary among the high-ranking countries, so too do the threats facing them. The countries we have identified as the 'threatened land-wealthy' are typically large countries with significant areas of vegetated and cropping lands, able to store and absorb large volumes of carbon – but with serious threats to those resources. Generally, the areas of most concern relate to environmental degradation and risk exposure, with recent tree cover loss being a particular problem.

In some cases, threatened land-wealthy countries also have less substantial economic and governance resources compared with land superpowers. Indonesia and India, for example, have more limited economic capacity than most of their G20 counterparts; for Indonesia, at least, this goes some way towards explaining the recent degradation of its resource base, as land-based assets have been

469 The Kunming-Montreal Global Biodiversity Framework includes four goals for 2050 and 23 targets to be achieved by 2030. Target 19 is: 'Substantially and progressively increase the level of financial resources from all sources, including domestic, international, public and private resources, in an effective, timely and easily accessible manner, … to implement national biodiversity strategies and action plans, mobilizing at least $200 billion per year by 2030.' Stimulating PES is identified as one of the key mechanisms to achieve this. See Convention on Biological Diversity Secretariat (undated), 'Kunming-Montreal Global Biodiversity Framework', https://www.cbd.int/gbf.

exploited for short-term economic returns. Despite scoring very highly across quantity indicators (except for biophysical redundancy), Indonesia has suffered significant degradation trends and also faces substantial water risks and exposures to future climate impacts. India's land wealth has multiple vulnerabilities, and the country also has limited biophysical redundancy and, across large extents, poor soil quality. These factors suggest it is likely to be less resilient to future risks compared with other countries with similar land quantity scores.

In other cases, risks to countries presently classed as land superpowers mean that the threatened land-wealthy typology also potentially applies to them. For example, Argentina, Australia, China, Spain and the US have significantly higher water risks than do most other land-wealthy countries. Australia, too, generally has poor soils in terms of carbon content and faces relatively high risks from climate change.

However, especially for the larger threatened land-wealthy countries, the risks will vary significantly across their landmass; how land is allocated to different ecosystem services will therefore be a crucial factor in managing such risks. In China, one of the world's most water-poor countries, 75 per cent of grains and more than 90 per cent of cash crops are grown on irrigated lands.[470] Inefficient water management compounds the problem: even though China's irrigated farmlands are generally located in water-stressed regions,[471] little more than half of the country's agricultural irrigation water is used effectively. Further tightening of water resource constraints can be expected over the coming decade as areas under irrigation expand.[472]

Risks to land wealth also apply to several of the countries primarily classed as potential land elites. For instance, Botswana, Iran and Kazakhstan have relatively low soil carbon content; and the latter two, together with Peru, are at high risk of water scarcity.

Such examples underscore the challenges of the global land crunch: even countries with comparative advantages in producing land-derived goods and services will face increasing environmental risks from exposure to climate hazards, while also being more vulnerable to these hazards as a result of overexploitation of lands. Solving the land-optimization puzzle therefore critically requires reducing overall demand for land, meeting the remaining demand more efficiently, and ensuring that production is not simply consolidated in regions with current comparative advantages.

7.4.4 Land-poor geopolitical elites

The group of countries we have termed 'land-poor geopolitical elites' are not well resourced with land assets but have significant economic and political power. For example, Qatar, Saudi Arabia and the UAE – all Gulf Cooperation Council (GCC) states – have low LWI rankings but are geopolitical elites given their degree of economic influence and strong ability to import land-dependent goods.

470 China Water Risk (2022), 'China Irrigation – Expanding irrigated land, improving efficiency & spending', https://www.chinawaterrisk.org/the-big-picture/china-irrigation.
471 Ibid.
472 MARA (2020), *China Agricultural Outlook (2020-2029)*, Beijing: China Ministry of Agricultural and Rural Affairs, https://aocm.agri-outlook.cn/2020/down_en.html.

As land assumes increasing strategic importance, the prospects for countries in this typology chiefly depend on the basis of their current wealth, on their economic structure, and on their capacity and willingness to diversify their economies and secure imports of land-dependent goods on an ongoing basis. There are three main circumstances under which land-poor countries are most likely to lose out.

The first is where global competition for land resources increases a land-poor country's trade deficit or presents absolute supply constraints. Trade in virtual land will continue to be significant in terms of both movement of physical goods – such as food and forestry products – and activity in carbon markets. This means that land-poor countries may increasingly find themselves paying for land-based resources from overseas. Countries that depend on imports for their food security perhaps stand to lose the most. The risks to their domestic agricultural production are likely to increase as the climate changes, while the international supply chains on which they rely may be disrupted by climate events, by institutional, security and conflict impacts, or by geopolitical tensions.

Countries that are highly dependent on extractives are likely to find their international influence waning if their assets become 'stranded'.

The second scenario potentially arises where a country has limited opportunity to capture value from new markets for ecosystem services. Although the ability to thrive in such markets – including those for services that are currently incompletely valued – is unlikely to be determined entirely by land wealth, land-poor countries may have little scope to profit from forest sequestration credits in carbon markets, REDD+[473] support, or international PES. Nonetheless, if they have the capacity to develop and invest in technology and green infrastructure such as non-land-intensive negative emissions technologies (NETs), they could still benefit from international carbon market credits. For some arid countries, land provides the potential for development of renewable energy for domestic and international markets (such as capturing energy from sunlight).

The third circumstance in which land-poor countries are most likely to lose out is where an economy depends heavily on fossil fuels and other extractive industries, rather than on service sectors or light industry. The economic contribution of fossil fuels and extractive industries is likely to decline in importance, relative to a country's land resources, much more rapidly than that of services or light industry. Countries that are highly dependent on extractives are thus likely to find their influence waning if their assets become 'stranded'. The risk of asset stranding arises from declining values of, and reduced demand for, fossil fuels and other products of extractive industries (such as minerals) as the world moves towards net zero and more circular economic models.

However, many of the countries likely to be in this situation, among them the GCC states, should be able to further transition their economies towards green growth opportunities, whether in renewable energy infrastructure or in science

473 REDD+ stands for 'Reducing Emissions from Deforestation and Forest Degradation in Developing Countries', and is a voluntary framework developed under the UN Framework Convention on Climate Change to guide activities to this end, as well as to support the sustainable management of forests and the conservation and enhancement of forest carbon stocks in these countries. First adopted in 2013, it has since been positioned as an integral element of the Paris Agreement on climate change. It is implemented in three phases, starting with the development of national strategies and action plans, followed by implementation, and evolving into results-based actions that should be fully measured, reported and verified, allowing countries to seek and obtain results-based payments from a variety of public, private, bilateral, multilateral and alternative sources. United Nations Climate Change (2022), 'What is REDD+?', https://unfccc.int/topics/land-use/workstreams/redd/what-is-redd.

and technology. This has less to do with the growing strategic importance of land than with a general economic shift towards cleaner energy, greater circularity of resource use and less resource-intensive economic development. As such, the challenges of this transition also apply to land-wealthy countries, such as Australia, that have significant extractive industries. What differentiates the land-wealthy is their potential for broader economic diversification, as well as their capacity to build and sustain influence in international diplomatic and security forums, where land-based environmental concerns are likely to figure increasingly prominently.

7.4.5 Land-poor developing countries

In common with land-poor geopolitical elites, the countries we have identified as 'land-poor developing countries' are not well resourced with land assets, and face many of the same challenges as better-off land-poor countries with respect to their land futures and interactions with the global economy and environment. However, land-poor developing countries typically have much less capacity to adapt to these challenges on account of their low levels of economic development, high levels of poverty, and increased vulnerability to economic and environmental shocks. Examples of countries within this typology include Bangladesh, Belize, Lebanon, Liberia, Malawi and Vanuatu.

Many land-poor developing countries, especially those classified by the UN as least developed countries (LDCs), find their sustainable development hindered by severe structural impediments such as limited economic and governance capacities. And, despite their relative lack of land wealth, many of these countries are far more dependent on agriculture than more developed, wealthier economies are. Virtually all countries where the value added from agriculture, forestry and fishing contributes over one-third of GDP appear outside the top 100 countries in the LWI,[474] and many of these are land-poor. Given their structural dependence on land-based sectors, the often precarious state of their land assets and mounting environmental pressures, many of these countries will find it increasingly difficult to derive value from their land sectors or – given the size of their economies – to compete internationally to secure virtual land from abroad.

Nonetheless, there are some notable differences among the land-poor developing countries in relation to what accounts for their lack of land wealth. For example, Haiti and Rwanda score higher than Russia, a land superpower, on soil quality and its change. Malawi scores higher than the top 15-ranked countries in the LWI on land resources and their change. Hence, while some components are structural, and some are constrained by territorial boundaries and physical characteristics, not all factors that currently position such countries at the lower end of the LWI are insurmountable under the right sets of conditions. Critically, however, the three circumstances mentioned above in relation to land-poor geopolitical elites are also likely to create problems for many land-poor developing countries, but to an even greater degree. Yet, given sufficient support from development partners and international investors, and with conducive market and regulatory

474 The exceptions are Ethiopia (77) and Kenya (93). World Bank (2022), 'Agriculture, forestry, and fishing, value added (% of GDP)', https://data.worldbank.org/indicator/NV.AGR.TOTL.ZS?most_recent_value_desc=true (accessed 1 Jun. 2022).

structures, even the most vulnerable countries may still be able to better deploy those elements of their land wealth in which they have greatest comparative advantage and thus bolster the resilience of their land resources. Ensuring the right mechanisms are in place should be an urgent priority for the international community in order to prevent land-poor developing countries from becoming even more vulnerable and potentially further marginalized as climate pressures mount and inequalities widen (see recommendations in Chapter 9).

7.5 Using land wealth well: the role of trade and markets

As land wealth is unevenly distributed and the supply of available land is tightening, it follows that land resources need to be used well – at local to global scales – to ensure both that countries thrive individually and in cooperation with one another, and that aggregate pressures on the land system are manageable.[475] Policy responses need to account not only for disparities in resources but also for asymmetries in power.

But what does 'using land wealth well' mean? Optimizing land use, so that lands provide the goods and services they are most suited to providing through natural comparative advantage, can broadly result from proscription or reward, or some combination of the two. Governments are typically wary of proscription, through measures such as land zoning or land-use strategies, as these approaches can introduce market barriers and reduce the freedom of landholders to use land as they want. Reward is often thought of as occurring implicitly through market mechanisms. For example, if a tract of land is best suited to producing a certain good (e.g. wheat) or providing a certain service (e.g. carbon storage), then in theory economic rationalization should lead to optimal land-use allocation, maximizing the land's comparative advantage.

But in practice things are not as simple as that. Some important services are not well monetized (for instance, assigning land for biodiversity is often not as economically rewarding as using the same land to produce crops such as soybeans or palm oil); some services rely on markets that don't function well (e.g. carbon markets); and some activities are incentivized even if they don't make the most economic or resource-efficient sense (as seen in the perverse incentives arising from some agricultural subsidies[476]). In some cases, too, a lack of access to markets (e.g. because of poor roads and other transport infrastructure) can make it hard to maximize comparative advantage.

At a national scale, determining the 'best' thing to do with land is often complicated by domestic resource security motivations. Assuming a stable world with liberalized markets, the most economically rational course of action for each country should

475 Benton, T. et al. (2018), 'Designing sustainable landuse in a 1.5°C world: the complexities of projecting multiple ecosystem services from land', *Current Opinion in Environmental Sustainability*, 31, pp. 88–95, https://doi.org/10.1016/j.cosust.2018.01.011.
476 Prakesh, A. (2021), *Repurposing Perverse Incentives for Land Restoration*, UNCCD Global Land Outlook Working Paper, Bonn: United Nations Convention to Combat Desertification, https://www.unccd.int/sites/default/files/2022-03/UNCCD%20GLO%20WP%20incentives.pdf.

in theory be to concentrate on producing goods or providing services in which it has the strongest comparative advantage. Each country would then export the produce and services that are surplus to its domestic requirements, and import the goods and services that it is less suited to (or less capable of) producing. In reality, many countries in such a situation may choose to retain domestic production of some strategic resources as insurance against market interruptions, even if this is not the most efficient use of land.

Trade is the enabler for distributing goods from countries that can produce an excess to others that have requirements they cannot meet through production within their own borders.

In contrast, the nationally rational land allocation looks very different if a country is isolated from external trade and has to be more self-sufficient. In such a scenario, a country may instead seek to produce a greater diversity of agricultural goods at home, optimizing its land use to fulfil local needs. But this would potentially result in less economically efficient aggregate land use on a global basis, at least in the short term. All things being equal, growing wheat in New Zealand or northwestern Europe, where yields can reach 18 tonnes per hectare, is a more efficient use of land than growing wheat in Kenya, for example, where the maximum yield is about 8 tonnes per hectare[477] and realized yields are often much lower. On the other hand, if more 'efficient' production comes with pollution, land degradation and other environmental harms that are not priced into the market value of the goods being sold, then even fully liberalized trade will result in sub-optimal global land allocations from a more holistic perspective that recognizes the long-term consequences of these unpriced costs.

Given that a combination of climate conditions, poor soil quality, and limited water and land availability[478] constrains the ability of many countries to produce sufficient quantities of goods (particularly food) for their own use, recourse to international markets to fulfil some or all domestic needs is a logical response. As such, trade is the enabler for distributing goods from countries that can produce an excess to others that have requirements they cannot meet through production within their own borders. Trade therefore also, in theory, serves as a distributional mechanism for improving land-use allocation based on the resources available globally. But as the world has become more globalized and interconnected, trade networks have become highly complex[479] – a process facilitated by the development of liberalizing frameworks such as the General Agreement on Tariffs and Trade (GATT) Uruguay Round, now subsumed into the World Trade Organization.[480]

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477 Haberl, H., Erb, K.-H. and Krausmann, F. (2014), 'Human Appropriation of Net Primary Production: Patterns, Trends, and Planetary Boundaries', *Annual Review of Environment and Resources*, 39(1), pp. 363–91, https://doi.org/10.1146/annurev-environ-121912-094620.
478 Food and Agriculture Organization of the United Nations (2018), *The State of Agricultural Commodity Markets 2018: Agricultural trade, climate change and food security*, https://www.fao.org/documents/card/en/c/I9542EN.
479 Dalin, C., Wada, Y., Kastner, T. and Puma, M. J. (2017), 'Groundwater depletion embedded in international food trade', *Nature*, 543 (7647), pp. 700–04, https://doi.org/10.1038/nature21403; MacDonald, G. K. et al. (2015), 'Rethinking Agricultural Trade Relationships in an Era of Globalization', *BioScience*, 65(3), pp. 275–89, https://doi.org/10.1093/biosci/biu225; Gephart, J. A. and Pace, M. L. (2015), 'Structure and evolution of the global seafood trade network', *Environmental Research Letters*, 10(12), p. 125014, https://doi.org/10.1088/1748-9326/10/12/125014; Ercsey-Ravasz, M., Toroczkai, Z., Lakner, Z. and Baranyi, J. (2012), 'Complexity of the International Agro-Food Trade Network and Its Impact on Food Safety', *PLoS ONE*, 7(5), p. e37810, https://doi.org/10.1371/journal.pone.0037810; Puma, M. J., Bose, S., Chon, S. Y. and Cook, B. I. (2015), 'Assessing the evolving fragility of the global food system', *Environmental Research Letters*, 10(2), p. 024007, https://doi.org/10.1088/1748-9326/10/2/024007; Wellesley, L., Preston, F., Lehne, J. and Bailey, R. (2017), 'Chokepoints in global food trade: Assessing the risk', *Research in Transportation Business & Management*, 2017 (25) pp. 15–28.
480 Intergovernmental Panel on Climate Change (2019), 'Summary for Policymakers', in Shukla, P. R. et al. (eds) (2019), *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*, https://www.ipcc.ch/srccl/chapter/summary-for-policymakers.

For the global land bank to be optimized,[481] markets and trade have to function effectively. Land governance mechanisms need to be robust, taking holistic account of multiple demands, risks and synergies. For example, a country that produces food less efficiently than it stores carbon in forests would have to increase its reliance on trade to ensure its own food security if it wished to capitalize on its comparative advantage in carbon storage. And it would need to be rewarded for doing so. However, a burgeoning literature on the growth of systemic risks in globalized trade systems suggests that such interdependencies, while often economically efficient under stable conditions, are frequently vulnerable to shocks.[482] Complex interlinkages and dependencies across sectors and through longer supply chains, with low transparency, are increasing the fragility of entire systems, allowing the greater amplification and propagation of shocks.[483] Strategies for optimizing land use therefore need to build in redundancies for resilience.

In a context in which many countries are increasingly inclined towards sourcing goods and services from a narrower set of political allies, and in which climate shocks are becoming more frequent, the world's ability to rely on open global trade to fulfil crucial needs is being increasingly called into question.[484] If the potential of free markets to enable globally efficient land-use optimization is undermined, an obvious hedge against market failure is for individual countries to diversify *domestic production* to ensure supplies where possible. This might, in the short term, increase local resilience to systemic market failures, but it also suggests land will not be globally optimized for production or preservation of ecosystem services. Such approaches may also exacerbate local vulnerabilities to short- or long-term environmental hazards.

An alternative, or additional, national response to market failure might be for individual countries to seek direct control over land in other territories through investments in large-scale land acquisitions.[485] This would likely have significant implications for the global commons and international relations – an issue discussed in depth in Chapter 8 – but it is already in evidence. Since the start of this century, at least 52 million ha of land (approximately the area of France) – and likely much more – has been acquired in this manner.[486] The countries where the investors responsible for acquiring the largest areas have their headquarters include both the land-wealthy, such as the US, China and the UK, and land-poor countries such

481 In this context, 'optimized' means that (1) goods are produced in areas with the greatest productivity, (2) areas of greatest ecological and sequestration potential are protected or managed appropriately (and such use rewarded), and (3) downside risks are capped and land-use co-benefits maximized.
482 Homer-Dixon, T. et al. (2015), 'Synchronous failure: the emerging causal architecture of global crisis', *Ecology and Society*, 20(3), https://doi.org/10.5751/ES-07681-200306; Bailey, R. et al. (2015), *Extreme weather and global food system resilience: Final Project Report from the UK-US Taskforce on Extreme Weather and Global Food System Resilience*, Swindon: UK Global Food Security Programme, https://www.researchgate.net/publication/281029049_Extreme_weather_and_resilience_of_the_global_food_system_-_Synthesis_Report; Challinor, A. J. et al. (2018), 'Transmission of climate risks across sectors and borders', *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 376(2121), p. 20170301, https://doi.org/10.1098/rsta.2017.0301.
483 Homer-Dixon et al. (2015), 'Synchronous failure: the emerging causal architecture of global crisis'; Challinor et al. (2018), 'Transmission of climate risks across sectors and borders'.
484 Wada, Y. and Bierkens, M. F. P. (2014), 'Sustainability of global water use: past reconstruction and future projections', *Environmental Research Letters*, 9(10), p. 104003, https://doi.org/10.1088/1748-9326/9/10/104003.
485 This covers land areas larger than 200 ha that are acquired through purchase, lease or concession for agricultural production, timber extraction, carbon trading, industry, renewable energy production, conservation and tourism in low- and middle-income countries. All such acquisitions have at least one transnational investor from the public or private sector.
486 Land Matrix (2022), 'Land Matrix', https://landmatrix.org.

as Malaysia, Singapore, Cyprus, Luxembourg and Saudi Arabia. Of the acquisitions concluded by 2016, most were made by private (non-listed) companies, supported to varying degrees by state-owned entities and/or government-mobilized private capital.[487] The vast majority of these acquisitions were for agricultural purposes, dominated by food and feed crop production. A particular concern is that local communities are often bypassed in negotiations for such transactions, and that the arrangements may lead to forced or voluntary displacement from acquired land, frequently without compensation, thereby jeopardizing domestic food security (see also Chapter 2, Box 2).[488]

The countries in which the most land has been acquired are distributed throughout the LWI, although typically they rank much higher for land quantity and quality indicators than they do for governance and economic capacity indicators. This suggests they are more exposed to land acquisitions that may be exploitative, in which domestic interests are not adequately compensated, or that do not fully account for the comparative advantage of the land, especially if the advantage lies in ecosystem preservation and/or restoration.

Exemplifying this, more land acquisition deals (by number of deals and total land area) have been concluded in African countries than in any other region.[489] Between 2000 and 2014, the total area of lands acquired on the continent roughly equated to the size of the UK; a fifth of these lands are hotspots for freshwater use, where crops demand more irrigation water than even the most efficient systems can sustainably supply.[490] Companies from Singapore and India are heavily involved in these investments. Notably, despite Chinese investors being responsible for one of the largest aggregate areas of land acquired globally, acquisitions of land for agriculture in African countries have not been a priority for China.[491] The significant inflows of Chinese capital on the continent in recent decades have tended to focus instead on mining and infrastructure development.

487 Nolte, K., Chamberlain, W. and Giger, M. (2016), *International Land Deals for Agriculture: Fresh insights from the Land Matrix: Analytical Report II*, Bern, Montpellier, Hamburg and Pretoria: Centre for Development and Environment, University of Bern; Centre de coopération internationale en recherche agronomique pour le développement; German Institute of Global and Area Studies; University of Pretoria; Bern Open Publishing, https://landmatrix.org/resources/transactions-foncières-internationales-dans-le-domaine-de-lagriculture-nouvelles-perspectives-offertes-par-land-matrix-rapport-analytique-ii.
488 Ibid.
489 Ibid., p. iv. No single African country is among the top five targeted countries globally on an area basis, although Ethiopia ranks third globally based on the number of investment deals.
490 Johansson, E. L., Fader, M., Seaquist, J. W. and Nicholas, K. A. (2016), 'Green and blue water demand from large-scale land acquisitions in Africa', *Proceedings of the National Academy of Sciences*, 113(41), pp. 11471–76, https://doi.org/10.1073/pnas.1524741113.
491 Most Chinese acquirers of land in Africa are individual farmers operating on a relatively small scale, focusing on supplying domestic African food markets. See Nolte, Chamberlain and Giger (2016), *International Land Deals for Agriculture: Fresh insights from the Land Matrix: Analytical Report II*, in particular p. 25, Box 6.

7.6 Conclusions: land as the strategic asset of the future

Land-rich countries with strong and stable governance have the potential to fare comparatively well in a future in which the strategic importance of land intensifies. Through trade, exporting 'virtual land' embodied in products or environmental regulation services, they have the potential both to develop economically and strengthen their political power and influence.

Effectively managing the risks to sustainable land use is made more challenging by the prospect of significant political and economic turbulence and uncertainty.

However, in the context of a general deterioration of the global commons, no country is likely to escape without suffering the impacts of increasing environmental risks. It is therefore – as set out in the recommendations in Chapter 9 – in all countries' interests to promote improved land management with the goal of building greater aggregate global land wealth and resilience. Effectively managing the risks to sustainable land use (both for individual countries and on a planetary scale) is made more challenging by the prospect of significant political and economic turbulence and uncertainty: it is likely that the shifts witnessed over the last few years towards greater multipolarity, competition, contestation and conflict will become more pronounced. And if existing trade dependencies become less reliable and supply chains less resilient due to climate impacts, increasing movement of people and hardening of borders, it is likely that recourse to liberalized trade to access virtual land will be a riskier strategy for land-poor countries to ensure national security.

A potential future of unreliable trade dependencies, growing strategic importance of land and increasing environmental risk presents significant threats to global cooperation on resource management. Three areas of risk merit particular attention. First, land-wealthy nations may accelerate the process of acting to secure their own land futures at the expense of the global commons, in turn generating an economic and political scramble among land-poor countries to fulfil their own needs through exploitation of others' resources.

Second, without adequate checks and balances, any country with globally important land wealth may continue (or begin) to exploit the resources within its own borders in ways that are unsustainable, further jeopardizing its own land asset base while also destroying or degrading the globally important resources over which it has stewardship.

Third, in the absence of strong and stable governance capacity, some otherwise land-wealthy countries, along with their people and resources, may be open to exploitation by actors – including corporations and other non-state entities as well as public-sector interests – from land-poor countries seeking to project power to maximize their own access to resources (see in particular Chapter 8, Section 8.5).

If national security considerations cause countries to retreat from multilateral resource governance – either by making bilateral acquisitions founded on power asymmetries or, for those that can, by seeking greater self-sufficiency – then, among the many undesirable outcomes that are likely to materialize, two key issues stand out. The aggregate pressures of the global 'land crunch' will intensify as land is used in suboptimal ways, at the very time when more sustainable and cooperative land use will become more critical for ensuring resilience to escalating environmental shocks. And inequalities are likely to widen, with land-poor and weakly governed countries becoming poorer and more vulnerable, and land-rich and well-governed countries becoming comparatively better off.

The next chapter explores in greater depth some of the plausible dynamics and outcomes in international relationships and geopolitics that may arise as land assumes a greater strategic importance, environmental threats accelerate, and evolving national priorities reshape countries' external engagements in novel ways.

08
Geopolitics and land-use ‘futures’

Solving the land crunch is an intrinsically global and political problem, but international cooperation on doing so is not guaranteed. Here, we examine four future scenarios indicating how geopolitical changes might affect land use for better or worse, and how pressures on land might impact international relations in turn.

8.1 Introduction

This chapter outlines four indicative scenarios or ‘futures’ designed to explore the interactions and dependencies between land use and geopolitics (Figure 39). It considers both how geopolitics could help or hinder international cooperation on sustainable land stewardship between now and 2050, and how countries’ land-use decisions could in turn affect geopolitics – for example, increasing international tensions and the risk of conflict over land, or easing such pressures. Each future, in essence, encapsulates a variation on the answer to the question of whether countries can balance their individual resource demands with the increasingly urgent collective imperative – in the context of climate change, biodiversity loss, and public health challenges – to manage land sustainably in the common interest.

The chapter also considers what each future might mean for the land wealth of different countries, taking into account the five typologies identified in the previous chapter (‘land superpowers’, ‘potential land elites’, ‘threatened land-wealthy countries’, ‘land-poor geopolitical elites’, ‘land-poor developing countries’). A summary of the characteristics of the five typologies, and an overview of how each might be affected by changing future dynamics, is set out in Box 14.

8.2 Key assumptions

For the analytical purposes of this chapter, we assume that every potential land-use outcome sits somewhere on a sustainability spectrum extending from extractive use optimized for short-term economic returns to sustainable land-use patterns optimized for ecologically beneficial and health-positive outcomes. To acknowledge the potential impacts of geopolitics on land use and vice versa, we also consider a spectrum of international cooperation, broadly from less to more cooperative. The potential geopolitical conditions along this spectrum can be characterized as ranging from 'deglobalized unilateralism' to 'multilateral rules-based cooperation'.

Each of the four indicative futures outlined in the chapter demonstrates a different combination of positions along these two spectrums, as illustrated in Figure 39. Depending on the permutation illustrated, each pattern of land use may be more or less conducive to sustainability, and the corresponding geopolitical dynamics more or less cooperative.

Geopolitical developments could, of course, follow any number of other conceivable trajectories, but the starting point for our assumptions is that today's Western-led multilateral system is under increasing pressure, and that current mechanisms for cooperative international problem-solving are of limited efficacy – at least, unless or until such a point as future efforts to strengthen them succeed (see Section 8.7, 'A land-wealthy world'). Interstate relations are being reshaped by forces that include Russia's war on Ukraine and US–China superpower rivalry. China is increasingly projecting its influence on global institutions and relationships, with potential consequences that range from more effective joint environmental and climate action to heightened resource competition and further strains in Chinese relations with the US – or indeed with other countries. The US, under Joe Biden's presidency, has made significant efforts to restore its standing as a global leader after the damage of the Donald Trump era, but is also now heading into a critically important election cycle that could determine whether the next administration engages constructively with the rest of the world or becomes more inward-looking again. Russian aggression, meanwhile, directly threatens Euro-Atlantic security arrangements. It is challenging Western solidarity in holding countries to their responsibilities under international law, and in achieving meaningful accountability for abuses. All these disruptive factors, as well as others not discussed here, point to the possibility of a fundamental reconfiguration of international economic and political architectures in the coming years, exacerbated by the retreat of democracy in some key regions and by the formation of new geopolitical alliances. However, while a drift away from the Western dominance of recent decades is evident, the pathways and destination ahead remain unclear.

8.3 Defining the four 'futures'

To organize our discussion in the following sections, we treat the sustainability of land use and the degree of international cooperation as critical variables that interact with one another to generate different dynamics between now and 2050 (Figure 39). In other words, more sustainable patterns of land use could have different geopolitical impacts compared with less sustainable patterns, while foreign policymaking based on multilateral cooperation could affect the sustainability of land use in different ways from more conflictual or unilateralist approaches to foreign relations. The interactions between different permutations of these two variables form the basis of our four potential 'futures'.

Foreign policymaking based on multilateral cooperation could affect the sustainability of land use in different ways from more conflictual or unilateralist approaches to foreign relations.

Under business-as-usual (BAU) dynamics – which we call **'tipping over the edge together'** – we assume that land use will continue to be dominated by extractive activities. In this future, the dwindling quality and availability of resources will lead to a deepening 'land crunch' (see Chapter 6, Box 12). Multilateralism will remain the prominent modality of interstate relations, and we assume that a similar level of international cooperation will be maintained to 2050.

In the second future, a shift towards greater unilateralism and a continuation of unsustainable land use will encourage an increase in 'resource-grabbing'. These dynamics will play out in a future we characterize as **'plunder thy foreigner'** – a term that intentionally echoes the concept of 'beggar thy neighbour' familiar in economic theory. In this future, countries seek to maximize their own welfare – or perceived self-interest – at the expense of others.

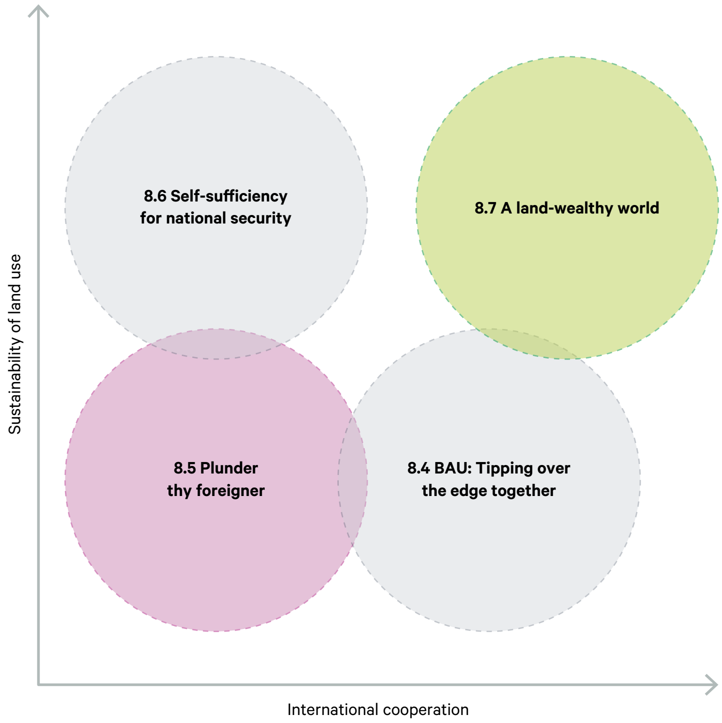
In the third future, which we label **'self-sufficiency for national security'**, unilateralism also dominates international relations, but the emphasis of countries' land policies is different. Land use is directed towards best supplying national demand and in turn reducing the potential for resource-grabbing. A key caveat is that countries' experiences of the limits of national self-sufficiency, when pursued at a global scale by many competing actors, may ultimately drive a reorientation of international relations towards multilateralism.

In the fourth future, high levels of multilateral cooperation enable land use to become optimized for global benefit, creating a more sustainable **'land-wealthy world'** in which the negative impacts of climate change, land degradation and biodiversity loss are reduced and competing land uses balanced more effectively.

These four futures are not intended to be monolithic or mutually exclusive. Nor should it be inferred that a rigid divide exists between each future, either globally or for individual regions and countries. One future may overlap to a certain degree with another – for example, there may be elements of BAU in a 'plunder thy foreigner' future (see Figure 39). Also, in any given future some divergences will likely remain in the policies and behaviour of different countries: in a 'land-wealthy world', for example, some countries may still try to take a 'plunder thy foreigner' approach; similarly, some countries may continue to appeal for multilateral cooperation even in a world in which a 'self-sufficiency for national security' approach predominates.

While our framework is not meant to be exhaustive – there is certainly the potential for other futures and dynamics to arise – we believe the four futures described in this chapter encompass what can be considered, for illustrative purposes, a reasonably full range of permutations between different levels of land-use sustainability and international cooperation. As Figure 39 shows, at one extreme (bottom left) a future characterized by 'plunder thy foreigner' dynamics combines both poor sustainability and low levels of international cooperation, while at the other (top right) a 'land-wealthy world' future displays a combination of high sustainability and a high degree of international cooperation.

Figure 39. Four permutations of land-use sustainability and international cooperation between now and 2050



Box 14. Summary characteristics of country typologies under changing dynamics of land use and international cooperation

'Land superpowers' are large or, occasionally, medium-sized countries that have significant vegetated and cropping lands able to store and absorb large volumes of carbon. They also have substantial economic and governance resources. Consequently, they have the highest scores on the Chatham House Land Wealth Index (LWI). They also have significant power and influence on the world stage. These characteristics position such countries most favourably across all the future sets of dynamics considered in this chapter. Land superpowers fare particularly well, relative to other country typologies, under business-as-usual (BAU) dynamics, since this pathway would be least disruptive for them in the near term. However, like all country typologies, land superpowers fare best in the longer term in a 'land-wealthy world'. Example countries include Australia, Brazil, Canada, China, France, Germany, Italy, Japan, Mexico, Russia, Spain and the US.

'Potential land elites' are countries with significant and highly productive land assets and plentiful natural vegetation. They have high LWI scores but are not (or not yet) geopolitical superpowers. Such countries enjoy the most favourable outcomes in a future in which land use is optimized and multilateralism dominates international relations. Under this dynamic, potential land elites have the potential to maximize the opportunities from their land-based wealth through international trade and cooperation. A future in which there is high reliance on acquiring land-based resources from other countries is least favourable for countries in this typology. As they are relatively lacking in economic resources and/or geopolitical influence, such a scenario could leave these countries' land-based wealth vulnerable to exploitation by wealthier and more influential states. Examples of potential land elites include Azerbaijan, Belarus, Bolivia, Botswana, Cameroon, Colombia, Kazakhstan, Lithuania, Mongolia, Pakistan, Peru, Poland, Romania, Türkiye, Venezuela and Zambia.

'Threatened land-wealthy countries' are well endowed with land wealth but have high levels of land degradation and exposure to climate risks. Recent tree cover losses, reduced soil carbon content and declining water resources are often particular problems. Such countries typically, therefore, have lower LWI scores. Threatened land-wealthy countries have the most favourable outcomes in a future in which land use is optimized and international relations are dominated by multilateralism. This future has the potential to provide opportunities that reward the restoration of degraded lands and habitats as nature-based solutions to the climate, biodiversity and pollution crises, and to avoid or reduce overuse of scarce resources such as water. A future in which land use is organized around self-sufficiency and in which global relations are dominated by unilateralism – 'self-sufficiency for national security' – is least favourable to countries in this typology. The pressures to further exploit degraded lands, combined with exposure to environmental risks, could threaten national resource security. The problem would be compounded by limited access to international trade to bridge any gaps in food supply. Examples of countries in this typology include Chile, Ecuador, Ethiopia, India, Kenya, Nigeria, the Philippines, Tanzania and Zimbabwe.

'Land-poor geopolitical elites' have significant economic and political power but are not well endowed with land wealth. Their lower LWI scores reflect their lower levels of physical land wealth despite their high capacity across other key metrics. Land-poor geopolitical elites are relatively well positioned to deal with 'tipping over the edge together' and 'plunder thy foreigner' dynamics. In a 'land-wealthy world' scenario, such countries might continue to rely heavily on imports of 'virtual' land, or might increase overseas land acquisitions to ensure national resource security. Land-poor geopolitical elites have least favourable outcomes in a 'self-sufficiency for national security' future, in which the possibility of meeting resource demand via imports would be severely compromised. Examples of such countries include Kuwait, Oman, Portugal, Qatar, Saudi Arabia and the United Arab Emirates (UAE).

'Land-poor developing countries' have relatively low levels of economic development and are not well endowed with high-quality land. Often, they have widespread poverty. Some are fragile and conflict-affected states. Land-poor developing countries have the lowest LWI scores. All four futures considered here are largely difficult for countries in this typology, but the worst outcomes are likely where trade and aid relationships suffer under dynamics that favour unilateralism. A future in which multilateralism is maintained and land use optimized for sustainable use provides the least unfavourable outcomes for this group of countries, as they could maximize income from their land-based resources without further degrading them, and thus bolster their resilience and ability to import key goods. Examples of land-poor developing countries include Bangladesh, Burundi, Eritrea, Guinea-Bissau, Haiti, Madagascar, Niger, Sri Lanka, Tajikistan and Uzbekistan.

Box 14 indicates the general direction of potential outcomes (i.e. mostly positive or mostly negative) for each LWI country typology (defined in Chapter 7) under different future dynamics. However, numerous caveats and exceptions apply to this broad picture; these are explored in the following sections covering each specific future.

8.4 'Tipping over the edge together': business-as-usual land use and international cooperation

This is the future that awaits humanity if business-as-usual dynamics persist. Predominantly extractive land-use patterns would continue, accompanied by a broad – if increasingly fragile – commitment to international cooperation. Planetary health continues to decline despite multilateral commitments on climate action, biodiversity and sustainable development. Land-poor developing countries and threatened land-wealthy countries face the most adverse impacts in this future.

8.4.1 Prevalent dynamics

In this future, today's patterns of largely extractive land use continue through to 2050, accompanied by a broad commitment to multilateralism in international affairs. Efforts to tackle climate change, biodiversity loss and threats to public health through international cooperation keep multilateral agreements alive. But a continuation of land-use strategies premised on productivity growth, and on the application of technological solutions to environmental problems and resource constraints, undermines the chances of successfully navigating land-related risks. Political aspirations and commitments to work 'together' consequently fall far short of what is required. Harmful climate change and biodiversity loss increase to irreversible levels, tipping the world 'over the edge' into a crisis of rapid environmental decline with cascading impacts that go on to affect people and ecologies far removed from the initial direct risks.

In this future, richer nations seek to enlarge their overseas land footprints, in order to support domestic growth in consumption of land-dependent goods while avoiding increased impacts (such as greenhouse gas emissions) within their own territorial boundaries. It falls to poorer nations to meet the resulting increase in demand. The majority of growth in global agricultural production thus occurs in emerging economies and low-income countries. Improvements in crop yields allow for increases in overall agricultural supply, but the rapid expansion and intensification of livestock production drive additional demand for these crops as livestock feed.

Prospects for aligning land use with more sustainable diets deteriorate. Under BAU conditions, the availability of animal products increases by 11 per cent per head in middle-income countries by 2030, according to projections jointly published by the Organisation for Economic Co-operation and Development (OECD) and the Food and Agriculture Organization of the United Nations (FAO).[492] Even with global agricultural production growing at 1.4 per cent a year over this period, under the same projections, achieving targets under Sustainable Development Goal (SDG) 2 ('zero hunger') to tackle malnutrition and diet-related ill-health would be challenging. There is a high likelihood of governments resisting, or failing sufficiently to encourage or accelerate, a shift to healthier diets.[493]

16.5

$GtCO_2$ could be emitted by 2030 under BAU deforestation – a volume that could not then be recovered through any means by 2050.

The wider implications for climate change and related planetary health indictors are also significant. By 2030, under BAU deforestation rates, 16.5 gigatonnes of carbon dioxide ($GtCO_2$) could be emitted – a volume that could not then be recovered through any means by 2050.[494] Forest loss continues in countries with significant biodiversity and carbon stocks, such as Brazil. The adverse impacts on the hydrological cycle, such as reduced rainfall, lead to wide-ranging environmental and socio-economic pressures, including reduced resilience of important ecosystems to future climate extremes, and widespread loss of income and livelihoods from agriculture.

Regional and international collaboration on sustainable trade probably continues in this future. Over time, however, more frequent disruptions to global production and trade – the result of largely unabated climate change and environmental degradation – prompt many governments to prioritize near-term resource security over long-term sustainability. Countries largely rely on market forces to regulate the production and consumption of land-dependent goods and services.

International relations continue to be strained by resource trade restrictions and supply shortages. To the extent that the politics of specific countries can even be anticipated over a span of 27 years, under BAU assumptions the land superpowers of Russia (see Box 15) and China (see Box 16) remain prominent in geopolitical tensions of the day. For China in particular, its actions continue to have a major effect on global demand for land-based resources. Even if US–China tensions persist over trade, Taiwan and security, climate diplomacy remains a potentially fruitful area of bilateral cooperation.[495]

Although BAU is not quite the *most* damaging of the four indicative futures for collective containment of planetary pressures, the largely unmitigated deterioration of the environment, coupled with pervasive malnutrition and worsening public health, creates substantial challenges for international relations. These test the efficacy of multilateral agreements designed to avoid such situations.

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492 Organisation for Economic Co-operation and Development (OECD)/Food and Agriculture Organization of the United Nations (FAO) (2021), *OECD-FAO Agricultural Outlook 2021-2030*, Paris: OECD Publishing, https://doi.org/10.1787/19428846-en.
493 Ibid.
494 Goldstein, A. et al. (2020), 'Protecting irrecoverable carbon in Earth's ecosystems', *Nature Climate Change*, 10 (4), pp. 287–95, https://doi.org/10.1038/s41558-020-0738-8.
495 The 'U.S.-China Joint Glasgow Declaration on Enhancing Climate Action in the 2020s' – announced at the UN climate summit in Glasgow in 2021 – was derailed by broader bilateral tensions for much of 2022, but climate talks between the two countries resumed in November of that year. US Department of State (2021), 'U.S.-China Joint Glasgow Declaration on Enhancing Climate Action in the 2020s', press release, 10 November 2021, https://www.state.gov/u-s-china-joint-glasgow-declaration-on-enhancing-climate-action-in-the-2020s.

8.4.2 Relative winners in a 'tipping over the edge together' future

Compared with other country typologies, land superpowers fare *relatively* well in a BAU future (Box 14), as they are not only resource-rich but wealthy enough to influence the global trade of land-dependent goods. Land superpowers often have the capacity to respond effectively to natural disasters and to adapt to the impacts of environmental degradation. In this future, they may invest in protecting and restoring key ecosystems such as forests and wetlands (as, too, may potential land elites with enough resources and governance capacity). At the same time, land superpowers with plentiful domestic agricultural resources remain relatively well placed to achieve food security predominantly through domestic production.

In a BAU future, international trade of land-dependent goods becomes increasingly susceptible to disruption by environmental disasters and geopolitical tensions. As a contingency, land-poor geopolitical elites – which are highly dependent on international trade – may seek a more active role in enhancing multilateral agreements on climate and biodiversity. They may also invest strategically in the countries and trade links most crucial to their own supplies of land-derived goods, in order to mitigate supply-chain risks. Relevant measures potentially include developing resilient transport infrastructure (both domestically and in supplier countries); protecting and restoring key ecosystems in partner countries; and deploying soft power to shape trade relationships, strengthen cultural exchanges, and leverage aid and development assistance more effectively.

While the principal aim for land-poor geopolitical elites in this context is to advance their own resource security agendas, countries that are targeted for such investment also potentially benefit. In particular, those with access to suitable climate financing are able to pursue economic development without further undermining their resource bases, and are thus better placed to withstand climate impacts.

8.4.3 Relative losers in a 'tipping over the edge together' future

Land-poor developing countries continue to lose out if the status quo prevails. Particularly at risk are countries with very limited governance and economic capacity (e.g. Haiti), and those with constrained governance and economic capacity that are also expected to see very large population increases (e.g. Burundi, Eritrea, Guinea-Bissau and Madagascar). Some countries in this typology already have low resilience to environmental risks (e.g. limited biophysical redundancy) and poor-quality soils, and so remain at high risk of adverse climate impacts and water stress (e.g. Niger) in a BAU future. A number of land-poor developing countries have very limited capacity to respond to the types of environmental and economic stresses that are expected to intensify under BAU dynamics, and thus become ever more vulnerable and marginalized.

While potential land elites can generally be classed as relative winners in this future, certain circumstances could alter such outcomes. For example, if resources remain poorly governed, potential land elites may overexploit their land assets in pursuit of economic wealth and political influence. Equally, demands from lower-income countries for 'loss and damage'[496] compensation from higher-income nations may, if only agreed to with conditions attached, devolve into exploitative trade relationships that tie poorer nations among the potential land elites into arrangements to supply wealthy nations with extractive, land-based commodities in exchange for climate finance. The risk is that such finance may compensate recipients for severe climate-induced harms without helping them to adapt their economies to become more climate-resilient. Instead, recipient countries may continue to pursue unsustainable land-use strategies, thus compromising their ability to realize their potential land wealth.

Threatened land-wealthy countries may also lose out in this future. Extractive activities and increased global trade are likely to incentivize land-use changes such as deforestation, exacerbating risks for countries with weak governance and low economic capacity (e.g. Mozambique and Myanmar).

Land-poor geopolitical elites generally fare well in a BAU future, *provided* they remain able to meet national demand for land-dependent goods via international trade. However, this advantage could be at risk if land superpowers – through resource depletion and the impacts of climate change, for instance – become increasingly reliant on international imports, and if competition for internationally traded resources thus intensifies.

There are also potential losers among the land superpowers: those with characteristics such as higher land degradation (e.g. Brazil), water stress (e.g. China) or both (e.g. Australia) may, over time, see their influence on global politics weaken due to an increasing reliance on imported goods (such as food and biofuel) and a reduction in export income. Underlying governance and capacity problems, and the terms on which countries choose to engage with the international community, may also influence whether individual land superpowers (e.g. China and Russia) gain or lose under BAU conditions.

8.4.4 Evolving dynamics of a 'tipping over the edge together' future

Deteriorating planetary and public health, aggravated by resource mismanagement, may significantly affect geopolitics in a 'tipping over the edge together' future, leading to the degradation of multilateralism and established trading relationships. A number of factors, in particular, risk undermining international cooperation. Entrenchment of the increasingly antagonistic and nationalist foreign policy positioning evident in many countries in the early 2020s, China's growing

496 While there is no internationally agreed definition of 'loss and damage', the term can essentially be understood as referring to the adverse impacts of climate change-induced events (such as extreme weather and sea-level rise) on livelihoods and property. These are impacts that cannot be adapted to, and include non-economic impacts such as loss of life and loss of biodiversity. Calls for funding flows from high- to low-income countries are based on the fact that loss and damage tends to be concentrated in countries that are historically low greenhouse gas emitters and have contributed the least to climate change – such as the least developed countries and small island developing states. A historic agreement was reached at the COP27 climate summit in 2022 to create a 'Loss and Damage' fund – although so far only relatively small amounts of money have been pledged, and these sums are not necessarily 'new and additional'. See Liao, C., Jeffs, N., Åberg, A. and Wallace, J. (2022), 'What is loss and damage?', Chatham House Explainer, 6 December 2022, https://www.chathamhouse.org/2022/08/what-loss-and-damage; Åberg, A. and Jeffs, N. (2022), *Loss and Damage finance in the climate negotiations: Key challenges and next steps*, Research Paper, London: Royal Institute of International Affairs, https://doi.org/10.55317/9781784135461.

assertiveness in international affairs, and the deep insecurity arising from Russia's war on Ukraine could all prove permanently destabilizing, prompting more inward-looking geopolitical agendas among many countries.

The result could be an increase in bilateralism (including a large-scale reversion to 'friendshoring'[497]) and unilateralism, with the imposition of export restrictions and a reshoring of production. Countries with geopolitical influence and economic wealth may feel compelled to seek control of further resources beyond their borders in a future we term 'plunder thy foreigner' (see Section 8.5); others with lesser geopolitical and economic heft may take a protectionist approach to resource security (in a 'self-sufficiency for national security' future – see Section 8.6).

Box 15. The land-use geopolitics of Russia's isolation as a pariah state

Russia ranks second on the Chatham House Land Wealth Index (LWI), and is categorized as a 'land superpower' in this report. An abundance of high-quality land and natural resources theoretically positions Russia as one of the countries likely to fare most favourably across the full range of potential futures. In the present context, however, Russia's ability to benefit from its land resources is complicated in practice by the consequences of its political estrangement with the West, its war on Ukraine, and the international responses to Russian aggression – including economic sanctions. In the short term, how Russia opts to manage these pressures, the extent to which its decisions meet Western opposition or prompt changes in other countries' resource supply policies, and the degree to which Ukraine's allies agree and maintain a unified response to Russian aggression could be a key determinant of global land-use dynamics. In the longer term, the evolution and impacts of such dynamics, along with the unknowable future trajectory of domestic politics in Russia, will play a role in determining whether the country's confrontation with the West persists in the decades to 2050.

Geopolitics could deteriorate further if Russia takes the most likely path of continuing its stand-off with the West while defying norms of accepted international behaviour.[498] In such a scenario, Russia would likely seek to exploit existing vulnerabilities in the international system and sow divisions between countries for its own benefit, undermining international security as well as global solidarity over any transition to a more sustainable land-use future. There would also be a heightened risk of Russia unduly influencing or seeking to subordinate smaller and less powerful countries. If international cooperation over Russia frays, or if Russian influence drives a wedge between groups of countries that are currently relatively cooperative on global issues, multilateral agreements would likely become less effective, and the impacts of climate change, biodiversity loss and land degradation could worsen beyond those expected under a BAU future. This, in turn, could cause increasingly frequent disruptions to global trade of land-dependent products, with particularly detrimental outcomes for land-poor developing countries.

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497 The term 'friendshoring', or 'ally-shoring', is used to refer to some countries' increasing appetite for sourcing raw materials and manufactured goods from a narrow group of allies or countries with shared values, rather than from a much broader range of trade partners under a globalized economy.
498 Allen, D. et al. (2021), *Myths and misconceptions in the debate on Russia: How they affect Western policy, and what can be done*, Report, London: Royal Institute of International Affairs, https://www.chathamhouse.org/2021/05/myths-and-misconceptions-debate-russia.

These variables, of course, will also determine outcomes for Russia's own resource security and geopolitical standing. While Russia might maintain trade links with some large supplier countries such as China, and would likely continue to supply at least some import-dependent countries across the Middle East and Africa, its disruptive and combative actions – in part a response to its decline as a major economic power – have narrowed its export base. A continuation of its war on Ukraine would see Russia become further isolated from the global economy.

The effects of Russian aggression and the response of the international community have implications for the geopolitical outlook under all four futures explored in this chapter, but could also prove influential in determining which of these futures is most likely to transpire. The use of food as a tool of political influence,[499] as seen after Russia launched its full-scale invasion of Ukraine in 2022, is a troubling illustration of this point. Further mass disruption to exports of grain and fertilizer from the Black Sea region could prompt waves of export restrictions in other producer countries, along with an increase in domestic production by importing countries. Such interrelated developments are characteristic of a shift to a 'self-sufficiency for national security' future. Should disruptions to globally important trade flows continue, countries' concerns for their resource security heighten, and multilateralism be further weakened by divisions over Russia, the conditions could be created for a more aggressive approach to securing access to land-based resources under a 'plunder thy neighbour' future.

To increase the prospects of achieving a 'land-wealthy world', international responses to Russian aggression will need to address the country's influence globally. This must include building more cooperative relations between countries with differing degrees of alignment with Russia, especially on urgent issues such as addressing climate change, biodiversity loss and land degradation.

8.5 'Plunder thy foreigner': unsustainable land-use patterns combined with reduced international cooperation

In a 'plunder thy foreigner' future, unilateralist tendencies define nations' approaches to resource use and foreign policy, with each nation prioritizing near-term domestic security of supply over the long-term conservation of the global commons. As a consequence, all countries lose out. Land-poor geopolitical elites increasingly seek to exploit further land resources overseas. Land superpowers may do much the same, adding to aggregate supply pressures by curtailing their own exports of land-derived goods. In this future, threatened land-wealthy countries and potential land elites become more vulnerable to exploitation by those with greater economic and geopolitical clout, while land-poor developing countries struggle to meet domestic demand through trade. Of the four scenarios explored in this chapter, a 'plunder thy foreigner' future has the worst outcomes for planetary health.

499 Brown, O. et al. (2023), *The consequences of Russia's war on Ukraine for climate action, food supply and energy security*, Research Paper, London: Royal Institute of International Affairs, https://doi.org/10.55317/9781784135836.

8.5.1 Prevalent dynamics

In a 'plunder thy foreigner' future, countries adopt narrowly self-interested geopolitical strategies in response to both rising competition for land and feared or actual resource shortages. Militarily, economically or geopolitically powerful countries increasingly rely on 'plundering' the resources of less powerful ones, and there is a generalized readiness to use coercive or predatory tactics to secure control of land and land-based resources. The risk of conflict over land is high in this future, and countries' commitments to upholding multilateral agreements are subordinated to the pursuit of short-term resource security.

Powerful countries, particularly land-poor geopolitical elites, will look to exploit the resources of those in a position of less influence.

Powerful countries, particularly land-poor geopolitical elites, look to exploit the resources of those in a position of less influence. As a result of coercion or power asymmetries, outsiders' interests may override local interests, as certain countries exploit weak governance in others to drive unsustainable increases in food and biofuel production beyond their own borders. Countries vulnerable to this type of exploitation include some that currently contribute substantially to global food production but are at high risk of – and have low resilience to – climate impacts and water scarcity. One example is India, which is the world's second largest wheat producer, the sixth largest producer of maize and soy, and a major producer of various animal products.[500]

The situation would be exacerbated if today's land superpowers, such as Brazil, China and the US, acquire more land resources abroad as a substitute or supplement for their own resources. Reductions in domestic production (either out of preference to preserve or repurpose land resources, or out of necessity due to the impacts of climate change) could diminish the position of land superpowers as global suppliers of staple crops and biofuels. This could seriously disrupt global food markets, much as occurred in 2022 when wheat supply from Ukraine, one of the world's most important producers, was dramatically curtailed in the aftermath of Russia's full-scale invasion.[501]

Prospects for sustainable trade falter in a 'plunder thy foreigner' future. A breakdown in international cooperation undermines efforts to govern the environmental and social impacts of supply chains, while the effectiveness of measures agreed in the early 2020s to reduce trade-related deforestation is limited by countries' increased pursuit of extractive activities overseas as a means of meeting demand at home.[502] Trade-related environmental destruction intensifies, driven by agricultural expansion in areas such as the Amazon and Congo basins. Such trends create a threat multiplier for food security, affecting even the wealthiest nations.

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500 FAO (2022), 'FAOSTAT > Crops and livestock products > Production quantity, 2019', https://www.fao.org/faostat/en/#data/QCL (accessed 1 Jun. 2022).
501 FAO (2022), 'FAOSTAT > Crops and livestock products > Production quantity, 2019', https://www.fao.org/faostat/en/#data/QCL (accessed 1 Jun. 2022).
502 Initiatives announced at COP26 included the Glasgow Leaders' Declaration on Forests and Land Use, which aims to halt forest loss and land degradation accounting for over 36,000 km^2 of forest cover; and the Forest, Agriculture and Commodity Trade Dialogue, which provides guidelines on challenges associated with increasing demand for agricultural commodities and increasing clearance of forests for unsustainable agriculture. The Forest & Climate Leaders' Partnership, announced at COP27 in late 2022, commits more than £150 million to the protection of rainforests and natural habitats, including the Congo and Amazon basins. See https://forestclimateleaders.org.

8.5.2 Relative winners in a 'plunder thy foreigner' future

Land superpowers, land-poor geopolitical elites and threatened land-wealthy countries fare best, relative to other typologies, in a 'plunder thy foreigner' future by capitalizing on their land wealth or ability to leverage access to foreign resources. The most likely winners include countries or territories with substantial existing land investments and trade facilitation arrangements (for example, Brazil, China, Cyprus, Hong Kong, Malaysia, Singapore and the US). Countries with significant control over existing or expanding trade networks (China, for example, through its Belt and Road Initiative), as well as import-reliant countries that have extensive established trade networks due to historical influence (e.g. the UK), are also better placed than many to secure continued access to internationally traded land-based resources.

However, even these relative winners still stand to lose out over the longer term: of the four futures explored in this chapter, 'plunder thy foreigner' has the worst outcomes for planetary health. All countries are negatively affected, to varying degrees, by the collapse of multilateral efforts to slow climate change, land degradation and biodiversity loss, and by the increased exploitation of land-based resources relative to BAU dynamics.

8.5.3 Relative losers in a 'plunder thy foreigner' future

Land-poor developing countries fare worst in this future. Their lack of resources becomes increasingly severe in a world dominated by unilateralism, and in which foreign aid, financing and development prospects for the poorest countries are diminished. Land-poor developing countries are typically least resilient to shocks, have high exposure and vulnerability to climate change impacts (such as temperature extremes, drought and flooding), and have limited governance capacity. Vietnam is an example of a developing country that broadly fits these characteristics, despite also having areas of cropland and natural/semi-natural vegetated land comparable with those of Germany, a land superpower. Partly due to financial constraints, land-poor developing countries are also relatively limited in their ability to meet domestic resource needs by increasing imports.

There are also significant risks for potential land elites and threatened land-wealthy countries in this future, although some of the latter have the potential to fare relatively well in some circumstances. Countries in both typologies become vulnerable to exploitation by land superpowers and land-poor geopolitical elites looking to secure access to foreign land-based resources. For threatened land-wealthy countries, the balance could tip either way: if their resources are well managed and well governed, they may be afforded relative security by a high degree of self-sufficient provisioning; if their governance is weak, their land resources may be exploited by other nations, or their own land resource base may become so degraded that they too resort to plundering foreign lands.

Exploitative practices by geopolitically powerful nations – whether land-poor or land-wealthy – to secure overseas land-based goods would have particularly catastrophic consequences when undertaken in carbon- or biodiversity-rich regions. The loss of carbon sinks and biodiversity would most heavily affect land superpowers such as Brazil, and potential land elites, such as the Democratic

Republic of the Congo (DRC) and Zambia, that are particularly well endowed with this form of land wealth but whose capacity or willingness to protect these resources is limited. The ability of such countries to sustain significant agricultural production and exports may be threatened by ecosystem degradation and climate risks, with the challenges exacerbated by large population increases (as projected in the DRC, for example). Also significantly impacted would be land-poor developing countries (such as Burundi) that might seek to increase agricultural or industrial production in carbon- and biodiversity-rich areas.

As well as the consequences for individual countries, such a trajectory has serious implications for preservation of the global commons. For example, the DRC has the world's third highest carbon stock in living forest biomass (after Brazil and Russia) and is highly resilient to environmental shocks; it thus plays an important global role in helping to limit temperature rise and the impacts of climate change. However, it also has very weak governance and economic capacity, and is highly vulnerable to exploitation under 'plunder thy foreigner' dynamics. Given the global importance of the country's resources (see Box 17), the negative outcomes of such exploitation could be far-reaching.

In sum, a 'plunder thy foreigner' future has negative outcomes for *all countries*. In an uncooperative, deglobalized world dominated by unilateralism, circumstances could arise that would disadvantage even the most geopolitically powerful and land-wealthy countries. 'Plundering' countries are likely to rely on global transport infrastructure for access to overseas resources, but this infrastructure may be deliberately disrupted by others for geopolitical leverage. The risk of such an event is particularly high at certain 'chokepoints' of international strategic importance.[503] This has been starkly illustrated since 2022 in the context of Russia's war on Ukraine. Russian use of blockades to cut exports of wheat and other commodities through Ukraine's Black Sea routes, along with the impact of Western sanctions on exports of food and fertilizer from Russia, caused severe food price inflation over a prolonged period. The ramifications for food security have been global, and at least in relation to food-price volatility are expected to persist in the medium term.[504]

8.5.4 Evolving dynamics of a 'plunder thy foreigner' future

A 'plunder thy foreigner' future is ultimately unsustainable. The worsening impacts of climate change and continued biodiversity loss, combined with exploitative practices by powerful nations and the reduced ability of low-income countries to use, protect or restore their land resources effectively, may reduce the availability of resources globally. In addition, safeguards to mitigate the worst effects of trade protectionism may diminish as multilateral agreements are disregarded and international relations veer towards unilateral decision-making.

503 Bailey, R. and Wellesley, L. (2017), *Chokepoints and Vulnerabilities in Global Food Trade*, Report, London: Royal Institute of International Affairs, https://www.chathamhouse.org/2017/06/chokepoints-and-vulnerabilities-global-food-trade.
504 Benton, T. G. et al. (2022), *The Ukraine war and threats to food and energy security: Cascading risks from rising prices and supply disruptions*, Research Paper, London: Royal Institute of International Affairs, https://doi.org/10.55317/9781784135225. Brown et al. (2023), *The consequences of Russia's war on Ukraine for climate action, food supply and energy security*.

With longer-term resource security in this future being severely eroded through short-termist and protectionist strategies, countries may resort to reducing their reliance on global trade and boosting domestic production (at the expense of land restoration and protection) to overcome some of the instability inherent in this future, thereby creating the conditions for our next indicative future, 'self-sufficiency for national security'.

8.6 'Self-sufficiency for national security': sustainable land use in an uncooperative world

In a 'self-sufficiency for national security' future, countries prioritize domestic resource self-sufficiency over trade and multilateralism. Domestic land use becomes more sustainable in countries with strong governance, but a retreat from international cooperation in tackling global challenges causes planetary health to decline alarmingly and precludes the possibility of achieving optimal global land-use allocations. Land-poor developing countries, threatened land-wealthy countries and land-poor geopolitical elites suffer the most adverse outcomes in this future.

8.6.1 Prevalent dynamics

A 'self-sufficiency for national security' future sees countries focus on becoming self-sufficient in the supply of land-based goods. This approach is prompted by increasingly frequent and severe disruptions to production and international trade of food, fuel and other commodities as a result of climate impacts, environmental degradation and biodiversity loss, together with health-related crises (such as pandemics), geopolitical tensions and conflict-related disruptions. As countries prioritize domestic supply of resources to meet their own consumption, international cooperation becomes increasingly fragile and eroded. Signals of intent – as already seen from certain countries, notably China (see Box 16) – on pursuing greater self-sufficiency potentially accelerate similar moves in other countries.

A more protectionist approach to achieving resource security affects geopolitics and trade. By seeking to boost domestic supply, countries export less and reduce the volume of international resource trade. The pursuit of overseas land acquisitions by land-constrained countries (seeking to meet domestic demand) becomes increasingly fraught and contested. The global composition and distribution of food production potentially change dramatically as major exporters reconfigure production to meet domestic nutritional needs and optimize agricultural resources accordingly, only exporting the surplus to neighbouring countries. As an increasing number of countries produce food largely for their own demand, this exacerbates the decline in the global availability of traded food.

At the global level, this realignment of resource production leads to large-scale inefficiencies and productivity losses. Some countries struggle to produce staple crops for which there is high domestic demand but for which national agroclimatic conditions are ill-suited. Conversely, the reduction in the size of export markets for land-based goods partially alleviates pressures on some existing production hotspots. This allows land use to be reconfigured to support a greater diversity of produce (although only for national consumption) and support the provision of more ecosystem services.

Global trade and its governance look more different from BAU conditions than in any other future. The World Trade Organization (WTO) becomes largely irrelevant as countries withdraw from global trade. Existing and emergent trading blocs such as the EU, Mercosur and the African Continental Free Trade Area (AfCFTA) become more isolated and inward-looking, pivoting to concentrate almost entirely on intra-regional trade, rather than advancing mutually beneficial agreements with other regions.

At a local or national level, countries see greater urgency in the need to avoid agricultural land expansion, instead optimizing food production for maximum nutrition and minimal resource use.

In international relations, the pursuit of narrow national self-interests takes precedence over multilateral cooperation on global goals, including climate change mitigation and adaptation financing. More positively, there are stronger commitments to action on environmental issues that pose more immediate or tangible threats to local livelihoods and productive capacity. Some countries see a greater interest in preserving and restoring their natural vegetation cover, and in improving stewardship of water flows and providing habitats and food sources for pollinators, to support functioning ecosystems, better meet provisioning requirements and build resilience to environmental shocks. Such incentives are potentially stronger than in a BAU future, where there might be assumptions that provisioning can be reliably secured through international trade. At a local or national level, countries see greater urgency in the need to avoid agricultural land expansion, instead optimizing food production for maximum nutrition and minimal resource use. Such an approach is particularly likely in high-income and upper-middle-income land superpowers with strong governance capacity.[505]

This future is not the most damaging to planetary health of the four explored here. However, it weakens international cooperation on collective goals in ways that endanger the very security that countries would be seeking to achieve through self-sufficiency.

8.6.2 Relative winners in a 'self-sufficiency for national security' future

Land superpowers such as the US and Australia, together with potential land elites such as Poland, fare best in a 'self-sufficiency for national security' future. This reflects their strong governance and economic capacity, good-quality soils and relative resilience to environmental shocks. Large food-exporting countries such as Argentina, Brazil, Canada, Russia and the US have the greatest scope to reconfigure their agricultural land to meet national requirements, and to restore portions of lost ecosystems to bolster biodiversity, sequester carbon and improve resilience to environmental impacts.

505 Hayek, M. N., Harwatt, H., Ripple, W. J. and Mueller, N. D. (2021), 'The carbon opportunity cost of animal-sourced food production on land', *Nature Sustainability*, 4(1), pp. 21–24, https://doi.org/10.1038/s41893-020-00603-4.

Certain land-poor geopolitical elites, such as Saudi Arabia and the UAE, also fare reasonably well in this future – provided they can decouple enough of their resource demands from land-based production to reduce their reliance on overseas supply. An ability to harness economic, technical and governance capacity is also important for their self-sufficiency initiatives, as countries must extensively reconfigure their domestic land use. Potential solutions include increasing fruit and vegetable production through technologies such as controlled-environment agriculture and water desalination powered by renewables. These methods allow for a greater range of produce to be grown in otherwise unfavourable agroclimatic conditions, with less dependence on fertile soils and rainfall, and with smaller absolute land footprints.

In such settings, clean energy needs are potentially met through land-sparing renewable technologies, with solar power offering promise in arid areas. A greater abundance of cheap and plentiful renewable energy increases the possibilities for developing and deploying land-sparing carbon sequestration technologies, especially in areas where nature-based solutions such as reforestation are less feasible because of previous degradation of the environment. Greater investment in, and adoption of, technologies to support the circular use of resources further supports self-sufficiency in countries where opportunities to import goods are limited.

Land acquisitions and leasing agreements are important determinants of outcomes in this future. Countries with a high capacity to purchase land overseas are better equipped to diversify their resource supply, while those with plentiful domestic land may benefit financially by leasing it to others. Import-dependent countries that have already acquired substantial areas of foreign land (e.g. Cyprus) may continue to exploit such assets, but managing land acquisitions and supplier relationships becomes challenging for them in an increasingly uncooperative and disconnected world.

8.6.3 Relative losers in a 'self-sufficiency for national security' future

Land-poor developing countries fare worst in this future. Countries such as Burundi, Guinea-Bissau and Haiti – which have poor governance capacity, high exposure to climate impacts and water scarcity, and a strong reliance on development aid – are particularly vulnerable. In these countries, reduced ability to import goods, cuts in development assistance and increasingly frequent climate-related disruptions to domestic food production threaten serious consequences for public health and livelihoods. The limited capacity of land-poor developing countries to mitigate, adapt to and build resilience to environmental shocks, including those resulting from climate change, amplifies the risks. Environmental degradation and climate impacts accelerate the deterioration of land-based resources and imperil people whose livelihoods depend on these resources, including in the food, forestry and tourism sectors. Social inequalities widen, and household insecurity deepens.

Along with the grave challenges for land-poor developing countries, a 'self-sufficiency for national security' future carries risks for countries across all other typologies. For example, the drive for self-sufficiency could result in unsustainable patterns of land clearance and exploitation among potential land elites such as the DRC and the Republic of the Congo, where high-quality land is abundant but governance and economic capacity are lacking. Unmanaged and unsustainable land use in these countries would have local, regional and global consequences, depleting globally significant ecosystems and land-based resources with significant environmental regulating functions (Box 17). Scope for peaceful interventions to mitigate such losses, or to incentivize their preservation and restoration, would be limited by the erosion of multilateral agreements and international cooperation.

Threatened land-wealthy countries – most notably Chile, India, Indonesia and Tanzania – may also suffer negative outcomes if opportunities for ecosystem restoration as a means of building resilience to climate and water risks are squandered through poor governance.

Countries such as the US have undergone extensive land-use change in the past. As a result, they have lost much natural habitat and seen their vulnerability to climate and water impacts increase.

While land superpowers, as mentioned, fare relatively well in this future, many struggle to balance the achievement of sustainable, self-sufficient provisioning with the maintenance or restoration of ecosystem services that enhance domestic and international resilience to environmental and geopolitical shocks. Countries such as the US have undergone extensive land-use change in the past. As a result, they have lost much natural habitat and seen their vulnerability to climate and water impacts increase. They may struggle to meet domestic demand if they are unable to make that demand sustainable and fail to undertake sufficient ecosystem restoration measures. Similarly, countries such as Australia, where past land exploitation has degraded soils, or China, where climate and water risks are high but resilience is low, may face difficulties despite their land wealth. In addition, reduced global trade may hurt economies that depend heavily on earnings from the export of land-based goods; such countries include Australia, New Zealand, Norway, Paraguay and Ukraine.[506]

A decline in global trade of land-based resources also poses serious risks to import-dependent countries, particularly land-poor developing countries that have high food import needs coupled with rapid population growth (such as Lebanon and Tunisia) and/or land or other natural resource constraints that limit the scope for increasing domestic production. Beyond the immediate risk to food supply in these countries, a large-scale reduction in imports may prompt them to make economic or other policy responses of international consequence.

Land-poor geopolitical elites could also lose out in this future. Particularly at risk are countries such as Kuwait and the UAE, both of which rely heavily on imports to meet nutritional needs and have few or no land acquisitions overseas. Countries that have already leased large portions of land (in a previous, more globalized context) to other users may have limited scope to become self-sufficient, as such land is presumably no longer available to service domestic needs. Equally, those with existing overseas land acquisitions may struggle to keep control of those assets in the event that other land-poor geopolitical elites try to appropriate them. Each such scenario raises the possibility of increased conflict over land resources. For example, where land-leasing countries renege on past transactions in an effort to increase their own self-sufficiency, this may prompt the use of hard power by their counterparties.

506 OECD/FAO (2021), *OECD-FAO Agricultural Outlook 2021-2030*, Paris: OECD Publishing, https://doi.org/10.1787/19428846-en.

8.6.4 Evolving dynamics of a 'self-sufficiency for national security' future

This future represents the furthest departure from BAU. It entails a significant erosion of globally interdependent trade networks, a retreat from multilateralism, and an increasing intent on the part of governments to preserve, restore and utilize land resources at locally sustainable levels. Although, in principle, more robust national commitments to protecting and restoring natural resources and ecosystems have the potential to benefit countries across all typologies, entrenched capacity and governance issues make the realization of this more optimistic outlook unlikely.

Rather, countries across all typologies are more likely to fare poorly in this future as protectionism and a lack of international cooperation increase the potential for conflicts and social inequalities. If such pressures undermine efforts to manage land in sustainable and progressive ways, it is foreseeable that the 'self-sufficiency for national security' future could degenerate into a 'plunder thy foreigner' type of dynamic.

More positively, this scenario's primary focus on domestic resource security could ultimately result in greater recognition by countries of the need to also optimize land use *globally*, including the need to protect and restore globally important resources to limit the impacts of environmental shocks. Over time, this recognition, in combination with the difficulties countries are likely to encounter in achieving self-sufficiency in practice, may foster greater cooperation in international relations, reopening opportunities for multilateral agreements and prompting a transition to the future we characterize as 'a land-wealthy world' (see Section 8.7).

Box 16. The global implications of China's resource strategy

China ranks fourth on the Chatham House Land Wealth Index, and is categorized primarily as a 'land superpower' in this report. Its size, economic and geopolitical power, environmental footprint and large share of global demand for many resources mean that China's resource strategy is likely to heavily influence the pursuit of a 'land-wealthy world' (see Section 8.7).

For example, partly in response to an increasingly competitive and volatile relationship with the US-led West, and partly in response to an increasingly uncertain trade context for land-based resources, China might take an increasingly protectionist and nationalistic approach to strengthening the resilience and security of its food, energy and mineral supplies.[507] However, the challenges stemming from China's resource constraints and burgeoning demand for land-based goods suggest it will continue to participate in global supply chains.

507 Yu, J. (2022), 'China Party Congress: Xi's political blueprint', *The World Today*, 28 September 2022, https://www.chathamhouse.org/publications/the-world-today/2022-08/china-party-congress-xis-political-blueprint; United Nations Development Programme (UNDP) (2021), *China's 14th five-year plan*, Issue Brief, 23 July 2021, https://www.undp.org/china/publications/issue-brief-chinas-14th-five-year-plan.

Water supply and quality are critical issues for China. More than half of the population is affected by water scarcity, and the problem of water shortage is exacerbated by problems of water quality.[508] The main underlying factors behind these issues of quantity and quality of supply are the huge demands from agriculture and industry, which together account for 85 per cent of the country's water use.[509] China's abundant land-based resources and associated geopolitical influence could be materially threatened by future environmental changes that further exacerbate water pressures. Thus, as noted in Chapter 7, China's current, and high risk of worsening, water scarcity means that in some respects it also falls in the 'threatened land-wealthy' category.

In addition to water issues, a declining availability of land for food production due to conversion to other uses (including urbanization and infrastructure development), soil degradation, and a range of environmental impacts including consequences of climate change could pose serious challenges to increasing or even maintaining production as demographic and dietary pressures also mount. China has a similar land area to the US (also classed as a land superpower under the typologies described in this report), but has five times less cropland and three times less pastureland per head, based on current population sizes.[510] China's dietary trends towards increasing consumption of animal products are also problematic in terms of resource use – with per capita supply levels already higher than in the US and the EU for products including eggs, pig meat, and fish and other seafood.[511]

These limiting factors suggest it is unlikely that China would pursue a path of self-sufficiency to the extent that it largely isolates itself from global markets. It is more likely that a change in Chinese trade with the US (which was overtaken by Brazil and the EU as China's largest agricultural suppliers)[512] coupled with the potential for worsening trade relations with the EU and growing domestic demand for land-intensive products such as meat and dairy (China is now the world's largest importer of dairy products),[513] will increasingly drive China to seek resource supplies elsewhere. Should its existing trading relationships with land superpowers such as Brazil and Australia prove unable to satisfy domestic demand, China may try the same approach as many other major economies and move to further draw on land-based resources in countries across Asia and Africa that have less geopolitical clout and, potentially, weaker governance. In line with this, China could leverage its existing trade and investment relationships with such countries through initiatives such as the Belt and Road Initiative, and could draw on its soft-power influence through the South–South cooperation framework and the China South–South Climate Cooperation Fund.

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508 Ma, T. et al. (2020), 'Pollution exacerbates China's water scarcity and its regional inequality', *Nat Commun*, 11, 650, https://doi.org/10.1038/s41467-020-14532-5.
509 Ghose, B. (2014), 'Food security and food self-sufficiency in China: from past to 2050', *Food and Energy Security*, 3(2), pp. 86–95, https://doi.org/10.1002/fes3.48.
510 Calculated from FAO (2022), 'FAOSTAT > Land Use', https://www.fao.org/faostat/en/#data/RL (accessed 1 Jun. 2022) and FAO (2022), 'FAOSTAT > Annual population', https://www.fao.org/faostat/en/#data/OA (accessed 1 Jun. 2022).
511 FAO (2022), 'FAOSTAT > Food Balances (2010-)', https://www.fao.org/faostat/en/#data/FBS (accessed 1 Jun. 2022); Zhu, Y., Wang, Z. and Zhu, X. (2023), 'New reflections on food security and land use strategies based on the evolution of Chinese dietary patterns', *Land Use Policy*, 126, 106520, https://doi.org/10.1016/j.landusepol.2022.106520.
512 Jiang, H. (2020), *China: Evolving Demand in the World's Largest Agricultural Import Market*, International Agricultural Trade Report, US Department of Agriculture Foreign Agricultural Service, https://fas.usda.gov/data/china-evolving-demand-world-s-largest-agricultural-import-market.
513 Ibid.

Recognition of the limits of self-sufficiency at the global level[514] could propel China, like other countries, to necessarily align policies and practices around the dynamics of a land-wealthy world, with flourishing international trade underpinned by sustainability principles and suitably proportioned resource demands. Given its recent history of successful engagement on climate, desertification and biodiversity loss at the multilateral level, there is reason to suggest that China could play a key role in addressing these globally important issues. Indeed, China's record in the presidency of the COP15 Biodiversity Conference in 2022, at which agreement was reached on a framework for global biodiversity (see Chapter 6, Box 13), could boost the country's leverage in advancing global biodiversity protection and international cooperation initiatives. This could, for instance, enable China to take a leading role in advancing work towards the framework's '30x30' target, which calls for the conservation of at least 30 per cent of terrestrial, inland water, and coastal and marine areas by 2030. For the West, sustaining constructive relations with China on climate change mitigation will nonetheless be an important task – and a challenge – over the coming years.[515]

8.7 'A land-wealthy world': highly cooperative international relations and sustainable land use

A future in which countries manage their land resources cooperatively brings the most favourable outcomes for all country typologies, and sees all planetary health indicators improve in line with global climate, biodiversity and public health goals.

8.7.1 Prevalent dynamics

In a 'land-wealthy world' future, sustainability becomes the defining principle of countries' management of land resources through to 2050. This is achieved through multilateral cooperation. Geopolitical relationships become more progressive and constructive than in other potential futures, and land use is more sustainable and less destructive (see Figure 39). Countries recognize the need for collective action on climate change and biodiversity, building on the groundwork of the Rio conventions, especially the 2015 Paris Agreement on climate change and the 2022 Kunming-Montreal Global Biodiversity Framework (GBF), as well as on the SDGs framework.[516]

In addition to aligning policies and actions with longer-term planetary health goals, governments respond to the impacts and threatened impacts of the land crunch in the 2020s by developing collective responses at regional and international levels. A wide spectrum of responses and solutions from all stakeholders drives systemic change and paves the way for the establishment of new processes, policies

514 Beltran-Peña, A., Rosa, L. and D'Odorico, P (2020), 'Global food self-sufficiency in the 21st century under sustainable intensification of agriculture', *Environmental Research Letters*, 15(9), https://doi.org/10.1088/1748-9326/ab9388.
515 Bergsen, P., Froggatt, A., Nouwens, V. and Pantucci, R. (2022), *China and the transatlantic relationship: Obstacles to deeper European–US cooperation*, Briefing Paper, London: Royal Institute of International Affairs, http://doi.org/10.55317/9781784135287.
516 The 'Rio conventions' are so called as their genesis was the 1992 Rio Earth Summit. Formally the United Nations Conference on Environment and Development (UNCED), this was convened as a forum for UN member states to cooperate on issues of sustainable development in the wake of Cold War.

and institutions. International cooperation is a central component of this approach: in the first instance, it enables implementation of the urgent changes needed to avert the worst of a land crunch; in the longer term, it ensures that processes for managing land use, resolving disputes and meeting basic needs (such as provision of food and water) are resilient to political, economic and environmental shocks.

In this more connected and cooperative world, countries recognize that the impacts of climate change and environmental destruction experienced globally in the 2020s – from disrupted supplies of land-dependent goods to the displacement of people – will worsen if commitments to limit temperature rise, land degradation and biodiversity loss are inadequate. If reinforced through ambitious, concerted and committed actions through the 2020s by all stakeholder groups, and especially by governments and businesses, targets to limit average global heating to 1.5°C and to reverse biodiversity loss and land degradation could become less far out of reach.

This future implies widespread recognition that environmental risks can be multi-layered and cascade through various human systems to affect all nations, including the wealthiest and most politically stable, in complex and often unforeseen ways.[517] Deeper understanding of the drivers of land-use change and the associated risks in different localities may be achieved through the development and implementation of a global horizon-scanning mechanism, as outlined in Chapter 9 (see Recommendation 2c). This would monitor and predict problems – providing early warnings and allowing countries better visibility of land-related risks, identification of appropriate mitigation and/or adaptation responses, and opportunities to optimize the allocation of land. To ensure open access to all countries and global relevance, such a risk-scanning mechanism would most likely be administered by an existing UN organization.[518]

Land use is most transformed under 'land-wealthy world' dynamics, relative to the other three futures explored in this chapter. Degraded and deforested areas are rejuvenated, pristine ecosystems are protected, and overall demand for land-based goods is reduced and reconfigured in line with planetary health goals. Such shifts in global land use bring greater resilience to environmental shocks and greater food and nutrition security.

Land-use policies and international relations start to reflect lessons learned from recent global crises. A greater appreciation for the complex interactions between the environment, society and public health, as highlighted by the COVID-19 pandemic, reinforces the crucial role of land-use reconfiguration in tackling the climate and biodiversity crises and mitigating future pandemics.[519] There is also much greater recognition of countries' interdependencies, and of the importance

517 See Quiggin, D., De Meyer, K., Hubble-Rose, L. and Froggatt, A. (2021), *Climate change risk assessment 2021*, Research Paper, London: Royal Institute of International Affairs, https://www.chathamhouse.org/2021/09/climate-change-risk-assessment-2021; and Carter, T. R. et al. (2021), 'A conceptual framework for cross-border impacts of climate change', *Global Environmental Change*, 69, p. 102307, https://doi.org/10.1016/J.GLOENVCHA.2021.102307.
518 This arrangement might, for example, be analogous to the Agricultural Market Information System (AMIS). Established at the request of the G20 in 2011, AMIS is an inter-agency platform designed to enhance food market transparency and policy responses for food security. The AMIS secretariat involves several relevant international organizations from the UN system and beyond, and is housed at FAO's headquarters in Rome. Its chair is elected for a one-year term from among member countries. See https://www.amis-outlook.org/amis-about/en.
519 Hayek M. N. (2022), 'The infectious disease trap of animal agriculture', *Science Advances*, 8(44), 2 November 2022, https://doi.org/10.1126/sciadv.add6681.

of global cooperation to maintain resource security – a challenge illustrated by the ripple effects of Russia's war on Ukraine. Countries also start to understand better the land-use implications of their economic, development and trade policies, and to take into account both production and consumption impacts.

Countries place increased importance on the optimal use of resources, maximizing positive outcomes for the climate, biodiversity and public health, and there is much more emphasis on increasing circularity in resource supply chains. Cooperative approaches to optimizing land use at the global level increase, with goods being produced in areas with the greatest productivity and resilience to environmental shocks, and with the least sensitivity to environmental damage.

Countries recognize the global importance of preserving carbon and biodiversity repositories, and take measures to limit the adverse environmental impacts of trade. Efforts to promote more circular trade and consumption patterns go beyond a reconfiguration of land use and trading relationships, facilitating the more sustainable production and transfer of goods. These efforts include incentives for creating markets for, and trading, land-based resources and services in ways that support ecological benefits such as carbon storage and biodiversity protection – for example, through carbon border adjustment mechanisms (CBAMs) and measures to limit trade-related biodiversity loss. Land-based resource production is relocated away from ecologically important carbon and biodiversity repositories to allow for their protection and restoration on the scale needed to address the biodiversity and climate crises. New mechanisms are potentially established to incentivize such practices.

Ensuring more resilient supplies of resources necessitates shifts away from the current dependence on a small number of complex, globalized 'just in time' supply chains to more flexible supply chains that incorporate a more diverse range of suppliers and transportation routes.

Embedding circularity and inclusivity within trade and economic cooperation agreements is fundamental to reshaping global trade in alignment with a land-wealthy world. Ensuring more resilient supplies of resources necessitates shifts away from the current dependence on a small number of complex, globalized 'just in time' supply chains to more flexible supply chains that incorporate a more diverse range of suppliers and transportation routes. It also requires trading partners to work together to manage natural resources appropriately. Appropriate incentives and penalties are established to ensure that key natural resources, including those that provide regulating functions for climate and water, are maintained in a healthy state and not degraded or destroyed for food or energy production. Increased transparency of trading dynamics and improved international trust in trading relationships facilitate such outcomes. The groundwork for increasing private sector disclosures regarding biodiversity impacts along supply chains, as set out in the Kunming-Montreal GBF, potentially proves vital.

In a land-wealthy world, consumption of land-intensive resources decreases. The optimization of land use sees a reduction in the global area of land available for food production, necessitating a focus on maximizing the supply of nutritional food from the land available. Global diets necessarily become much more plant-based, nutritionally complete and diverse, and consumption of land-intensive animal products falls dramatically. Renewed efforts to limit global warming to 1.5°C above pre-industrial levels in this century lead to an overall reduction in demand for energy. In the now likely event that atmospheric greenhouse gas concentrations still result in this target being overshot, effective use of nature-based sequestration options supplemented by land-sparing negative emissions technologies ensures that overshoots are minimized and temporary. Land-hungry 'decarbonized' energy supply from biofuels is minimized and their use limited to unavoidable liquid or solid fuel requirements. Instead, most energy is supplied from wind, solar and hydropower. The limited amount of land available for biofuel production prompts a substantial rethink of current climate change mitigation policy aspirations that rely heavily on land-intensive bioenergy with carbon capture and storage (BECCS).

8.7.2 Relative winners in a 'land-wealthy world' future

All countries stand to achieve their most beneficial outcomes in a land-wealthy world. This future is characterized by the most cooperative state of international relations to date, with most superpowers and land-poor geopolitical elites maintaining, at least initially, their geopolitical influence. They use this influence to bring a greater focus on environmental sustainability and robust global land governance to international diplomatic and security forums. Potential land elites establish a more prominent role in international relations by optimizing their globally valuable land resources. For some countries, this involves increasing food production to supply international demand; for others, it involves large-scale ecosystem restoration and/or protection; for others still, it involves differentiated land use that maximizes the potential of multiple ecosystem and land types.

In this future, threatened land-wealthy countries (such as India, Indonesia and Peru) potentially hold an important position in international relations as custodians of globally important ecological reserves. However, their influence remains contingent on their being able to restore degraded lands and build resilience to environmental shocks. Some land-poor developing countries are able to play a similar role, focusing their development strategies around restoring their ecological reserves. A large number of African countries across the tropical belt, both land-poor and land-wealthy, are well positioned to optimize their land for ecological outcomes in this way. Such countries potentially include Burundi, Cameroon, the Central African Republic (CAR), the DRC, Ethiopia, Gabon, Niger and Sudan.

For land-poor developing countries, the potential gains are greater in a land-wealthy future than under the other scenarios. Countries in this typology notably stand to benefit from increased multilateral cooperation to raise finance to mitigate, adapt to and build resilience to the impacts of climate change. They also benefit from international development assistance and funding that is specifically channelled into the protection and restoration of key ecosystems, along with the transformation of food and energy systems in line with planetary health goals.

8.7.3 Relative losers in a 'land-wealthy world' future

While land-poor developing countries fare better in a land-wealthy world than in the other three futures explored in this chapter, entrenched inequities in global resource use and international relations see them remain as the 'relative losers' compared with other country typologies. A concerted effort at the international level will still be required to enable the poorest and most fragile countries to realize the full benefits of this future. For example, the allocation of development assistance and finance will not only need to account for a country's reserves of globally important carbon or biodiversity (Box 17), or for its role as a global supplier of food or energy; it will also need to recognize interconnections and dependencies across countries and regions, and the importance of such support in facilitating a land-wealthy future for all.

Box 17. The future of key global climate regulators and biodiversity repositories

The largest 'irrecoverable' carbon reserves – i.e. reserves of carbon that, if lost, cannot be recovered by 2050 – are found in the tropical forests and peatlands of the Amazon (31.5 GtC), in the Congo Basin (8.2 GtC) and on the islands of Southeast Asia (13.1 GtC).[520] While important carbon reserves also exist in North America and Siberia,[521] tropical primary forests support at least two-thirds of the world's biodiversity despite covering less than 10 per cent of Earth's land surface.[522] Their protection thus presents a 'double dividend'.

The largest area of tropical forest is in the Amazon biome, and spans 650 million hectares (ha) across nine territories – mostly Brazil (around two-thirds), and smaller proportions in order of land area: Peru, Colombia, Venezuela, Bolivia, Guyana, Suriname, Ecuador and French Guiana.[523] This forest stores approximately 10 per cent of global forest carbon.[524] However, between 2002 and 2022, the total area of humid primary forest in Brazil alone decreased by 8.6 per cent, largely due to the cultivation of agricultural commodities.[525] By far the highest global rates of deforestation since 1990 have occurred in Brazil, with an average rate of 1.7 million ha of forest lost each year in 2015–20.[526]

The Congo Basin contains the second largest expanse of tropical forest, with 240 million ha of contiguous forest spread across eight countries – Nigeria, Cameroon, South Sudan, the Central African Republic (CAR), the Democratic Republic of the Congo (DRC), the Republic of the Congo (Congo), Gabon and Equatorial Guinea. In addition to playing an important role in removing emissions from the atmosphere (each year absorbing an amount equivalent to the past decade of fossil fuel emissions from the entire African continent), the region directly supports the livelihoods of 80 million people, and the rainfall generated by its forest benefits a further 300 million rural Africans from the Sahel to the Ethiopian highlands. Despite its crucial role in regulating climate and supporting biodiversity and regional livelihoods, the Congo Basin's forest is under multiple and growing threats. These include: deforestation (more than 500,000 ha of forest were lost in 2019 alone); climate stress (the forest's ability to absorb carbon dioxide is slowing as temperatures rise[527] – and a temperature

520 Noon, M. L. et al. (2021), 'Mapping the irrecoverable carbon in Earth's ecosystems', *Nature Sustainability*, 5(1), pp. 37–46, https://doi.org/10.1038/s41893-021-00803-6.
521 Goldstein et al. (2020), 'Protecting irrecoverable carbon in Earth's ecosystems'.
522 Giam, X. (2017), 'Global biodiversity loss from tropical deforestation', PNAS, 114(23), pp. 5775–77, https://doi.org/10.1073/pnas.1706264114.
523 Vergara, A. et al. (2022), *Living Amazon Report 2022*, Quito: WWF, https://www.wwf.org.uk/sites/default/files/2023-01/Living%20Amazon%20Report%202022.pdf.
524 Heinrich, V. H. A. et al. (2021), 'Large carbon sink potential of secondary forests in the Brazilian Amazon to mitigate climate change', *Nature Communications*, 12(1), p. 1785, https://doi.org/10.1038/s41467-021-22050-1.
525 World Resources Institute (2023), 'Brazil Deforestation Rates & Statistics', *Global Forest Watch*, https://www.globalforestwatch.org/dashboards/country/BRA.
526 Food and Agriculture Organization (FAO) of the United Nations (2020), 'Global Forest Resources Assessment', https://fra-data.fao.org/assessments/fra/2020/WO/sections/forestAreaChange (accessed 7 Jul. 2023).
527 White, L. J. T. et al. (2021), 'Congo Basin rainforest – invest US$150 million in science', *Nature*, 598(7881), pp. 411–14, https://doi.org/10.1038/d41586-021-02818-7.

rise in line with the current trajectory of approximately 3°C this century could destabilize its ecosystems[528]); human population needs (exacerbated by population growth); and resource extraction.[529] The dynamics of a 'land-wealthy world' – i.e. a future in which international cooperation is high and land use sustainable – offer the best chances of protecting these vital regions from human-induced risks, and of minimizing their vulnerability to climate impacts.

8.7.4 Evolving dynamics in a 'land-wealthy world' future

Unprecedented levels of multilateral cooperation act as an anchor in this future, sustaining the benefits of a land-wealthy world for current and future generations. A common interest across all countries in maintaining this new set of dynamics, coupled with more effective mitigation of climate change, biodiversity loss and environmental degradation, sees conditions in this future remain stable relative to other futures. In other words, once a land-wealthy future is achieved, it stands a good chance of persisting rather than transitioning or degrading to a different future. However, this stability is not guaranteed. It depends on the extent to which all countries, whatever their wider geopolitical ambitions, are willing to align their policies and actions with the requirements of attaining and maintaining a land-wealthy world.

8.8 Conclusions

The outlook for planetary and public health, while distressing across three of the four futures explored here, is prosperous in a 'land-wealthy world' (Table 6). But fundamental shifts in both land use and global governance are essential if this future is to be achievable. Today's extractive land uses will need to be replaced with management strategies that recognize the finite nature of land as a resource, that prioritize the protection and restoration of native habitats and ecosystems, and that reduce overall demand for land through dietary change and limited use of bioenergy. The limited amount of land available for biofuel production will necessitate a substantial rethink of current policy aspirations for climate change mitigation, which rely heavily on land-intensive BECCS technologies.

528 Steffen, W. et al. (2015), 'Planetary boundaries: Guiding human development on a changing planet', *Science*, 347, https://doi.org/10.1126/science.1259855.
529 White et al. (2021), 'Congo Basin rainforest – invest US$150 million in science'; and Réjou-Méchain, M. et al. (2021), 'Unveiling African rainforest composition and vulnerability to global change', *Nature*, 593(7857), pp. 90–94, https://doi.org/10.1038/s41586-021-03483-6.

Table 6. Key outcomes for planetary and public health under the four futures

Future	Indicators of outcomes for planetary and public health					
	Land-use area	**GHGs**	**Deforestation rate**	**Biodiversity status**	**Global health**	**International governance**
'Tipping over the edge together'	🔴	🟡	🟡	🟡	🔴	🟡
'Plunder thy foreigner'	🔴	🔴	🔴	🔴	🔴	🔴
'Self-sufficiency for national security'	🟢	🟡	🟢	🟡	🟡	🔴
'Land-wealthy world'	🟢	🟢	🟢	🟢	🟢	🟢

Note: Outcome indicators are coloured according to prospects under each descriptive scenario: positive/improving prospects (green), mixed prospects (amber), negative/worsening prospects (red). Comparisons should be made against today's situation.

The reallocation of large areas of farmland to reinstating native ecosystems will necessitate a redirection of agricultural policies, which currently disproportionally benefit large farms with large cultivated areas and incentivize increased production of land-intensive products such as meat and dairy.[530] Increased international cooperation and multilateralism will be required to enable the introduction, enforcement and achievement of progressive commitments under existing and/or new international treaties to tackle climate change, land degradation and biodiversity loss. And far greater political and financial support will be needed from land superpowers, land-poor geopolitical elites and threatened land-wealthy countries to incentivize and reward the preservation of important carbon and biodiversity repositories in potential land elites and land-poor developing countries.

Implementing these shifts and advancing towards a 'land-wealthy world' will involve many overlapping steps and committed actors. All countries will need to: (a) adopt progressive policies at the national level that are commensurate with global climate, land-use, biodiversity and public health goals; (b) redress the impacts of land-use change in more vulnerable countries by protecting and restoring key ecosystems and reducing demand for land-intensive goods; and (c), perhaps most importantly, strengthen international cooperation around addressing climate change, land degradation and biodiversity loss. These themes, and recommendations for achieving the above goals, are considered in more detail along with concluding reflections in Chapter 9.

530 Springmann, M. and Freund, F. (2022), 'Options for reforming agricultural subsidies from health, climate, and economic perspectives', *Nature Communications* 13, 82, https://doi.org/10.1038/s41467-021-27645-2.

09 Conclusions and recommendations

Creating a sustainable, 'land-wealthy world' will require nothing less than a transformation in land use, allied with more enlightened politics around resource competition. This means, first and foremost, reducing humanity's land footprint, governing global land resources systemically and cooperatively, and changing how land is valued and its stewardship financed.

The challenges of optimizing global land use to maximize societal and environmental prosperity, resilience and security, both now and in an uncertain and turbulent future, are collectively and individually immense. How can governments, societies and businesses mitigate an emerging 'land crunch' – sustainably feeding and providing energy for a rising global population without taking up land critically needed for climate action and biodiversity protection, and vice-versa?

In simple terms, the answer is that a multitude of coordinated actions must occur across geographic, sectoral, disciplinary and political divides. The interventions and adjustments required will be extraordinarily varied, but many will depend on incentives to promote international cooperation around planetary sustainability and resource security. Reform will be disruptive. In many cases, current economic practices and resource consumption will need to change significantly.

As this report has shown, a transformation of this nature poses fundamental challenges not just to scientists, technocrats and bureaucrats, but to politicians, nation states, and all consumers and citizens. Getting countries and people to use land differently, and in some cases to tolerate the inconvenience of re-engineering their economies for the sake of a common interest, is an inherently political undertaking (Box 18). Innovations in land-use policies and practice will need to account not only for Earth system processes but also for domestic political and economic realities and wider geopolitical considerations. There is a real risk that, as the land crunch worsens and competition for land resources intensifies, governments will be tempted to cooperate *less* in a misguided effort to secure more resources for their own populations.

Countries need to be persuaded that land-use risks transcend borders, and that it is in their interests to align their land use with protecting and restoring the global commons.

As explained in Chapter 8 ('Geopolitics and land-use "futures"'), this sort of response to rising resource pressures would make a bad situation worse. The solution, we argue here, is to cooperate *more*, and better. Ultimately, countries need to be persuaded that land-use risks transcend borders, and that it is in their interests to align their land use with protecting and restoring the global commons.

At the same time, given the very real prospect that humanity's medium-term future will depart significantly from the recent status quo – and follow an even more damaging trajectory in terms of climate change, land pressures and resource competition – governments and societies need to be equipped to cope with a broad range of *undesirable* futures. They must anticipate the possibility of widespread policy failure and increased resource competition, and make contingencies accordingly. In other words, they must aim to minimize the magnitude of the land crunch but be prepared to deal with greater pressures and tensions if they arise.

Box 18. Political realities: the problem of 'systemic intransigence'

The ambition for a 'land-wealthy world' – the most optimistic of the four futures presented in Chapter 8 – collides with some uncomfortable political realities. Global patterns of land use arise from many interacting factors, some of which create significant barriers to change. In particular, prevailing models of economic growth, deeply embedded in value systems and ideologies, create path dependencies that lock countries and companies into unsustainable land use, resulting in what can be termed 'systemic intransigence'.

Most governments firmly believe that economic growth – based, to a greater or lesser extent, on consumption growth – is the primary means of achieving national economic well-being. Alongside neoliberal perspectives on free-market primacy, this has resulted in the entrenchment of a globalized economy, consolidated by weakly regulated corporations that drive production efficiencies through a combination of scale, comparative advantage and the externalization of costs on to the environment. Economic investments in research, infrastructure, product development and global consolidation further lock in incumbents' interests and make the transition to more sustainable economic models difficult.

In many countries, the fact that citizens have benefited from consumption growth makes it politically complicated to introduce policies that might disrupt business-as-usual supplies or prices of goods and services. Political commitments to liberalizing markets, reducing trade barriers, and driving economic growth and development (whether sustainable or not) have also created significant barriers to reform. The multilateral system, based around bodies such as the World Trade Organization (WTO), World Bank, International Monetary Fund and other international financial institutions, is structured in a way that arguably contributes to this inertia. Transformative change is widely perceived as prohibitively challenging – politically, geopolitically and economically.[531]

Furthermore, events of the past decade have contributed to a rise in geopolitical and geostrategic tensions. Critical supply chains have increasingly been viewed from a security perspective, issues of migration have become increasingly weaponized in public discourse, and economic competition and contestation have intensified. All these developments have been accentuated by power asymmetries and inequalities within and between countries. These pressures are creating a world in which multilateral cooperation to deal with global threats – unsustainable land use, environmental degradation, biodiversity loss and climate change – is harder to achieve at precisely the time when cooperation is *more* necessary.

The realpolitik of today's global relationships and leadership means that it has become difficult to imagine systemic change happening at the speed and scale now required. A fundamental transformation is needed in 'how the world works', politically and economically. Yet as the limited progress of policy cooperation within the United Nations Framework Convention on Climate Change (UNFCCC) and of broader attempts to decarbonize the global economy painfully illustrates, it is increasingly clear that change will continue to be incremental and inadequate.

As a consequence, for the foreseeable future it is likely that growth in demand for goods and services from land will exceed the planet's ability to supply them sustainably. This will create vicious cycles of greater land-use intensification and degradation, more climate change and biodiversity loss, and thus more crises and political tensions. Eventually, of course, crises *will* create new drivers for change because business-as-usual practices will become self-evidently unsustainable. More serious turbulence could counter systemic intransigence and create greater political space for transformation in economies and a resurgence of multilateral cooperation. However, waiting for disaster to spark meaningful policy change is neither a sensible nor effective approach, and would waste opportunities for earlier interventions to prevent problems or minimize their subsequent effects.

Swift action is particularly important because measures to mitigate the emerging land crunch (see Chapter 6) will require significant shifts in politics and markets, which may themselves take years or decades to materialize. The paradox is that what should be done is politically highly difficult in today's world, yet may become more feasible in future when it will be too late to act (at least, too late to do so as effectively). Conversely, what likely can be achieved in today's world is insufficient, absent a much bigger shift in political priorities, to avert the potential problems ahead.

531 United Nations Environment Programme (UNEP) (forthcoming), *Unlocking transformation among the world's agribusinesses,* Nairobi: UNEP.

Recommendations

In the context of these daunting challenges, what can and should decision-makers do now to avert the worst impacts of the land crunch, and to improve the chances of achieving globally sustainable land use? Our recommendations can be divided into three categories of action: 1) reduce humanity's land-use footprint and related pressures; 2) govern global land resources systemically and cooperatively; 3) value land differently and finance its stewardship.

Success will require a whole-of-society effort, so the recommendations that follow are aimed at a wide variety of stakeholders – including governments, regulators, international organizations, scientists and businesses.

Part 1. Reduce humanity's land-use footprint and related pressures

More than any other action, humanity needs to reduce its demand for land and land-based resources to sustainable levels. Without this, other solutions for addressing land-use pressures simply cannot succeed. In one way or another, all of the recommendations in this chapter serve the overarching aim of using land more sparingly or intelligently.

The challenge is that much of the modern economy is essentially designed to meet resource demand through supply-side technology innovations (albeit supposedly with lower environmental impacts per unit of production as technology improves). Examples include intensive, industrialized farming and the substitution of fossil fuels with bioenergy. However, boosting supply, no matter how efficiently, without also tempering demand is not the answer to alleviating pressures on land use. Demand-side options – such as changing dietary consumption patterns to reduce the land footprint of food production, and reducing the energy requirements of industry – will inevitably also be needed, even if such options are politically unpalatable. In short, countries will increasingly need to decouple resource dependency from economic growth.

Key tasks:

a. Transform food systems

As agriculture is by far the largest land use, and food systems are central to rising pressures on land, efforts to promote transformation throughout food systems need to be redoubled to reduce those pressures and achieve better planetary health outcomes. Crucially, this will include shifting from animal- to more plant-based diets, and reducing supply-chain food losses and consumer waste.

Compared with producing animal-sourced foods, production of plant-based foods requires much less land and emits far fewer greenhouse gases, meaning less land is also required to sequester food system emissions.

These ideas have long been acknowledged as essential elements for sustainability, but have yet to translate into the meaningful policy changes that would drive widespread commercial and consumer adoption. However, their potential to significantly reduce land use means they simply cannot be ignored and must become a priority. Compared with producing animal-sourced foods, production of plant-based foods requires much less land and emits far fewer greenhouse gases, meaning less land is also required to sequester food system emissions. Such a shift would also free up land for other uses, meaning for example that land-wealthy countries could restore native ecosystems – in line with meeting biodiversity goals – without having to compromise food and nutrition security to do so.

Though less of a factor than dietary change, reducing the amounts of food lost in production and transit, or wasted by consumers, is also important for shrinking the land-use footprint of food production (see Chapter 4). Typical industry responses are often confined to boosting supply-chain efficiencies and developing highly processed 'shelf-stable' foods that keep for long periods. While it is important that produce reaches consumers in good condition, changes must also include promoting regenerative and resilient agriculture to counter the negative environmental impacts associated with many current industrialized food supply chains.

As noted, however, for change to be achieved at the scale needed, food systems need to attract much greater international political attention. Just as biodiversity protection had its 'Paris moment' at the COP15 summit of the Convention on Biological Diversity (CBD) in 2022 (see Chapter 6, Box 13), food system transformation needs a similar galvanizing moment in international relations. In this regard, the upcoming COP28 climate summit scheduled for November/December 2023 could provide an early opportunity to advance transformative action as part of the summit's 'non-negotiated outcomes'. The extensive diplomatic groundwork around food systems undertaken in the run-up to COP28 confirms that the urgency to act is now widely understood internationally. However, this must be backed by concerted, ongoing and holistic action to match the rhetoric. In the longer term, the food systems reform agenda needs to be reinforced by continued advocacy and persistent and ambitious actions by politicians, industries and civil society.

b. Avoid 'high-risk' climate change mitigation strategies, such as BECCS, that require a lot of land

Reliance on high-risk climate change mitigation technologies such as bioenergy with carbon capture and storage (BECCS) – which, worryingly, is increasingly central to many climate action plans – needs to be minimized. BECCS may have some future role as part of a diverse portfolio of climate solutions, but it should be used sparingly. In many instances BECCS will need to be avoided because, if deployed at scale, it will amplify land crunch risks worldwide.

Certainly, the common notion that widespread deployment of BECCS is a desirable and feasible climate 'get-out-of-jail card' needs to be more convincingly dispelled, as BECCS is prohibitively land-intensive (see Chapter 5) and its effectiveness in reducing net emissions at scale is unproven. Unrealistic expectations for BECCS are also causing other necessary climate change mitigation actions to be deferred or overlooked.

A corollary of reduced reliance on BECCS is the need to explore other technological and nature-based carbon dioxide removal (CDR) solutions. These include: direct air carbon capture and storage (DACCS); forest and grassland protection and natural forest expansion; peatland restoration; agriculture-compatible solutions such as chemical weathering, biochar, no-till agriculture and regenerative agriculture; and 'blue carbon' sequestration options such as mangrove and seagrass restoration.

At the same time, there is an urgent need for civil society to deliver systematic, country-by-country analysis of the practical applications of nature-based solutions (NBS), including their limitations, their net carbon, biodiversity and livelihood impacts, and their suitability for different geographies and economies. There is an equally pressing need for governments and businesses to take heed of this analysis in their decision-making and investment decisions. Only then can risk-calibrated investment and financing options be mobilized for appropriate portfolios of technological and nature-based solutions to limit the overshooting of carbon budgets.

c. Use marginal lands better

'Marginal lands' of little current productive value, particularly extensive areas of degraded or barren lands such as deserts, must be harnessed for sustainable use – for example, for nature restoration, carbon capture and storage, or solar energy generation – to reduce pressures on other, more viable land. Alternatively, such areas could be used for 'land-sparing' food production facilities, such as vertical hydroponic/aquaponic farms or cultured-meat laboratories. However, as such facilities often have significant indirect land-use impacts (for example, requiring transport corridors) and non-land footprints in the form of water and energy requirements, they should only be situated in environments that can sustain them. Where lower-value lands support fragile ecosystems or marginalized communities, or are inaccessible wildernesses, they should either be left untouched or, through careful management and restoration, returned to their full ecological potential.

One way of facilitating such changes could be for development donors to use foreign aid and other financial flows to build local resilience through appropriate land restoration and investment in sustainable economic activities in marginal areas. This could help to reduce aid recipient countries' direct vulnerabilities to climate change and land degradation, and limit their exposure to the land supply crunch.[532]

d. Increase the circularity of the global economy

Inclusive 'circular' economies need to be developed and widely adopted to decouple economic prosperity from growth in material consumption and its reliance on land.[533] This transition will rely, in particular, on private sector innovation to slow the flow of materials through the economic system by extending product lifespans, using fewer resources per product, and maximizing opportunities for recycling

532 Quiggin, D., Townend, R. and Benton, T. (2021), *What near-term climate impacts should worry us most?*, Research Paper, London: Royal Institute of International Affairs, https://www.chathamhouse.org/2021/10/what-near-term-climate-impacts-should-worry-us-most.
533 Schröder, P. (2020), *Promoting a just transition to an inclusive circular economy*, Research Paper, London: Royal Institute of International Affairs, https://www.chathamhouse.org/2020/04/promoting-just-transition-inclusive-circular-economy; and McCarney, G. (2021), *Primary materials in the emerging circular economy: Implications for upstream resource producers and primary material exporters*, Ottawa: Smart Prosperity Institute, https://institute.smartprosperity.ca/sites/default/files/emerging_circular_economy_report.pdf.

and reuse. Such measures will be especially important as demand increases for biomaterials as substitutes for extractive resources like critical minerals and fossil fuels. Existing bio-based economic practices such as land-intensive agriculture and forestry will also need to be replaced with alternatives that have smaller land footprints and are associated with fewer environmental and societal harms.

The transition to a circular economy will further depend on governments lowering or removing technical barriers to trade in second-hand and remanufactured goods, recycled raw materials and waste for recovery – for example, by unifying regulatory and trade requirements between jurisdictions. Policymakers and legislators will need to improve trade facilitation measures to address the complexities of product classification associated with these innovative types of trade flows, streamlining the current cumbersome authorization processes for trade in the relevant categories of secondary goods. They will also need to embed the principles of circularity and inclusivity within trade and economic cooperation agreements.[534]

Part 2. Govern global land resources systemically and cooperatively

International cooperation will be critical to reducing land-use pressures, as all countries will suffer if the geopolitics around land use degenerate towards zero-sum approaches. As the challenge is global, and the distribution of land wealth between countries uneven, cooperation and coordination must account for asymmetries in political and economic power – and circumvent the obstacles these present – to help unlock collective solutions.

Yet the outlook for multilateralism is deteriorating. Given the events of the past decade, in which competition between countries over resources and in other areas has intensified and the architecture for international cooperation has become weaker, relying solely on multilateral solutions to global problems is unlikely to be effective. This is especially the case given that many multilateral commitments are generally not subject to hard laws or clear enforcement mechanisms.[535] Equally, the prospects for forging new binding agreements or creating brand new global institutions look remote.

To mitigate the worst risks, and to avoid the 'plunder thy foreigner' future outlined in Chapter 8, countries must therefore not only persevere with multilateralism under the current architecture but also find new ways of working together to reduce demand for land-dependent goods and services, and to ensure land-use decisions are optimized and coordinated globally. While minilateral or ad hoc arrangements must not supplant broad-based multilateral action, novel mechanisms will at times be required to raise ambition, especially as achieving universal action may become progressively more challenging as the geopolitics of land use becomes more contested in the future (see Chapter 8).

534 Ibid.
535 The United Nations Convention on the Law of the Sea (UNCLOS) is a notable exception.

Key tasks:

a. Coordinate between the 'Rio conventions'

Redoubled political investment in multilateral governance is required to ensure responsible stewardship of globally significant land resources. Yet in the context of today's trend towards 'reglobalization' – in which some established alliances and networks have fractured and other bilateral or multi-country arrangements have emerged – progress remains more likely via established treaties and UN conventions than through fundamental reform of the international architecture for environmental governance.

Redoubled political investment in multilateral governance is required to ensure responsible stewardship of globally significant land resources.

An immediate priority should be greater alignment between the bodies and workplans of the three 'Rio conventions': the United Nations Framework Convention on Climate Change (UNFCCC), the United Nations Convention to Combat Desertification (UNCCD), and the CBD (see Chapter 6, Box 13 for background on all three conventions). Central to this will be the development of mechanisms that incentivize and legislate for sustained increases in policy ambition, financial contributions and meaningful action, and that are coherent across all three conventions (so that, for instance, the design of climate change mitigation takes biodiversity implications into account). An example of where this is needed is the UNFCCC's new four-year Sharm el-Sheikh programme of 'joint work on implementation of climate action on agriculture and food security'.[536] This work needs to broaden its scope from focusing predominantly on agricultural systems to tackling food systems holistically and in a manner that is consistent with, and advances, their wider roles in responding to biodiversity and land degradation challenges as articulated through the CBD and UNCCD.

At the national level, greater effort is required in many countries to ensure that domestic policymaking coherently advances progress towards meeting the objectives and targets enshrined in all three conventions. Economic development and investment plans, policies and legislation need to be designed with consideration of national commitments under all relevant conventions and multilateral environmental agreements. For each country, this approach should reflect an overarching, coherent 'masterplan' coordinated across government offices and agencies, as opposed to the piecemeal and often discordant policymaking currently observed.

International forums such as the UN Food Systems Summit offer mechanisms through which to strengthen domestic action and international cooperation on governance of land policies, for example by refining and bolstering national food system transformation strategies. One useful approach could be to integrate such strategies both into countries' nationally determined contributions (NDCs) on emissions reductions within the UNFCCC, and into their national biodiversity strategies and action plans (NBSAPs) under the CBD's new Global Biodiversity Framework (GBF). However, participating countries need to use such initiatives to drive ambition forward rather than make lowest-common-denominator pledges.

536 UNFCCC (2022), 'Draft decision -/CP.27 Joint work on implementation of climate action on agriculture and food security', FCCC/CP/2022/L.4, https://unfccc.int/documents/622325.

b. Measure, report and verify land use consistently

Awareness and understanding of global land resources and how they are used is urgently needed to help policymakers to assess the risks of land degradation – both locally and in relation to cross-border flows of goods, services, finance and people – and to take appropriate action. In the first instance, this will depend on significant improvements in reporting on land availability and management.

At a country level, much can be learned from the experiences of measurement, reporting and verification (MRV) under the UNFCCC's framework on Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (REDD+).[537] In addition to its focus on emissions, REDD+ includes reporting on activities such as sustainable forest management and the conservation and enhancement of forest carbon stocks. If a new and expanded MRV framework were to cover all land uses (not just forestry), all countries (not just developing countries), and a wider range of ecological metrics (such as biodiversity) and societal metrics (for instance, farmer incomes) at a higher spatial resolution than under REDD+, it could offer a template for managing and reducing a wider regime of land-use pressures.[538]

More stringent target-setting around land management will be needed to inform and drive policy change. The voluntary reporting metrics of the UN's Land Degradation Neutrality Target Setting Programme[539] offer a potential model for monitoring progress and increasing accountability. This programme quantifies aspects of land cover, land productivity (or 'net primary production' – NPP) and soil organic carbon stocks.[540] However, for greater effectiveness, the adoption of its land degradation neutrality (LDN) targets needs to be extended beyond the 129 participating countries that have committed to setting national targets, and there is a particular gap in commitments in North America and Europe.

To bolster target-setting, global mechanisms will be required to ratchet up national ambitions to combat land degradation and increase scrutiny of compliance with domestic targets. Widespread adoption of the UN's new 'SEEA Ecosystem Accounting' framework – part of the UN's System of Environmental-Economic Accounting (SEEA), which recognizes natural capital in economic reporting – would represent a major step forward by enabling the incorporation of sustainable development concerns into economic planning and policy decision-making.[541] (See also Recommendation 3a for more on natural capital accounting.)

537 Angelsen, A. et al. (2017), 'Learning from REDD+: a response to Fletcher et al.', *Conservation Biology*, 31(3), pp. 718–20, https://doi.org/10.1111/cobi.12933.
538 This would be more akin to the holistic lens of the IPBES global assessment. See Delabre, I. et al. (2020), 'Unearthing the myths of global sustainable forest governance', *Global Sustainability*, 3, p. e16, https://doi.org/10.1017/sus.2020.11; and Krause, T. and Nielsen, M. R. (2019), 'Not Seeing the Forest for the Trees: The Oversight of Defaunation in REDD+ and Global Forest Governance', *Forests*, 10(4), p. 344, https://doi.org/10.3390/f10040344.
539 United Nations Convention to Combat Desertification (UNCCD) (2022), 'LDN target setting', https://www.unccd.int/actions/ldn-target-setting-programme.
540 UNCCD (2022), 'Land Degradation Neutrality', https://www.unccd.int/land-and-life/land-degradation-neutrality/overview.
541 For further details, see United Nations (undated), 'System of Environmental Economic Accounting: Ecosystem Accounting', https://seea.un.org/ecosystem-accounting; and UNEP (2021), 'UN launches the first artificial intelligence tool for rapid natural capital accounting', 29 April 2021, https://www.unep.org/news-and-stories/press-release/un-launches-first-artificial-intelligence-tool-rapid-natural-capital.

In the private sector, fuller disclosures on land use are required to understand the climate and environmental risks associated with companies' business operations and investments. As a first step, one option for improving transparency is for governments to advance efforts to meet Target 15 of the new GBF: 'Take legal, administrative or policy measures to encourage and enable business, and in particular to ensure that large and transnational companies and financial institutions: (a) Regularly monitor, assess, and transparently disclose their risks, dependencies and impacts on biodiversity, including … along their operations, supply and value chains and portfolios … .'[542]

Existing corporate disclosure frameworks, coupled with regulation and policy galvanized by the GBF, could be used to make land- and nature-related disclosures a core part of every company and financial institution's annual reporting. Two significant initiatives in this area are the Taskforce on Climate-related Financial Disclosures (TCFD),[543] run by the G20-mandated Financial Stability Board (FSB); and the new Taskforce on Nature-related Financial Disclosures (TNFD).[544] Widespread adoption of reporting under the TCFD and TNFD land-use headings (i.e. pertaining to climate risks as well as other ecological and societal risks) among companies with material land footprints (whether direct or indirect[545]), or for investments in such companies, would increase the transparency, resiliency and societal benefits of the operations involved. To increase demand for such disclosures, more stock exchanges, fund providers and institutional investors should make reporting of, and performance against, these measures a condition of market listings or investments.

Mandatory non-financial reporting frameworks should also be expanded to provide for greater disclosure on corporate land footprints. Such frameworks already exist in some jurisdictions, such as under the EU's non-financial reporting directive (NFRD),[546] and are increasing transparency around the broader social and environmental impacts of business activities.[547]

c. Anticipate and communicate land-use risks to inform decision-making

Improved monitoring and modelling of the quality and condition of land are needed so that the risks to land sustainability associated with environmental change – as well as the risks associated with different policy options – can be more accurately and convincingly communicated and acted on. Determining whether one policy option is preferable to another in terms of land-use sustainability,

542 Convention on Biological Diversity (CBD) (2022), 'COP15: Final Text of Kunming-Montreal Global Biodiversity Framework', 22 December 2022, https://www.cbd.int/article/cop15-final-text-kunming-montreal-gbf-221222.
543 Task Force on Climate-related Financial Disclosures (TCFD) (2021), 'Task Force on Climate-related Financial Disclosures: Overview', https://www.fsb-tcfd.org/wp-content/uploads/2020/03/TCFD_Booklet_FNL_Digital_March-2020.pdf.
544 Taskforce on Nature-related Financial Disclosures (TFND) (2022), 'TNFD Nature-Related Risk & Opportunity Management and Disclosure Framework', https://framework.tnfd.global.
545 Referred to as 'scope 1' where the footprints are direct, i.e. from sources owned or controlled by the company or entity; 'scope 2' where they are indirect from energy use; and 'scope 3' where they arise from activities up and down the value chain, or otherwise not in scope 1 or 2 but for which the company or entity bears indirect responsibility.
546 European Commission (2022), 'Corporate sustainability reporting', https://ec.europa.eu/info/business-economy-euro/company-reporting-and-auditing/company-reporting/non-financial-reporting_en.
547 Jackson, G. et al. (2020), 'Mandatory Non-financial Disclosure and Its Influence on CSR: An International Comparison', *Journal of Business Ethics*, 162(2), pp. 323–42, https://doi.org/10.1007/s10551-019-04200-0.

for instance, depends on quantifiable, context-specific information on the characteristics and performance of each solution, benchmarked against best practice and/or theoretical models of globally optimized land use.

Developing this information requires action from scientists and policymakers alike. The scientific community needs to provide analysis of contemporary and future land, climate and biodiversity interactions in more policy-actionable formats. This should include scenarios highlighting the potential sectoral and temporal trade-offs associated with different land-use, trade, development and climate strategies. (For instance, does an energy decarbonization policy have unintended consequences for food security; or does an agricultural policy to boost food security today undermine food security tomorrow by irreversibly degrading productive lands and reducing communities' options to adapt to climate change?)

Such work would lead to the development of clearly articulated global pathways and guidelines for responsible investment, dietary change, and technological and nature-based climate change mitigation, which are needed to inform national-level action plans on the collective transformation of land use.[548] Work could be overseen, at least initially, by the United Nations Environment Programme (UNEP) under the authority of the United Nations Environment Assembly (UNEA). In consultation with the Food and Agriculture Organization of the United Nations (FAO) and the World Health Organization (WHO), the development of global, sustainable land-use pathways could foster new collaborations between the respective assessment processes of the Intergovernmental Panel on Climate Change (IPCC), the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), the UNEP Global Environment Outlook (GEO) and the UNEP 'Emissions Gap Report'. Such collaborations could draw on new assessment frameworks to strengthen the systemic evidence base and contribute to better understanding of the risks associated with the land crunch.

Policymakers must then use this information to make appropriately risk-adjusted decisions within domestic and multilateral contexts, including accounting for the domestic and international land-use consequences of proposed emissions reduction pathways. This would mean, for example, greater recognition of the 'embedded' land associated with each country's consumption of resources and services imported from other countries, and improved recognition of the indirect land-use impacts associated with offshoring production of goods and services, or with devolving carbon sequestration to external trading partners.

Using this information, countries would be better placed to design regulations and incentives to ensure lands are used, restored or preserved appropriately. Decision-makers would also be better placed to identify options that provide the right balance (and combinations) of climate change mitigation, climate change adaptation, nutrition security, and ecological and economic benefits.[549]

548 Benton, T. et al. (2021), *Food system impacts on biodiversity loss*, Research Paper, London: Royal Institute of International Affairs, https://www.chathamhouse.org/2021/02/food-system-impacts-biodiversity-loss.
549 Seddon, N. et al. (2020), 'Global recognition of the importance of nature-based solutions to the impacts of climate change', *Global Sustainability*, 3, p. e15, https://doi.org/10.1017/sus.2020.8.

'Horizon scanning' of potential sources of pressure arising from global land demand is needed to provide decision-makers with better visibility of land-related risks and early warnings of future problems.

'Horizon scanning' of potential sources of pressure arising from global land demand is also needed to provide decision-makers with better visibility of land-related risks and early warnings of future problems, especially given the volatility in environmental conditions and commodity markets that is increasingly apparent from land–climate interactions. This may be best realized through the establishment of an inter-agency global risk-scanning institution, for example using the G20's Agricultural Market Information System (AMIS) as a template.[550] The G20 could invite UNEP to establish and host a similar mechanism devoted to land use. The new agency could identify and audit risks from land-use changes and land degradation, as well as cascading risks from biodiversity loss and climate change. In the first instance, such risk-scanning could help countries to mitigate or avoid negative outcomes. But it could also eventually play a broader role: informing strategic planning on navigating longer-term issues such as the resilience and functionality of different supply chains in a changing world.

d. Increase enforcement of land rights and protections

Novel approaches are needed to enforce better land and environmental management at the domestic level. The prospect of mounting pressures on land and more securitized land-related geopolitics points to likely increases in environmental damage and attempted land grabs – whether involving 'virtual' land embedded in supply chains or through physical land acquisitions – by states and multinational corporations.

Even in the absence of overt transgressions, countries, landowners and land-using communities will need legally enforceable preventive measures that they can use when their land resources are at risk of expropriation and/or degradation (for example, by private profit-making entities). They will also require mechanisms for legal redress when abuses occur. However, enforcement within domestic jurisdictions will require the relevant national environmental regulatory agencies to receive political support and sufficient resources.

Litigation, already becoming more prevalent over environmental issues, will become increasingly necessary to plug regulatory gaps. In the context of efforts to achieve sustainable land use, environmental and rights-based litigation (already being used by affected communities and non-governmental organizations[551]) could force action to prevent 'ecological bankruptcy'[552] by holding companies responsible for acts and omissions in their value chains. Improved safeguards for weakly governed countries with exploitable land resources will still be needed, but lawsuits against international actors in more strongly regulated jurisdictions could also have a valuable role.

Concerted efforts will be needed to safeguard the rights of local communities, and to ensure that protection of high-value lands is not at the expense of local, indigenous or vulnerable stakeholders who may be displaced or denied access

550 AMIS is an inter-agency platform that essentially exists to prevent market failure. It aims to enhance food market transparency and boost coordination in times of market uncertainty. Participants include the principal agricultural commodity-trading countries. See https://www.amis-outlook.org/amis-about/en.
551 Setzer, J. and Higham, C. (2021), *Global trends in climate litigation: 2021 snapshot*, London: Grantham Research Institute on Climate Change and the Environment and Centre for Climate Change Economics and Policy, London School of Economics and Political Science, https://www.lse.ac.uk/granthaminstitute/publication/global-trends-in-climate-litigation-2021-snapshot.
552 In other words, a situation in which natural resources are used at a faster rate than they can regenerate.

to economic resources. Decision-making around land protection should involve the participation of communities most affected by land-use change. It should be complemented by financial mechanisms to compensate communities and/or invest in local livelihoods, and by robust land rights legislation that protects landowners, land users and land with high ecological value. To ensure legal certainty – both for indigenous peoples and society at large – institutions and regulatory frameworks governing the participation and consultation of indigenous peoples will need to be strengthened, or created where lacking.[553] One development worth watching is the work of Brazil's new Ministry of Indigenous Peoples,[554] set up in response to the dismantling of indigenous and environmental protections that occurred during the administration of the country's former president, Jair Bolsonaro. Protections are especially urgent in jurisdictions where land governance is weak, weakly enforced or contested, including where customary tenure arrangements may be vulnerable to being overturned.[555]

Part 3. Value land differently and finance its stewardship

To incentivize the protection of land, its value in providing long-term public goods needs to be systemically recognized and accounted for. Protecting land with a high ecological value from conversion or exploitation is the most effective way of preserving carbon sinks and biodiversity, but current protections are typically based more on an area's intrinsic and cultural value, rather than on recognition of its economic value in the short and long term.

At the same time, accelerated mobilization of financial resources, particularly in support of 'ecological governance' in lower-income countries, will be needed to incentivize and enable sound environmental stewardship. While this is difficult politically in the current economic environment, as many higher-income countries are fiscally constrained following the COVID-19 pandemic and as a result of the economic impacts of Russia's war against Ukraine, low- and middle-income countries will need financial help to maintain and increase the vitality of their terrestrial ecosystems. Many countries will also need financial support to adapt sustainably to competition for land and land-related resources in a context of more challenging environmental conditions. Despite the cost, supporting poorer countries with these efforts will have global benefits.

Key tasks:

a. Formalize the value of protected and ecologically rich land

The long-term value that protected and other ecologically rich lands provide – both for the countries in which they are situated and for planetary health – needs more formal, institutional recognition. Ad hoc, intrinsic valuations need to be replaced with regulations or payment schemes and other market-based instruments that

553 Kumar Dhir, R. et al. (2020), *Implementing the ILO Indigenous and Tribal Peoples Convention No. 169: Towards an inclusive, sustainable and just future*, Geneva: International Labour Organization, https://www.ilo.org/global/publications/books/WCMS_735607/lang--en/index.htm.
554 Ministério dos Povos Indígenas, https://www.gov.br/povosindigenas/pt-br.
555 Brack, D. and King, R. (2021), 'Managing Land-based CDR: BECCS, Forests and Carbon Sequestration', *Global Policy*, 12(S1), pp. 45–56, https://doi.org/10.1111/1758-5899.12827.

explicitly assign financial values to social and environmental goods, including biodiversity. Reductionist carbon accounting that fails to reflect the importance of broader ecosystem integrity and functionality needs to be avoided.[556]

An important signal of increased political intent on this issue was delivered at the CBD COP15 biodiversity summit in December 2022. The 116 members of the High Ambition Coalition for Nature and People (HAC N&P)[557] secured the inclusion in the Kunming-Montreal Global Biodiversity Framework (GBF) of a '30x30' target to protect or conserve at least 30 per cent of the planet's land and ocean by 2030. All parties to the CBD have agreed to adopt the GBF, notwithstanding objections from the Democratic Republic of the Congo over the lack of a new biodiversity fund.[558]

The adoption of 'natural capital accounting' (see also Recommendation 2b) would allow for jurisdictions to ascribe economic value to land in a manner commensurate with the value of its biodiversity, ecosystem functions and utility as a carbon sink. Natural capital accounting measures changes in the extent and conditions of ecosystems at a variety of scales in a standardized format, and its wider use would allow the flow and value of ecosystem services to be integrated more fully into economic accounting and reporting systems.

b. Use regulation and market-based approaches to incentivize land-use optimization and sustainable trade

There is a pressing need to incentivize sustainable trade and to find ways, through regulation or changes in market structures, to optimize use of global land resources. New measures will be required to ensure that the environmental and social costs and benefits of land-based products and services are better reflected in economic valuations and trade. As a starting point, this will require nations and trading jurisdictions to institute economy-wide carbon pricing for emissions and sequestration.

As this step alone is unlikely to provide sufficiently comprehensive valuations,[559] additional carbon-accounting measures could include requiring emitters who wish to avoid further emissions taxes or the imposition of carbon border adjustment mechanisms[560] to hold verifiable sequestration certificates commensurate with the volume of their emissions.

Applying similar pricing mechanisms to the valuation of *non-carbon* elements of land wealth, such as embodied biodiversity costs or land footprints, is more complicated because the impacts would be more varied and geography-specific.

556 Seddon, N. et al. (2019), 'Grounding nature-based climate solutions in sound biodiversity science', *Nature Climate Change*, 9(2), pp. 84–87, https://doi.org/10.1038/s41558-019-0405-0.
557 High Ambition Coalition for Nature and People, https://www.hacfornatureandpeople.org/home.
558 The US, though not a party to the CBD, is a member of the HAC N&P and had already committed to a 30x30 goal in 2021 under the G7's 2030 Nature Compact. See G7 (2021), 'G7 2030 Nature Compact', London: UK Government Cabinet Office, 12 July 2021, https://www.gov.uk/government/publications/g7-2030-nature-compact/g7-2030-nature-compact. The land-wealthy nations of Brazil and China were not part of the HAC N&P in pushing for this target but have adopted it under the CBD. Other than the US, only the Holy See is not a party to the CBD.
559 Brack and King (2021), 'Managing Land-based CDR: BECCS, Forests and Carbon Sequestration'.
560 Kardish, C., Mäder, M., Hellmich, M. and Hall, M. (2021), 'Which countries are most exposed to the EU's proposed carbon tariffs?', Chatham House resourcetrade.earth, https://resourcetrade.earth/publications/which-countries-are-most-exposed-to-the-eus-proposed-carbon-tariffs.

However, such issues, and their alignment with global trade rules, could usefully be explored through the Trade and Environmental Sustainability Structured Discussions (TESSD) at the World Trade Organization (WTO). TESSD was launched in late 2020 to advance discussions on how – among other objectives – trade-related measures can contribute to climate and environmental goals, and to promote and facilitate trade in environmental goods and services. This is an opportunity to make much-needed progress in multilateral dialogues on land–environment–trade intersections and to bring more focused attention to these issues in the WTO's regular committees.[561]

Other options for addressing the environmental impacts of trade could include the following: 'behind the border' measures such as quotas and regulatory standards in importer and exporter countries; ensuring compatibility between national trade policies and multilateral environmental agreements (i.e. negotiated international conventions and treaties); voluntary measures; and the tracing and disclosure by private sector companies of environmental impacts in specific supply chains, accompanied by relevant consumer labelling.[562]

All such mechanisms would need to be structured to incentivize land uses that enhance land wealth holistically rather than, for example, incentivizing monoculture-based carbon sequestration at the expense of broader ecological resilience. Currently, enforceable climate-related provisions in trade agreements are rare, and high environmental standards may be regarded as discriminatory market barriers if they treat otherwise 'like' products differently based on environmental criteria. Such discrimination is potentially illegal under WTO rules (and may not be treated as an essential requirement for managing the ability of land to sustain its output).[563] However, trade agreements will increasingly need to take greater account of signatories' environmental responsibilities – this is particularly the case for agreements involving major economies and land powers.

c. Redirect public funds towards sustainable land use, and end inappropriate agricultural subsidies

Public money should be redirected to supporting the development and deployment of land management practices and technological and market solutions that reduce, rather than increase, pressures on land. Publicly funded subsidies need to be reallocated, perverse incentives removed, and market failures corrected to enable better use of private and public goods. Agricultural subsidy reforms to support environmental improvements without reducing economic welfare are a particularly

561 See also Deere Birkbeck, C. (2021), *Priorities for the climate-trade agenda: How a trade ministers' coalition for cooperation on climate action could help*, London: Royal Institute of International Affairs, https://www.cascades.eu/publication/priorities-for-the-climate-trade-agenda.
562 Vause, J., King, R. and Harwatt, H. (2022), *Two for One: Are the climate impacts of trade a good proxy for biodiversity impacts?*, Trade, Development and The Environment Hub Discussion Paper 8, http://tradehub.earth/wp-content/uploads/2022/11/FAQ8-1.pdf.
563 The basic principle of WTO rules is to ensure that environmental objectives do not protect domestic producers and that all trade partners are treated equally. However, as many governments are only just beginning to design and implement the ambitious policies needed to meet the Paris Agreement goals, it is too early to know whether the WTO compatibility of these policies will be challenged. The EU's forthcoming carbon border adjustment mechanism (CBAM) will provide an interesting test case of whether imports from different countries can be treated differently from one another based on their carbon content without violating the WTO's 'most-favoured nation' non-discrimination principle. See Le Blanc, B. (2023), 'Potential conflicts between the European CBAM and the WTO rules', Norton Rose Fulbright, February 2023, https://www.nortonrosefulbright.com/en/knowledge/publications/9c5d9ec6/potential-conflicts-between-the-european-cbam-and-the-wto-rules; and Deere Birkbeck (2021), *Priorities for the climate-trade agenda*.

urgent priority: currently, nearly 90 per cent of the direct financial support provided by governments to agricultural producers is spent on foods and agricultural practices associated with negative social, environmental and nutritional outcomes.[564] One of the most important steps is to repurpose funding towards production methods and foods that offer health and environmental benefits through a 'public money for public goods' strategy.[565]

Since redirecting subsidies carries political risks (as existing subsidy recipients are likely to seek to preserve the status quo), reforms will need to be complemented by significant policy and communications groundwork. One example would be to raise awareness of the necessity of change in stakeholder communities and civil society.

Progress towards achieving this recommendation – at least in terms of elaborating indicative pathways for redirecting public funding towards public goods – may be accelerated by the fact that governments urgently need to identify, by 2025, how they will meet the 2030 targets of the Kunming-Montreal GBF. This may force the issue, with Target 18 of the GBF potentially proving particularly catalytic: 'Identify by 2025, and eliminate, phase out or reform incentives, including subsidies, harmful for biodiversity, in a proportionate, just, fair, effective and equitable way … starting with the most harmful incentives, and scale up positive incentives for the conservation and sustainable use of biodiversity.'[566]

d. Invest in nature-based solutions and create a 'Rio convention fund'

More public and private sector financing for nature-based solutions (NBS) is urgently needed to avert a land crunch. The term NBS refers to a wide variety of activities involving the conservation, management and restoration of ecosystems (see also Recommendation 1b). Beyond their carbon sequestration and emissions mitigation roles, NBS offer myriad climate change adaptation and biodiversity benefits if sensitively and appropriately deployed in each landscape.

One means of financing NBS is through 'payments for ecosystem services' (PES – see Chapter 3), which can involve payments made by government or by private beneficiaries of the services in question. While PES activity is increasing, especially in domestic contexts, such initiatives need to go further, faster. More research is needed into the factors that determine the success or failure of PES financing schemes, particularly at scale, but there is certainly an expanding role for governments to provide finance and policy oversight in this area.

In addition to domestic public financing, more international public finance and private capital are required. As the UNCCD cautions: 'It is unrealistic to expect developing countries to cover the entire bill for a "just transition" to a restoration economy and climate-resilient future. Extra-budgetary support will be needed –

564 FAO, UNDP and UNEP (2021), *A multi-billion-dollar opportunity – Repurposing agricultural support to transform food systems,* Rome: FAO, https://doi.org/10.4060/cb6562en.
565 Although such an approach would represent a reversal of the move towards decoupled payments in recent decades in response to the overproduction of subsidized commodities, a coupling based on health and environmentally sensitive approaches could be more politically feasible than past approaches and could be an important component of holistic agricultural subsidy reform. See Springmann, M. and Freund, F. (2022), 'Options for reforming agricultural subsidies from health, climate, and economic perspectives', *Nature Communications*, 13(1), p. 82, https://doi.org/10.1038/s41467-021-27645-2.
566 CBD (2022), 'COP15: Final Text of Kunming-Montreal Global Biodiversity Framework'.

from corporate investment, climate finance, debt relief, and donor/development aid to a range of innovative financial instruments that explicitly include environmental, social, and governance criteria.'[567] One urgent priority, requiring immediate action from 'all sources', is ensuring that the financial commitments of the Kunming-Montreal GBF are delivered.[568] However, as with multilateral financing for climate action and 'loss and damage' compensation under the UNFCCC, governments are struggling to find the fiscal space or political will to deliver on biodiversity funding.

Since public funding is difficult to secure in the current political and economic environment, the onus will increasingly fall on private investors to provide financing for NBS.

Since public funding – both domestic and international – is difficult to secure in the current political and economic environment, the onus will increasingly fall on private investors to provide financing for NBS. However, because of the largely intangible economic yields (other than for emissions offsets), NBS often struggle to attract capital investment. To scale up investment in NBS will require addressing risk aversion among private investors, whose concerns partly reflect the difficulty of coordinating and measuring the impact of investments spanning multiple and diverse landscapes (including forests, fields, farms, savannahs, etc.).[569] Effective approaches might include addressing currency risks through blended finance developed with international development institutions; implementing policies that seek to provide long-term certainty for investors through the development of novel markets for nature-based products and services; and partnering with local experts on appropriate ecosystem management practices to mitigate risks.[570]

In the longer term, the creation of an additional 'Rio convention fund' using public or blended finance may offer a promising means of mobilizing finance to address the land crunch. Such funding could be made available for integrating ambitious action spanning all three Rio conventions, for example through governments creating country masterplans supporting the alignment of (a) NDCs on greenhouse gas emissions; (b) national biodiversity strategies and action plans (NBSAPs); and (c) national plans for achieving land degradation neutrality (LDN) targets. As many of the most pressing land-use challenges are at the local level – and hard to reach for national or federal government policy – measures will be required to channel funding effectively to subnational governments and non-state actors so that the issues can be addressed close to the source.[571]

567 UNCCD (2022), *The Global Land Outlook Second Edition: Summary for Decision Makers*, https://www.unccd.int/resources/global-land-outlook/glo2-summary-decision-makers.
568 Target 19 of the GBF is as follows: 'Substantially and progressively increase the level of financial resources from all sources, in an effective, timely and easily accessible manner, including domestic, international, public and private resources, in accordance with Article 20 of the Convention, to implement national biodiversity strategies and action plans, by 2030 mobilizing at least 200 billion United States dollars per year.' For the full text, see CBD (2022), 'COP15: Final Text of Kunming-Montreal Global Biodiversity Framework'.
569 Henderson, B. et al. (2022), 'Soil carbon sequestration by agriculture: Policy options', *OECD Food, Agriculture and Fisheries Papers*, 174, Paris: OECD, https://doi.org/10.1787/63ef3841-en.
570 Throp, H., Yang, A. and Sherman, S. (2021), 'Building Investor Confidence in Nature-based Solutions', Chatham House Sustainability Accelerator, 29 November 2021, https://accelerator.chathamhouse.org/article/building-investor-confidence-in-nature-based-solutions.
571 For lessons from the Forest Law Enforcement, Governance and Trade (FLEGT) and Extractive Industries Transparency Initiative (EITI) on fiscal management conditions and disbursements, see Hoare, A. and Kanashiro Uehara, T. (2022), *Forest sector revenues in Ghana, Liberia and the Republic of the Congo*, Research Paper, London: Royal Institute of International Affairs, https://www.chathamhouse.org/2022/03/forest-sector-revenues-ghana-liberia-and-republic-congo.

Final words

All of the above are vital actions, which need to be taken by a multitude of stakeholders if humanity is to avert the worst outcomes from the deepening land crunch. But perhaps most fundamentally, governments have to make land an urgent priority. They need to start recognizing and acting on the land crunch as one of the existential issues of our time. Governments need to acknowledge the magnitude of the challenge, take responsibility for addressing it, and effect institutional changes that embed land crunch planning at the centre of domestic, foreign and economic policy.

Governments have to make land an urgent priority. They need to start recognizing and acting on the land crunch as one of the existential issues of our time.

Challenges, contests and conflicts over land are as old as human history. Yet the pressures created by humanity's current and prospective land uses are perhaps unprecedented. This is the first time that choices over land use are accelerating global environmental threats – which are existential for many and will affect us all. It is also the first time since the dawn of globalization that land use is so closely entwined with geopolitics: land use could become a major factor in reshaping international relations, while equally being more susceptible to foreign policy agendas. As this report has illustrated, the land crunch is already a real problem for the world, and the risks associated with it are intensifying.

However, calamity is not inevitable. Land use is as much a part of the potential solution as it is a part of the problem, and with the correct choices it could be harnessed to decelerate, rather than accelerate, environmental threats. Through a range of actions to reduce pressures on land – along with international cooperation to mitigate impacts, innovations to enhance understanding of sustainability in land use, and adaptive measures to cope with economic and geopolitical realities – a course can be charted away from the folly of business-as-usual land use towards a more land-secure and cooperative future.

Doing so will not be easy. It will require fundamental changes at all levels in the ways in which societies use and value land wealth. It will require societies to rethink how they work together to distribute land wealth sustainably and equitably in line with climate, biodiversity and other sustainable development goals. Given the enormous heterogeneity of land wealth between countries, and the asymmetries in economic and political power that shape how this wealth is spent or reinvested, global cooperation is vital.

The urgent need for coordinated and deep-rooted action demands a foundation of pragmatic and enlightened multilateralism. The frameworks established through the three Rio conventions – on tackling climate change, land degradation and biodiversity loss – provide a potentially expedient means of harnessing global efforts and actors, but these strands must be brought together more coherently, ambitiously and urgently. While addressing the risks from a land crunch presents many unprecedented and formidable challenges, doing so successfully is necessary to safeguard a habitable planet for current and future generations.

Acronyms and abbreviations

AFOLU	agriculture, forestry and other land uses
AMIS	Agricultural Market Information System
AMOC	Atlantic Meridional Overturning Circulation
BAU	business as usual
BECCS	bioenergy with carbon capture and storage
CAR	Central African Republic
CBAM	carbon border adjustment mechanism
CBD	[United Nations] Convention on Biological Diversity
CCS	carbon capture and storage
CDR	carbon dioxide removal
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalence
CO_2-fe	carbon dioxide forcing equivalence
COP	Conference of the Parties
CRISPR	clustered regularly interspaced short palindromic repeats
CSP	concentrated solar power
DACCS	direct air carbon capture and storage
DRC	Democratic Republic of the Congo
EJ	exajoule
EROEI	energy return on energy invested
EU	European Union
EW	enhanced weathering
FAO	Food and Agriculture Organization of the United Nations
FOE	Friends of the Earth
FOLU	forestry and other land uses
FSB	Financial Stability Board
GBAM	ground-based albedo modification
GBF	[Kunming-Montreal] Global Biodiversity Framework
GCF	Green Climate Fund
GDP	gross domestic product
GEO	Global Environment Outlook
GHG(s)	greenhouse gas(es)
GNI	gross national income
GtC	gigatonne(s) of carbon
$GtCO_2$	gigatonne(s) of carbon dioxide
GW	gigawatt(s)
GWh	gigawatt hour(s)
GWP	global warming potential
ha	hectare(s)
HAC N&P	High Ambition Coalition for Nature and People
IAMs	integrated assessment models
IEA	International Energy Agency
IFL(s)	intact forest landscape(s)
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency

kcal	kilocalorie(s)
LDN	land degradation neutrality
LMICs	low- and middle-income countries
LULUCF	land use, land-use change and forestry
LWI	Land Wealth Index
MRV	measurement, reporting and verification
MW	megawatt(s)
MWh	megawatt hour(s)
NBS	nature-based solution(s)
NBSAPs	national biodiversity strategies and action plans
NDCs	nationally determined contributions
NETs	negative emissions technologies
NFRD	non-financial reporting directive
NGOs	non-governmental organizations
NPP	net primary production
NREL	National Renewable Energy Laboratory
OECD	Organisation for Economic Co-operation and Development
PCA	principal component analysis
PES	payments for ecosystem services
PV	photovoltaic
RCP	Representative Concentration Pathway
REmap	Renewable Energy Roadmap
SCS	soil carbon sequestration
SEEA	[UN] System of Environmental-Economic Accounting
SIC	soil inorganic carbon
SOC	soil organic carbon
TCFD	Taskforce on Climate-related Financial Disclosures
TESSD	Trade and Environmental Sustainability Structured Discussions
TNFD	Taskforce on Nature-related Financial Disclosures
UAE	United Arab Emirates
UNCCD	United Nations Convention to Combat Desertification
UNEA	United Nations Environment Assembly
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
W	watt(s)
WTO	World Trade Organization

Appendix: Supplementary referencing and permissions

Full source details for Table 5 (Chatham House Land Wealth Index and component scores)

Quantity indictors

- **Cropland:** OECD (2019), 'OECD.Stat > Land cover in countries and regions', https://stats.oecd.org/OECDStat_Metadata/ShowMetadata.ashx?Dataset=LAND_COVER (accessed 1 Oct. 2019).
- **Natural and semi-natural vegetated land:** OECD (2019), 'OECD.Stat > Land cover in countries and regions', https://stats.oecd.org/OECDStat_Metadata/ShowMetadata.ashx?Dataset=LAND_COVER (accessed 1 Oct. 2019).
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- **Net primary production:** Peng, D. et al. (2017), 'Country-level net primary production distribution and response to drought and land cover change', *Science of The Total Environment*, 574, pp. 65–77, https://doi.org/10.1016/j.scitotenv.2016.09.033.
- **Biophysical redundancy:** Supplementary data to Fader, M. et al. (2016), 'Past and present biophysical redundancy of countries as a buffer to changes in food supply', *Environmental Research Letters*, 11(5), p. 055008, https://github.com/SESYNC-ci/tfs-data.

Degradation and utilization trend indicators

- **Species habitat loss:** Yale Center for Environmental Law & Policy (2018), '2018 Environmental Performance Index > biodiversity and habitat data', https://epi.envirocenter.yale.edu/2018-epi-report/biodiversity-habitat (accessed 1 Oct. 2019).
- **Tree cover loss:** Yale Center for Environmental Law & Policy (2018), '2018 Environmental Performance Index > biodiversity and habitat data', https://epi.envirocenter.yale.edu/2018-epi-report/biodiversity-habitat (accessed 1 Oct. 2019).
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- **Biophysical redundancy change:** Supplementary data to Fader, M. et al. (2016), 'Past and present biophysical redundancy of countries as a buffer to changes in food supply', *Environmental Research Letters*, 11(5), p. 055008, supplementary data: https://github.com/SESYNC-ci/tfs-data (accessed 1 Oct. 2019).

Risk indicators

- **Carbon content in the topsoil:** FAO (2019) 'Harmonized World Soil Database v 1.2', https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/harmonized-world-soil-database-v12/en (accessed 1 Oct. 2019).

- **Biodiversity and habitat protection:** Yale Center for Environmental Law & Policy (2018), '2018 Environmental Performance Index > biodiversity and habitat data', https://epi.envirocenter.yale.edu/2018-epi-report/biodiversity-habitat (accessed 1 Oct. 2019).

- **Water risk:** World Resources Institute (2019) 'Aqueduct Country and River Basin Rankings', http://www.wri.org/resources/data-sets/aqueduct-country-and-river-basin-rankings (accessed 1 Oct. 2019).

- **Climate exposure:** University of Notre Dame (2019), 'Notre Dame Global Adaptation Initiative > ND-GAIN data', https://gain.nd.edu/our-work/country-index/download-data (accessed 1 Oct. 2019).

Governance and economic capacity indicators

- **Governance:** World Bank (2018), 'DataBank > Worldwide Governance Indicators', https://databank.worldbank.org/reports.aspx?source=worldwide-governance-indicators (accessed 1 Oct. 2019).

- **Gross national income (GNI) per head:** World Bank (2019), 'DataBank > World Development Indicators', https://databank.worldbank.org/data/reports.aspx?source=world-development-indicators (accessed 1 Oct. 2019).

Population indicators

- **Population change:** UN Department of Economic and Social Affairs, Population Division (2017), World Population Prospects: 2017 Revision, https://population.un.org/wpp (accessed 1 Oct. 2019).

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Cover image: People participating in a voluntary afforestation campaign at the edge of the Badain Jaran Desert in Linze County, Gansu Province, on China's 43rd national tree-planting day, 12 March 2021.
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