Regenerative Agriculture

Identifying the impact; enabling the potential

Report for SYSTEMIQ

School of Water, Energy and Environment

17 May 2019

Burgess PJ, Harris J, Graves AR, Deeks LK (2019) Regenerative Agriculture: Identifying the Impact; Enabling the Potential. Report for SYSTEMIQ. 17 May 2019. Bedfordshire, UK: Cranfield University.

Photo on the front page is of an integrated crop, livestock and forest system in the Cerrado region of Brazil (Photo: Paul Burgess)

Table of contents

Executive Summary

The current degradation of biodiversity and soil fertility has led to increasing calls internationally to "reverse the direction of travel" of global agriculture from degenerative to regenerative approaches. The definition of "regenerative agriculture" used in this report is "*a system of principles and practices that generates agricultural products, sequesters carbon, and enhances biodiversity at the farm scale*". Important practices associated with regenerative agriculture are: 1) minimising or avoiding tillage, 2) eliminating bare soil, 3) encouraging plant diversity and 4) water percolation, and 5) integrating on-farm livestock and cropping operations. Some systems also prioritise the minimisation of pesticides and synthetic fertilizers i.e. regenerative organic agriculture. The regenerative systems examined in this report are conservation agriculture; organic crop production and grazing; tree crops; agroforestry including tree-intercropping, multistrata agroforestry and permaculture, and silvopastures; multi-paddock grazing systems, and rewilding. The purpose of the report is to identify the impact of these systems on food production, carbon sequestration and biodiversity enhancement, to determine their current extent, and to explain ways in which they can be scaled.

The opportunities for regenerative agriculture occur in the global context of limited land, an increasing population and demand for food, and the need to reduce greenhouse gases and enhance biodiversity. There is agreement that existing intact ecosystems of high biodiversity need to be protected from agricultural expansion. There is also agreement that reducing waste and constraining per capita consumption of animal products is desirable. Whilst some have contrasted "land sparing" and "land sharing" approaches, there is increasing agreement that enhancement of biodiversity will benefit from land sparing approaches at a range of scales.

Each of the nine regenerative agriculture systems investigated can offer environmental benefits in terms of increased soil and above-ground carbon storage and/or enhanced on-farm biodiversity. Their effects on yield, revenue, and production costs depend on the baseline situation and the specific system. In many situations, conservation agriculture can sustain yields and/or lead to reduced production costs. Adding organic amendments to crops not receiving fertiliser can increase crop yields. Although certified organic production generally reduces crop and livestock yields compared to well-managed non-organic production, securing an organic premium typically results in greater profitability. The effects of agroforestry systems on food production are closely linked to the tree densities and whether the trees also provide feed and/or food. In some places, rewilding can be appropriate.

Regenerative systems are already used on large areas and their extent is increasing. In Section 5, we estimate current global areas and annual rates of expansion of conservation agriculture (180 Mha + 11 Mha/year), certified organic crop production (12 Mha + 1 Mha/year), certified organic grassland (48 Ma + 5.2 Mha/year), tree crops (158 Mha + 2.4 Mha/year), and agroforestry (324 Mha + 2.6 Mha/year). Assuming that 15% of the tree crop, grassland and organic crop systems are also agroforestry, these represent a current area of 689 Mha and a plausible area of 1426 Mha by 2050.

The continued expansion of regenerative agriculture can be supported by actions at international, national and local scales involving policy makers, farmers, researchers, consumers and those

involved in the food chain. Policy-led initiatives such as “4 per 1000” are important. Facilitating market- and consumer-driven processes such as continued expansion of certified organic agriculture, which includes a consumer-derived price premium, is also necessary. The good news is that there are many regenerative agricultural systems that are profitable, sequester carbon, and enhance biodiversity. Globally such systems are becoming more widely adopted.

1 Introduction

The United Nations Sustainable Development Goals (SDGs) provide a comprehensive framework to help decision makers and governments to balance social, economic and environmental challenges up to 2030 (United Nations, 2015). They include targets related to zero poverty (Goal 1), zero hunger (Goal 2), climate action (Goal 13) and life on land (Goal 15). The goals bring together individual sectoral goals such as the United Nations Framework Convention on Climate Change (UNFCCC), and the Convention on Biological Diversity and the Aichi Biodiversity Targets for 2011-2020.

The increasing global demand for food can be met by agricultural expansion (e.g. clearing forest land for crop production) or intensification (e.g. increasing yields from existing crop and grassland) (Tilman et al. 2011). For the past 50 years, the dominant form of agricultural development has been intensification with low consideration of the environmental effects (Pretty et al. 2018). To counter this, "sustainable intensification" is promoted as an approach for increasing food production from existing farmland whilst placing less pressure on the environment and without undermining future production (Godfray and Garnett 2014). The approach is goal-, rather than means-orientated, with the most appropriate form of farming dependent on the context (Garnett et al. 2013).

Recent studies continue to highlight the ongoing decline in global biodiversity (e.g. IPBES 2018b; Sanchez-Bayo and Wyckhuys 2019). One approach has been to protect an increasing proportion of land for conservation (Mehrabi et al. 2018), i.e. increasing from 11.5% (1500 Mha) in 2000 to 15% (2000 Mha) in 2018 (FAO 2019). The Aichi Biodiversity Target 11 specifies a target of 17% for 2020 (Convention on Biological Diversity 2010). A second approach is to promote the ecological intensification of existing agricultural land (Altieri 1999, United Nations 2013, Rodale Institute 2014) to regenerate soils and conserve biodiversity. The process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed is also known as ecological restoration (Society of Ecological Restoration 2004).

In the above context, the structure of the report is:

1) A review of definitions of regenerative agriculture.
2) A review of where "Business as Usual" agriculture is taking us, based on a framework describing the interactions between global population, waste, crop- and animal-based food consumption per capita, mean yields, greenhouse gas emissions and biodiversity.
3) A review and synthesis of the impact of selected regenerative agricultural systems in terms of food production, carbon sequestration and biodiversity.
4) A review of the current extent and rates of expansion of the selected regenerative systems.
5) A review on how regenerative agriculture can be enabled and promoted.
6) A reference list and associated appendices of key evidence related to regenerative agriculture.

2 Definitions of regenerative agriculture

2.1 Introduction

This section reviews the term "regenerative agriculture", examines how it has been used in the literature, and provides a working definition. It then proceeds to identify the key practices and systems.

2.2 Method

Terms like "sustainable agriculture", "climate-smart agriculture" and "agroecology" are widely used in academic literature. However, the term "regenerative agriculture" has not been widely been used in scientific publications. A search in the SCOPUS database of peer-review literature in January 2019 found only 23 papers used the term in the article title, the abstract or key words (Appendix A). We reviewed 20 of the relevant papers to examine the use of the term regenerative agriculture. Regenerative agriculture appears more widely as a term in the grey literature with Google identifying 42,100 pdf documents. The diversity of literature means that there is a wide range of regenerative agriculture definitions. In our review we identify three main ways of defining regenerative agriculture: including 1) a set of practices, 2) which may or may not avoid synthetic fertilizer and pesticides, and 3) a focus on going beyond the reduction of negative impacts to ensure that agriculture has a positive environmental effect.

2.3 Regenerative agriculture as a set of practices

The TED talk by Gabe Brown (2016) provides a good introduction to regenerative agriculture on his farm in northern USA, highlighting the importance of minimising cultivation and bare soil, encouraging diversity and water percolation, and integrating crop and livestock production at a farm-scale. Building on this, five practices that are widely associated with regenerative farming are: 1) abandoning tillage, 2) eliminating bare soil, 3) fostering plant diversity, 4) encouraging water percolation into the soil, and 5) integrating livestock and cropping operations. Practices 1, 2, 3 and 5 are also highlighted by LaCanne and Lundgren (2018).

1) Abandoning tillage: almost all definitions and descriptions of regenerative agriculture highlight the benefits of minimising or avoiding tillage. Minimising tillage reduces the oxidation of soil carbon, leading to higher soil carbon contents and increased water and nutrient holding capacity.
2) Eliminating bare soil: this helps to reduce soil erosion and the increased production of dry matter, such as through cover crops, can again increase soil carbon.
3) Fostering plant diversity: encouraging plant diversity and avoiding monocultures can also lead to greater dry matter production because of the complementarity of light, water, and nutrient use of different crops.
4) Encouraging water percolation into the soil: in many areas, agricultural production is limited by water, and hence there are benefits from increasing the amount of water percolating in the soil. This is an objective of keyline technologies used in Australia (Savory and Duncan, 2016; Duncan 2016).
5) Integrating livestock and cropping operations can be particularly useful in systems where there is a focus on minimising synthetic inputs as the manure from livestock can help maintain soil nutrient levels.

2.4 Regenerative organic agriculture

Pearson (2007) reports that regenerative agriculture seeks to minimize external inputs and negative external impacts outside the farm. Francis et al. (1986) also argue that regenerative agriculture “emphasizes the use of resources found on the farm”, minimising the use of chemical fertilizers and pesticides. Lovins (2016) argues for a “circular economy of the soil” and Brown (2016) also highlights that on his farm they do not use synthetic fertiliser and pesticides (Table 1). California State University (CSU) (2017) also emphasises the negative effects of synthetic fertilisers in terms of energy costs, environmental pollution, and their effect on soil biology.

Table 1. Some definitions of regenerative agriculture include the avoidance or prohibition of synthetic fertilizers and pesticides. This report refers to such a system as regenerative organic agriculture.

Practice	Brown (2016)	Regenerative agriculture		Regenerative organic agriculture
		CSU (2017)	Drawdown (2017)[a]	Rodale Institute (2018)
Minimise tillage	✓	✓	✓	✓
Minimise bare ground	✓	✓	✓	✓
Foster plant diversity	✓	✓	✓	✓
Increase water percolation	✓	✓		
Integrate crops and animals	✓	✓		Optional
Add green manures			✓	
Add compost			✓	
Avoid synthetic fertilizers and pesticides	✓	Minimise	✓	✓

Legend: ✓ means includes; a blank space indicates no data

[a]: Four of the six to be present

Drawdown (2017) identifies methods to reduce global greenhouse gas emissions. The Drawdown Assessment is a comprehensive and useful survey of a range of interventions including estimates of their current extent and potential extent by 2050. Although they recognise a range of regenerative agricultural systems, they use the term “regenerative agriculture” for annual cropping systems that include at least four of the following six practices: no-till or reduced tillage, cover crops, crop rotations, compost applications, green manures, and/or organic production (Table 1). Although their definition includes systems that are not “organic”, the associated technical notes imply that many systems are. A detailed description of regenerative organic agriculture is provided by the Rodale Institute (2018). It is not essential to integrate animals and crops to achieve “regenerative organic agriculture” certification, but the use of synthetic fertilizers and pesticides is prohibited if the label organic is to be applied. The regenerative organic certification scheme builds on USDA’s certified organic standards and has three pillars relating to soil health, animal welfare, and social fairness.

2.5 Regenerative agriculture as farming that enhances

Many current agricultural systems whilst providing safe nutritious food result in reduced soil fertility, carbon storage and biodiversity. Such systems can be termed “degenerative agriculture”. To address this, FAO (2014a) promotes “sustainable agriculture” that “conserves land, water, and plant and animal genetic resources, and is environmentally non-degrading, technically appropriate, economically viable, and socially acceptable” (Figure 1).

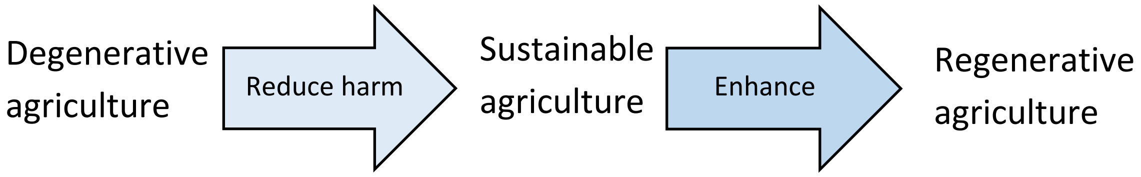

Figure 1. Regenerative agriculture aims to go beyond the “do no harm” principles of sustainable agriculture

Whilst some authors (e.g. Pretty et al. 2018) emphasise that sustainable agriculture also includes environmental enhancement, the specific focus of moving agriculture from being “non-degrading” to being “enhancing” is a particular focus of regenerative agriculture (e.g. Rhodes 2015). The Oxford English Dictionary defines regeneration as the “bringing of new and more vigorous life”. In the same way that many people want their life and their relationships to be more than “just sustainable”, many authors (Table 2) argue for a similar positive vision for agriculture. In the UK, the Food, Farming and Countryside Commission proposes “not just sustaining, but regenerating and restoring ecosystems” (RSA 2018). In some certification programmes, this regeneration extends beyond the environment to include enhanced human communities (General Mills, 2018; Boyer quoted by Reguzzonia 2018).

Table 2. Definitions of regenerative agriculture focused on enhancement

Definitions of regenerative agriculture	Reference
• Farming and grazing practices that, among other benefits, reverse climate change by rebuilding soil organic matter and restoring degraded soil biodiversity – resulting in carbon drawdown and an improved water cycle.	California State University (2017)
• Regenerative agriculture actively builds the “system”, or resource base, it utilises.	Modified from Inwood (2012)
• A system of farming principles and practices that increases biodiversity, enriches soils, improves watersheds, and enhances ecosystem services.	Terra Genesis (2017)
• “Built on biological principles, regenerative agriculture seeks to concurrently enhance productivity and environmental management”.	Sherwood and Uphoff (2000)
• “For the system to be regenerative there must be an increase in both biodiversity and quantity of biomass”	Rhodes (2017)
• “Any system of agriculture that continuously improves the cycles on which it relies, including the human…, the biological…, and the economic community.”	Kevin Boyer quoted by Reguzzonia (2018)
• Agriculture that protects and intentionally enhances natural resources and farm communities.	General Mills (2018)

2.6 Selected regenerative agriculture systems

There are a wide range of potential regenerative agricultural systems and practices. Serle (2017) identified the regenerative capacity of conservation tillage, cover cropping, enhanced crop rotations, residue retention, pasture cropping, and planned grazing. The Ellen MacArthur Foundation and SYSTEMIQ (2017) considered regenerative practices to include permaculture, organic agriculture, no-till polyculture, holistic grazing and keyline land preparation. Building on these together with Toensmeier (2016) and Drawdown (2017), this report examines the extent to which nine systems can be considered as regenerative. Each of the nine systems meets at least two of the three criteria of minimising tillage, minimising bare soil, and fostering plant diversity. The animal-based silvopasture and multi-paddock and organic grazing systems meet all four of the criteria (Table 3).

Table 3. Selected regenerative agricultural systems and how they include five regenerative agriculture practices

System	Minimise tillage	Minimise bare soil	Foster plant diversity	Integrate crops and animals	Synthetic fertilizers/ pesticides
Conservation agriculture	✓	✓			
Organic crop production	✓	✓	✓		×
Tree crops	✓	✓			
Tree intercropping	✓	✓	✓		
Multistrata agroforestry	✓	✓	✓		
Silvopasture	✓	✓	✓	✓	
Multi-paddock grazing	✓	✓	✓	✓	
Organic grassland systems	✓	✓	✓	✓	×
Rewilding	✓	✓			

Legend: ✓ means necessary; × means prohibited; blank space means optional

Conservation agriculture*:* is a cropping system with minimum tillage that ensures retention of crop residue mulch on the soil surface. Some definitions also include the diversification of plant species (Kassam et al. 2019) through intercropping, cover cropping, green manuring, and agroforestry, the integration of manure and organic materials, and judicious use of chemical fertilizers (e.g. Lal 2009).

Organic crop production: the Rodale Institute (2018) uses the term regenerative organic agriculture to describe conservation agriculture that prohibits the use of pesticides and synthetic fertilizers. Whilst regenerative organic agriculture can include animals, it is not a specific requirement. Increased plant diversity is generally a feature of organic systems. Soil health, animal welfare and social fairness are specifically presented as three pillars of regenerative organic agriculture.

Tree crops include tree crops used for food production including nuts, staple fruits (e.g. bananas, plantains, breadfruit, and avocado), fruits (e.g. citrus, apple), and beverages (e.g. coffee, tea, and cocoa). Such tree crops are often planted in orchards or in plantations, but many are also used in agroforestry systems. Drawdown (2017) focused specifically on the role of tropical staple crops on carbon sequestration, but this report examines both temperate and tropical species. Such crops typically minimise tillage and the level of bare soil. Plant diversity may not be high.

Tree intercropping, or silvoarable agroforestry, is the integration of woody perennials with arable or horticultural crops at field scale. The presence of trees reduces the need to cultivate the soil and plant diversity is typically increased.

Multistrata agroforestry is a farming system that integrates different layers of multiple woody perennials often with understorey herbaceous crops. It differs from multistrata forestry as food is an output. The presence of trees means that tillage and bare ground is minimised and plant diversity is increased.

Permaculture, which was coined in the 1970s, is "an integrated, evolving system of perennial or self-perpetuating plants and animal species useful to man" (Mollison and Holmgren, 1981). Holgrem (2002) has also defined permaculture as "consciously designed landscapes which mimic the patterns and relationships found in nature, while yielding an abundance of food, fibre and energy". Whitefield (2011) reports that the inspiration for permaculture is to combine the self-reliance of a wood with the highly edible nature of a wheat field.

Silvopasture is the practice of integrating trees and the grazing of animals in a mutually beneficial way (Rodale Institute 2018). Because grass is largely a perennial crop, tillage and bare soil is minimised, and plant diversity is greater than conventional grassland.

Multi-paddock grazing refers to rangeland management where the grazing unit has livestock on it for less than 10% of the time (Rhodes 2017). It is also known as "holistic planned grazing" (Teague et al. 2013) and has been called a regenerative practice (Lovins 2016; Teague and Barnes 2017). Like most grazing systems it minimises soil tillage and bare ground, but it also includes more complex rotations. It has also been termed "pulse grazing" and a "permaculture approach to rangeland management" (Rhodes 2017).

Organic grazing refers to certified organic livestock systems that prohibit the use of synthetic pesticides and fertilisers.

Rewilding and agricultural land abandonment can mean different things in different locations. In America rewilding generally relates to the restoration of large wilderness areas with a focus on a dominant carnivore such as wolves (Corlett 2016). In this report, we use "rewilding" in the European sense of assisting the "regeneration of natural habitats through passive management approaches" (Navarro and Pereira 2015), which has also been termed "ecological rewilding". Rewilding is likely to minimise the extent of bare soil and it can include food production (Lorimer et al. 2015).

2.7 Conclusions

The definition of regenerative agriculture used in this report is "*a system of principles and practices that generates agricultural products, sequesters carbon, and enhances biodiversity at the farm scale*". This definition is very close to the definition of organic agriculture which has been defined as "a production management system which promotes and enhances agroecosystem health, including biodiversity, biological cycles, and soil biological activity" (FAO and WHO 1999). However organic agriculture specifically avoids the use of synthetic fertilizers and pesticides (FAO and WHO 1999).

An attraction of the term regenerative agriculture is that it provides an engaging narrative to promote change. In a similar way that a “circular” economy approach contrasts with a “linear” economy, regenerative agriculture can be contrasted with degenerative agricultural practices that degrade the soil and reduce biodiversity. Important practices associated with regenerative agriculture are: 1) abandoning tillage, 2) eliminating bare soil, (3) encouraging plant diversity and 4) water percolation, and 5) integrating livestock and cropping operations. Some proponents of regenerative agriculture emphasise the need 6) to minimise inputs, including synthetic fertilizer and pesticides. Systems that purport to regenerate agriculture are conservation agriculture; regenerative organic agriculture for cropland and grassland; tree crops; agroforestry systems including tree-intercropping, multistrata agroforestry and permaculture, and silvopasture; multi-paddock grazing; and rewilding. Each of these systems includes at least two of the first three regenerative agriculture practices. The context for the uptake of regenerative agriculture is described in Section 3, and the impact of each system is considered in Section 4.

3 Context for regenerative agriculture

3.1 Introduction

There are increasing calls to “reverse the direction of travel” regarding land management (Kotiaho et al. 2016; Pandit et al. 2018) in order to restore natural capital and the ecosystem services which flow from them. This section explains the principal land use implications of a drive to increase food production, reduce greenhouse gas emissions and enhance biodiversity. It highlights that regenerative agriculture is more likely to be successful if it implemented alongside initiatives to protect existing intact ecosystems, reduce food waste, and constrain per capita consumption of animal products. The final paragraphs examine the role of land sharing and land sparing.

3.2 Linking land, food demand and production

An improved understanding of the challenges of food production and land use can be developed by being aware of the current status of the finite global land resource. There are many ways of describing global land use (e.g. Hurtt et al. 2011; Chang et al. 2016), but the analysis by Smith et al. (2014) divides land use into five major categories. Using a 2000 baseline, the sum of ice-free land (13000 Mha) can be categorised as urban (200 Mha), cropland (1300 Mha) plus fallow (200 Ma), grassland (4600 Mha), forest (4100 Mha), or unused (2600 Mha) (Figure 2). Depending on whether extensive grazing is included, agriculture covers between 38% and 47% of the land area.

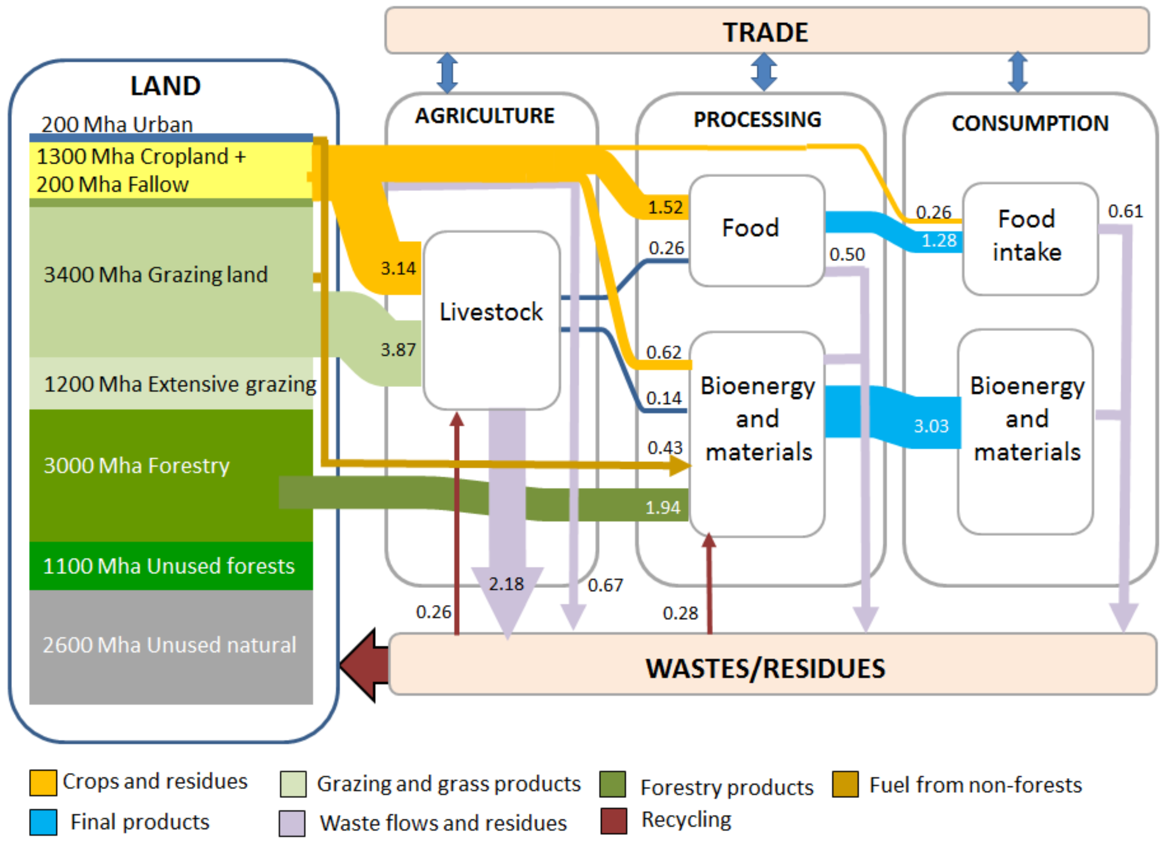

Figure 2. Global land use and arising biomass flows for human use in 2000. Values are in Gt dry matter biomass/yr (after Smith et al., 2014). The areas are from Erb et al. (2007) and flows from Wirsenius (2003). Cropland includes arable and permanent crops.

3.2.1 Land use in 2000

As shown in Appendix B, the required area of cropland and grazing land can be related to the global population, the degree of wastage, the per capita demand for different types of food and other products, the efficiency of the conversion of crops and grass to animal products, and the yield of grass and crops per hectare. Using the values in Table 4 and simple algorithms (Table B.1) it is possible to demonstrate that in 2000, the demand for animal products required 3400 Mha of grazed grassland to generate a harvested dry matter yield of 1140 kg/ha. In a similar way, the global demand for crop products required 1300 Mha of cropland to generate a harvested dry matter yield of crop and crop residues of 4260 kg/ha (Table 4; Table B.2).

Table 4. Indicative areas of cropland and grazing land in 1900, 1950, 2000 and assumed areas required for a default and a diet-related scenario in 2050 (Derived from Smith et al. 2014 and Krausmann et al. 2008). A detailed explanation of the values is provided in Appendix B in Table B.3.

Year	World population (billion)	Level of food waste (%)	Crop-based demand per capita (kg DM/capita/y)	Animal product-demand (kg DM/capita)	Crop used for animal production (kg DM/capita)	Cropland area (million ha)	Mean crop and crop residue yield (kg DM/ha)	Demand for grass feed per capita (kg DM/capita)	Assumed harvest of grass (kg DM/ha)	Grazed land area (million ha)	Total managed (million ha)
1900	1.65	30	390	18.6	224	758	**1336**	277	**312**	1466	**2224**
1950	2.50	30	390	18.6	224	1083	1417	277	259	2666	3743
2000	6.15	30	390	**42.3**	510	**1300**	**4260**	629	**1137**	**3400**	**4700**
2050 default	*9.77*	*30*	*390*	***56.0***	*675*	***1600***	***6503***	*833*	***2000***	***4070***	*5107*
2050 diet	*9.77*	*30*	*390*	***42.3***	*510*	*1352*	*6503*	*629*	*2000*	*3072*	*4398*

Values in bold are mentioned in the text; italicised values are scenario estimates for 2050.

3.2.2 Land use from 1900 to 2000

Before examining where current agricultural trends are taking us, it is useful to look at where we have come from. The global population increased from 1.65 billion in 1900 to 6.15 billion in 2000, and Table 4 suggests that this was associated with an estimated 111% increase in the global area of managed land from 2224 Mha in 1900 to 4700 Mha in 2000, with 78% of the increase related to a greater area of grazed grassland. The analysis also suggests a trebling of mean crop and crop residue yields from 1336 kg/ha in 1900 to 4260 kg/ha in 2000; similarly the mean yield of grass from grazed areas increased almost four-fold from 312 kg/ha in 1900 to 1137 kg/ha in 2000. A trebling of annual yields over a 100 year period can be achieved by an annual yield increase of 1.1%. In fact the values in Table 4 suggest that prior to 1950 the yield increases were minimal but between 1950 and 2000 crop and harvested grass yields showed a mean annual increase of 2.2% and 3.0% respectively. These increases were achieved through: 1) improved varieties or breeds of crops and livestock, 2) improved crop or livestock nutrition, 3) improved husbandry (e.g. less disease and pests, and more effective management), and 4) planting or growing crops and livestock in the correct place. Against this, the predicted net effect of climate change on mean yields, even allowing for a positive effect of increased carbon dioxide concentrations, is about -0.1% per year (IPCC 2014; page 506). These yield increases have enabled food prices to remain relatively low so that absolute and relative undernourishment has decreased and internationally food riots are relatively rare (Berazneva and Lee 2013).

3.2.3 Land use from 2000 to 2050

Looking forward to 2050, the global population is predicted to grow to 9.77 billion and the mean annual consumption of animal products has been predicted to increase from 42.3 kg/capita to 56.0 kg/capita (Table 4). The default calculation indicates that one way to address this is to expand the area of cropland from 1300 Mha in 2000 to 1600 Mha in 2050 and for mean crop and crop residue yields to increase from 4260 kg/ha to 6503 kg/ha (equivalent to a 0.85% annual increase). Similarly the area of grazed grassland could increase from 3400 Mha to 4070 Mha with harvested yields increasing from 1137 kg/ha to 2000 kg/ha (equivalent to a 1.1% annual increase). It has been argued that the application of existing knowledge and technology could lead to 100-200% yield increases in many parts of Africa, and a 100% increase in Russia (Foresight 2011 page 16).

The demand for land can be moderated by changes in diet. If the global per capita consumption of animal products in 2050 remains at the 2000 level of 42.3 kg/person/year then, assuming the same yield per hectare increases, there is minimal need to expand the area of cropland and the area of grazed land could actually decrease (Table 4). This is due to the high quantities of grass and crops needed to produce animal products. Although Mottet et al. (2016) reports that about 86% of the materials eaten by livestock are not currently eaten by humans, stabilising per capita consumption of meat products will have major effects on future land use (e.g. Wirsenius et al. 2010). There are also potential health benefits from reducing meat consumption in developed countries (Whitmee et al. 2015; Willett et al. 2019). The analysis in Table 4 also highlights the benefits from reducing waste, assumed to be 30%.

3.3 Carbon sequestration and greenhouse gas emissions

Agriculture, Forestry, and Other Land Use (AFOLU) is responsible for about a quarter of global greenhouse gas (GHG) emissions (~10 billion t CO_2eq/yr), and about half is due to land use change (4.3–5.5 billion tCO_2eq/yr in 2010) (Smith et al. 2014).

Using the land areas in Table 4 for crops (A_{crop}), grass (A_{grass}) and forests (A_{forest}) and making indicative assumptions about mean above-ground and soil carbon storage per land use (e.g. C_{crop}), it is possible to estimate the carbon storage (C_{total}) and thereby the possible changes in storage (Table 5).

$$C_{total} = A_{crop}\, C_{crop} + A_{forest}\, C_{forest} + A_{grass}\, C_{grass}$$

Such analyses highlight the importance of minimising losses of forest and wooded land to reduce the release of carbon dioxide. The net annual carbon changes of 0.3 to 1.2 Gt C, equate to 1.1 to 4.4 Gt CO_2, which is comparable to the calculated annual loss of 5.9 ± 2.9 Gt CO_2eq from land use change during the 1990s (Flynn et al. 2011). Other sources of agricultural emissions (~5.2 billion t CO_2eq/yr) include poor soil management (~1.5-2 billion t CO_2eq/yr) and enteric fermentation by cattle (2 Gt CO_2eq/yr) (Smith et al. 2014). Agriculture-related fossil fuel emissions (included in energy figures) amounted to ~0.5 Gt CO_2eq/yr in 2010 (Smith et al. 2014).

Table 5 Indicative analysis of how the land use changes in Table 4 could affect carbon storage

Year	Area (Mha)						Above-ground storage (billion t C)[b]	Total SOC storage (billion tonnes)[c]	Net carbon loss (Gt C y^{-1})[c]
	Crop land	Grazed land	Total grass land	Forest and woods	Unused, fallow and urban[a]	Total			
1900	758	1466	4542	4700	3000	13000	700	2332	
1950	1083	2666	4617	4300	3000	13000	648	2324	1.2
2000	1300	3400	4600	4100	3000	13000	621	2318	0.8
2050	*1600*	*4070*	*4300*	*4100*	*3000*	*13000*	*621*	*2304*	*0.3*

[a]: Estimates of forest cover in 1900 and 1950 are derived from Ramankutty et al. (2006).

[b:] Values for 2000 from Smith et al. (2014)

[c]: Assumes cropland above- and below-ground C (5 + 142) is 147 t C ha^{-1}, and grassland C (7 + 189) is 196 t C ha^{-1} (Houghton (1999). The mean forest above ground dry matter is assumed to be 137 t C ha^{-1} (Houghton, 1999). It is assumed that the mean soil C content under forest is 10% lower than for grassland i.e. 170 t C ha^{-1} (Guo and Gifford, 2002). This is higher than the mean of 121 t C ha^{-1} for forest soils proposed by Houghton (1999).

3.4 Biodiversity

Recent studies have highlighted the continued decline in global biodiversity (e.g. IPBES 2018b; Sanchez-Bayo and Wyckhuys 2019). The current global decline in biodiversity has been driven by land use change (Sala et al. 2000; Wilting et al. 2017) and the increasing intensity of land use (Alkemade et al. 2009). One method for expressing the effect of land use on biodiversity is in terms of the mean species abundance (i.e. the ratio of the mean species abundance relative to the original abundance). The mean species abundance can range from 1.0 in primary forests and grassland to 0.1 and below for intensive agriculture and urban areas (Table 6). These values highlight the conservation benefits of preserving areas of primary habitat. However some agricultural methods such livestock grazing on unimproved pasture (e.g. rangeland systems), agroforestry, and mosaics of crops and native trees can still maintain relatively high levels of biodiversity.

Table 6. Relationship between global land use and mean species abundance, with intact areas of forest and grass and shrubland given a value of 1 (Alkemade et al. 2009)

Land use	Mean species abundance	Standard error
Forest (Primary vegetation)	1.0	0.1
Forest (lightly used naturally occurring tree species)	0.7	0.07
Forest (Secondary vegetation with different cover)	0.5	0.03
Forest (Plantation with exotic species)	0.2	0.04
Grass and shrubland (Primary vegetation)	1.0	<0.01
Grass and shrubland (Wildlife replaced by livestock grazing)	0.7	0.05
Man-made pasture including forests converted to pasture	0.1	0.07
Agroforestry and mosaics of crops and native trees	0.5	0.06
Low-input agriculture	0.3	0.12
Intensive agriculture	0.1	0.08
Urban area	0.05	

The mean species abundance is also responsive to the level of excess nitrogen; for example it can decline by 40% when the surplus nitrogen changes from 0 to 50 kg N/ha (Alkemade et al. 2009). The mean species abundance is also a function of patch-size, with mean species abundance reducing from about 0.8 with a patch size of 10,000 ha to less than 0.1 with a patch size of less than 100 ha (Alkemade et al. 2009).

3.5 Land sparing and land sharing

The above paragraphs frame the use and promotion of regenerative agriculture in the context of the global challenges of population growth, the demand for food, climate change, and biodiversity loss. Within the scientific literature there is often a debate between the benefits of "land sparing" (where large reserves are set aside for conservation and other ecosystem services delivery) and "land sharing" approaches (where on-farm practices increase on-farm biodiversity) (POST, 2012; Hobbs et al. 2014). Sections 3.3 and 3.4 highlight that a key component of a global drive to store carbon and enhance biodiversity (particularly for specialist species) is to protect existing primary forests and grasslands in large non-fragmented areas i.e. land sparing is necessary. The current proportion of land protected because of their biodiversity and associated ecosystems services is 15% (FAOSTAT 2019), which is close to the 17% specified in the Aichi targets (Convention on Biological Diversity 2010).

Assuming the above need for protected areas, the question is then how sufficient food can be provided on the existing farmland. The analysis highlights that demand-reduction strategies such as minimising waste and constraining per capita consumption of animal products can reduce the required yield increases per hectare. Assuming that mean per capita meat consumption remains at its current level, the global mean annual yield increase required per hectare is about 1%. For the next 30 years with good governance, such yield increases should be exceeded in regions like Russia and Africa where yields are currently low. In areas like Oceania, North America and Western Europe where yields are currently high, despite the increasing global demand for food, agricultural land is actually being abandoned (See Section 5.2.4). In such regions, there are options to either focus on either increased food production on a smaller area, or to continue the production of food whilst improving carbon sequestration and biodiversity on the same area of land.

Recently some authors argue that in practice the choice is not between land sparing and land sharing, but that land sparing needs to implemented at a range of scales e.g. multiple-scale land sparing (Kremen 2015; Ekroos et al. 2016). At a field- or farm-scale, this may include a range of diversified and regenerative farming systems (Kremen et al 2010; Loos and von Wehrden 2018). Sparing land at field-scale, such as providing refuge for pollinators, can also provide yield benefits. The success of land sparing from a conservation perspective also depends in part on ensuring that, for example, "spared land" actually enhances biodiversity (Balmford et al. 2018), and it may depend on spatial differences in the environmental and agricultural suitability of land (Grau et al. 2013).

The rest of this report focuses on selected regenerative agricultural systems that combine agricultural production, with reduced greenhouse gas emissions, and enhanced biodiversity at the farm-scale.

4 Impacts of regenerative agriculture systems

4.1 Introduction

The eventual success of regenerative agriculture systems does not rest on their promise, but on their capacity to deliver on the ground. Some people are sceptical. For example, McGuire (2018) has defined regenerative agriculture as "conservation agriculture and holistic grazing plus exaggerated claims". This section reviews the evidence regarding the impact of the selected systems.

4.2 Method

For each regenerative agricultural system we developed a spreadsheet of evidence based on published literature (Appendix C). Building on the review in Section 3, there was a particular focus on the effect of the system on crop and livestock yields, greenhouse gas emissions, and biodiversity. The effect on water storage was not specifically examined. The number of references was greatest for conservation agriculture (n = 21) and organic agriculture (n = 33) and least for tree crops (n = 6). The analysis of the level of confidence was based on the IPBES "four-box" model for qualitative communication of evidence (IPBES 2017, 2018a). The definitions of the terms relating to confidence are:

Inconclusive: existing as or based on a suggestion or speculation; no or limited evidence.

Unresolved: multiple independent studies exist but conclusions do not agree.

Established but incomplete: general agreement although only a limited number of studies exist but no comprehensive synthesis and, or the studies that exist imprecisely address the question.

Well established: comprehensive meta-analysis or synthesis or multiple independent studies that agree.

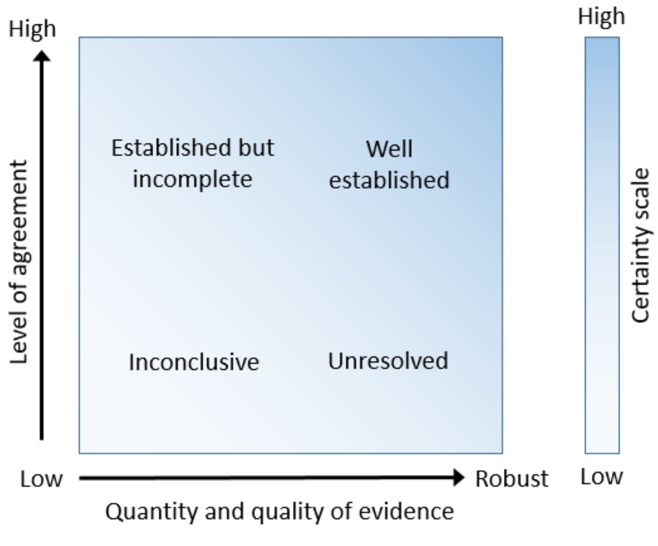

Figure 3. Four box model of the level of agreement and the quantity and quality of evidence (IPBES, 2018a).

An important part of the method was to define a specific base-line or counterfactual for each intervention. For example organic agriculture may only provide mean yields of 0.68-0.90 of a well-fertilised and well-managed non-organic system (Lesur-Dumoulin et al. 2017). However, it can provide a yield equivalent to 1.43 to 1.87 of a non-fertilised control plot of sorghum in Africa

(Tonitto and Ricker-Gilbert 2016). It is also important to note that the analyses focus on the **mean** response. For example, Lesur-Dumoulin et al. (2017) in a global meta-analysis also reported that whilst the mean yields of organic horticultural crops were 0.68 to 0.90 of non-organic crops, there was variation: with 10% of incidence resulting in only 50% of the yield, and a 20% chance of higher yields.

4.3 Results

Each of the nine regenerative systems leads to increases in soil carbon and similar or enhanced levels of on-farm biodiversity (Table 8). However their effect on yields, input costs, and tree carbon and products varies according to the specific system and the baseline comparison. Each is considered in turn.

4.3.1 Conservation agriculture

We reviewed 21 papers that quantified the impact of conservation agriculture or more specifically the effect of no tillage relative to conventional tillage (See Table C.1 in the Appendix). The main impacts are described in Table 7 and below with the quality of evidence indicated in brackets. Because large areas of conservation agriculture depend on the use of glyphosate (Schmitz and Garvert 2012), the current risk of a glyphosate ban in some countries is an area for further research.

Soil carbon: the lack of tillage associated with conservation agriculture leads to increases in soil carbon in the surface layers (Well established). For example Haddaway et al. (2017) report a 9% increase in soil organic carbon at a depth of 0-30 cm. However there is no clear evidence that it increases soil carbon below the surface layers (Well established).

Biodiversity: Doran (1980) reports that the level of soil biodiversity in the top 7 cm of soil increased with no-tillage, but that it decreased below 7 cm (Established but incomplete).

Table 7. Impacts of conservation agriculture, and specifically no-tillage (NT) relative to conventional tillage (CT)

Statement	Confidence	Effect
Soil carbon: NT, relative to CT, increases soil carbon in surface layers	Well established	Benefit
NT and CT result in similar levels of soil carbon below 20 cm	Well established	Similar
Biodiversity: NT, relative to CT, increased diversity in surface layers but decreased it at depth	Established but incomplete	Similar
Yields: NT and CT result in similar mean yields of oilseed and cotton	Well established	Similar
NT and CT results in similar mean yields of maize and wheat under dry unirrigated conditions	Well established	Similar
NT, compared to CT, reduces mean yields of root crops	Well established	Disadvantage
NT, compared to CT, reduces mean yields of maize and wheat when there is no or minimal drought stress	Well established	Disadvantage
Other: NT and CT have similar greenhouse gas emissions per unit food	Unresolved	
NT, relative to CT, reduces fuel costs	Well established	Benefit
NT, relative to CT, increases farm profitability	Inconclusive	
References reviewed for no-tillage: Alluvione et al. (2009); Bayer et al. (2015); Blanco-Canqui and Lal (2008); Doran (1980); Drawdown (2017); Fernandez (2016); Haddaway et al. (2017); Halvorson and Grosso (2009); Huggins and Reganold (2008); Hutchinson et al. (2007); Mathew et al. (2012); Metay et al. (2009); Passianoto et al. (2003); Pittelkow et al. (2015); Potter et al. (1997); Robertson et al. (2000); Roldan et al. (2004); Smith et al. (1998); Tuomisto et al. (2013); VandenBygaart et al. (2003); West and Post (2012)		

Table 8. Indicative main effects of nine regenerative systems (expressed as effect of intervention divided by baseline) with illustrative references

Regenerative Intervention	Counterfactual or baseline	Soil carbon	On-farm biodiversity	Mean crop, grass or livestock yield	Input costs	Tree carbon and products
Conservation agriculture	Crop production with intensive tillage	1.09 (Haddaway et al. 2017)	~1.00 (Doran 1980)	0.86-1.01 (Pittelkow et al. 2015)	Lower (Huggins and Reganold 2008)	0
Regenerative organic (e.g. organic crop production with organic amendments)	Crop production with fertilizers and/or agrochemicals	1.07-1.09 (Mondelaers et al. 2009; Tuomisto et al. 2012)	1.30-1.50 (Bengtsson et al. 2005)	0.48-0.92 (Clark & Tilman 2017; Cooper et al. 2016)	Lower to higher (LaCanne and Lundgren 2018; Crowder and Reganold 2015)	0
	Crop production with no amendments or fertilizers	1.07-1.09 (Mondelaers et al. 2009; Tuomisto et al. 2012)	Inconclusive	1.01-1.07 (Hijbeek et al. 2017)	Higher (Crowder and Reganold 2015)	0
Tree crops	Annual crop production	1.18 (Guo and Gifford 2002)	Higher (Simon et al. 2010)	0.75-1.60 (Bidogeza et al. 2015)	Inconclusive	Higher
Tree intercropping	Annual crop production	1.16 (Kim et al. 2016)	1.37 (Torralba et al. 2016)	0.42-1.00[a] (Garcia de Jalon et al. 2018a)	Lower to higher (Garcia de Jalon et al. 2018b)	Higher
Multistrata agroforestry	Monoculture permanent crops	1.57 (Zake et al. 2015)	Higher (De Beenhouwer et al.2013)	Variable (Niether et al. 2019)	Inconclusive	Higher
Silvopasture	Grassland	1.00-1.18 (Upson et al., 2013; Seddaiu et al. 2018)	1.21 (Torralba et al. 2016)	0.77-1.18[a] (Seddaiu et al. 2018) (Torralba et al. 2016)	Similar to higher (Garcia de Jalon et al. 2018b)	Higher
Multi-paddock Grassland	Grassland; continuously grazed	0.99-1.50 (Sanderman et al. 2015; Teague et al. 2011)	Inconclusive	0.98-1.00[b] (Hawkins 2017) (Derner and Hart 2007)	Higher (Hawkins 2017)	0
Grassland receiving organic fertiliser but not synthetic fertilizer	Grassland: receiving synthetic fertilizer	1.20 (Kidd et al. 2015)	Higher (Mueller et al. 2014)	0.70-1.50 (Mueller et al. 2014) (Kidd et al. 2015)	Inconclusive	0
	Grassland: receiving no fertilizer	1.30 (Gravuer et al. 2019)	0.94 (Gravuer et al. 2019)	1.98 (Gravuer et al. 2019)	Inconclusive	0
Rewilding and abandonment of agriculture	Crop and grazing systems	Higher (Conant et al. 2001)	Variable (Rey Benayas et al. 2007) (Lasanta et al. 2015)	0.11-0.80 (Cerqueira et al. 2015) (derived from Spencer 2017)	Inconclusive	Higher

[a]: Crop and grass yield responses in agroforestry are very sensitive to number of trees per unit area;
[b]: Whilst grass production may be similar; multi-paddock systems may allow higher stocking rates.

Positive effect: [dark green] Positive/similar: [light green] Similar or very variable: [yellow] Similar or negative: [orange] Negative: [red]

Yield: Pittelkow et al. (2015) in a global meta-analysis reports that conservation agriculture results in mean yields that were 86% to 101% of those obtained with tillage. They reported similar yields for oilseeds, legumes and cotton, and under dry conditions for maize and wheat (Well established). One reason for this is improved soil moisture retention. However in other environments there was typically a yield loss (Well established). Possible reasons for this include poorer seed-soil contact at establishment and weed control (Giannitsopoulos et al. 2019). Compared to this, the mean 8% yield benefit of conservation agriculture relative to conventional agriculture quoted by Drawdown (2017) seems high. The reason for the discrepancy may be the choice of case-studies used by Drawdown.
Other: there was no consistent reported effect on greenhouse gas emissions (Unresolved), with a tendency for CO_2 emissions to reduce and N_2O emissions to increase. Conservation agriculture typically results in lower machinery and fuel costs associated with no tillage relative to ploughing (Well established). We did not find clear evidence of the effect of conservation agriculture on farm profitability (Inconclusive), but the combination of similar yields with reduced costs means that it is financially profitable in some places. In fact in many regions, conservation agriculture is now viewed as “conventional” agriculture (Pretty 1995, page 208).

4.3.2 Organic crop production

Management: a European meta-analysis by Tuomisto et al. (2012) found that organic, compared to non-organic, farms apply a higher level of organic amendments (Table 9).
Soil carbon: Across a wide range of systems, organic agriculture results in a higher level of soil organic carbon (Well established). However it should also be noted that the application of chemical fertilizer (Han et al. 2016) increases soil organic carbon relative to adding no fertiliser (Well established) (Box 1; Table 9; Table C.2 in the Appendix).

Box 1: Organic amendments and chemical fertilizers both increase soil carbon relative to no addition
Levels of soil organic matter depend primarily on the annual organic matter input either from plant inputs or animal manure. Greenland (1997) reported that nutrients removed by a crop need to be replaced in some way and that any other approach will be a “dangerous illusion” unless it can do this. Smaje (2018) notes that “anecdotal claims that crops will do better without synthetic fertiliser are all very well, but such claims have to stay on amber until more quantitative data is forthcoming”.

Our review demonstrates that the overall effect of adding organic amendments (compared to no amendment) is to increase soil organic matter levels. A recent meta-analysis by Han et al. (2016) indicates that the overall effect of adding chemical fertilizers (compared to no fertilizer) is to increase soil organic matter, due to increased dry matter production. However over a period of time, although adding fertiliser is better than adding no fertiliser, the soil organic matter below arable crops can still decline due to cultivation and the enhanced activity and respiration of soil organisms (Khan et al. 2007). Van Groenigen et al. (2017) also note that a global drive to increase soil organic carbon will need increased levels of soil nitrogen. Syers (1997) argues that in most cases both inorganic and organic inputs are beneficial.

Biodiversity: Studies such as Bengtsson et al. (2005) and Lichtenberg et al. (2017) have demonstrated that organic systems increase the on-farm diversity of birds, soil invertebrates, and arthropods including pollinators (Well established). However in terms of crop yields this also includes the presence of weeds (Well established). We did not find evidence of the effect of adding organic amendments on the biodiversity of non-fertilised cropland (Inconclusive).

Yields: studies such as Cooper et al. (2016) and Clark and Tilman (2017) demonstrate that organic crop production generally results in yields between 48% and 92% of those achieved in well-managed conventional farming systems well-supplied with nutrients (Well established) (Table 9). At a national level, Smith et al. (2018) modelled the effect of an immediate conversion of all agriculture in the UK to organic production. They predicted a change in the product mix and that the total national food output, in terms of metabolisable energy, would be 64% of that under conventional farming.

Nitrogen is typically the limiting nutrient in organic systems (Seufert et al. 2012) and Connor (2018) argues that the yield penalty can be larger if there is a need to include nitrogen-fixing legumes (which would otherwise not be required) within a rotation. Such yield penalties contrast with the 8% benefit of converting from conventional arable cropping to regenerative agriculture assumed by Drawdown (2017) derived from three unspecified sources.

Table 9. Impact of organic crop systems (OS) relative to non-organic systems (non-OS)

Statement	Confidence	Effect
Management: OS tends to receive higher organic inputs than non-OS	Established but incomplete	
Soil carbon: OS tends to have higher soil carbon levels than non-OS	Well established	Benefit
Chemical fertiliser increases soil carbon relative to adding no fertilizer	Well established	Benefit
Biodiversity: OS have higher levels of abundance and species richness of birds, soil organisms, and arthropods than non-OS	Well established	Benefit
OS have higher levels of weeds than non-OS	Well established	Disadvantage
Effect of adding organic amendments to nutrient-stressed crops	Inconclusive	
Yields: OS are lower than those of well-fertilised non-OS	Well established	Disadvantage
Adding organic amendments increases yields of non-fertilised crops	Well established	Benefit
Under non-nutrient stress conditions, adding organic amendments increases potato and maize yields	Established but incomplete	Benefit
Under non-nutrient stress conditions, adding organic amendments resulted in similar yields for winter cereals	Established but incomplete	Similar
Other environmental: OS and non-OS has similar GHG emissions per unit food	Unresolved	
OS and non-OS have similar nitrate leaching per unit area	Unresolved	
Economic: OS uses less energy per unit hectare than non-OS	Well established	Benefit
OS have higher labour requirements and costs than non-OS	Well established	Disadvantage
OS provide lower margins if there is no premium for the product	Well established	Disadvantage
OS provide higher margins than non-organic systems if there is a premium for the product	Well established	Benefit
References for organic crop systems: Abeliotis et al. (2013); Aguilera et al. (2013); Bengtsson et al. (2005); Clark and Tilman (2017); Cooper et al. (2016); Crowder and Reganold (2015); Diop (1999); Drawdown (2017); Drinkwater et al. (1998); Elshout et al. (2014); Gomiero et al. (2001); Han et al. (2016); Hanson et al. (1997); Hijbeek et al. (2017); Kamenetsky and Maybury (1989); Knudsen (2011); Korsaeth (2012); Kranmer et al. (2006); Lichtenberg et al. (2017); LaCanne and Lundgren (2018); Lesur-Dumoulin et al. (2017); Lin et al. (2017); Metcalfe and McCormack (2000); Mondelaers et al. (2009); Ponisio et al. (2014); Rahmann (2011); Robertson et al. (2000); Seufert et al. (2012); Skinner et al. (2014); Tonitto and Ricker-Gilbert (2016); Tuomisto et al. (2012); VandenBygaart et al (2003); Ziesmer (2007).		

The counterfactual is important in describing the yield response. The addition of manure and organic amendments can increase crop yields compared to fields where no other nutrients and amendments are added (Well established; e.g. Pretty, 1996; Tonitto and Ricker-Gilbert 2016), such as in sub-Saharan Africa where in 1996 most soils were losing the equivalent of 22 kg N and 17 kg P per hectare per year (Vlek et al. 1997). However, even in developing countries, the yield loss in organic systems, relative to generally high input conventional systems, can still be large (Seufert et al. 2012). A recent meta-analysis of data from Europe indicated that adding organic amendments increased the yields of some crops such as potatoes and maize under non-nutrient stress conditions, but other crops such as winter-sown cereals did not show a benefit (Hijbeek et al. 2017).

Other environmental: the effect of organic agriculture (compared to non-organic agriculture) on net greenhouse emissions per hectare tends to be more positive when expressed per unit area rather than per unit food, because of the generally lower crop yields. However a recent meta-analysis by Clark and Tilman (2017) suggests that the overall effect of organic agriculture on net greenhouse emissions per unit food is generally similar to non-organic farming, with some studies showing benefits and some disadvantages (Unresolved). The net effect of organic, relative to non-organic, agriculture on nitrate leaching, eutrophication, and acidification is also largely unresolved.

Economic: meta-analyses such as Clark and Tilman (2017) indicate that organic, relative to non-organic practices, require less energy per unit food and increase the energy-use efficiency of agriculture (Well established). This is primarily by avoiding the use of synthetic fertilisers, as energy use can increase in organic systems. There is also evidence (e.g. Crowder and Reganold 2015) that organic systems require more labour than non-organic systems (Well established). The meta-analysis by Crowder and Reganold (2015) indicates that organic agriculture leads to reduced profitability if there is no organic premium for the final product. However where there is a premium, this is generally sufficient to overcome the shortfall with the effect that most organic systems are more profitable (Well established).

4.3.3 Tree crops

Our assumption is that new areas of tree crops are grown on existing areas of annual crop production.

Soil carbon: soil carbon under tree crops can be greater than that achieved with annual crop production (Guo and Gifford 2002), but the actual level of response will depend on the soil management regime which can range from regular tillage to the use of cover crops (Vicente-Vicente et al. 2016) (Established but incomplete). For example, vineyards can be susceptible to soil erosion (Maetens et al. 2012).

Table 10. Impacts of tree crops relative to arable cropping (AC)

Statement	Confidence	Effect
Soil carbon: Tree crops increase soil carbon relative to AC, but can vary according to soil management.	Established but incomplete	Benefit
Biodiversity: Tree crops increase biodiversity relative to AC	Established but incomplete	Benefit
Yields: Tree crops increase calorie production relative to AC	Unresolved	Benefit
Tree crops decrease protein production relative to AC	Unresolved	Disadvantage
Other environmental: Tree crops increase above-ground carbon storage relative to AC	Well established	Benefit
Tree crops have similar N_2O emissions compared to AC	Established but incomplete	Similar
Economic: Tree crops increase profitability relative to AC	Established but incomplete	Benefit
References: Bidogeza et al. (2015); Guo and Gifford (2002); Kim et al. (2016); Mutuo et al. (2005); Simon et al. (2010); Vicente-Vicente et al. (2016)		

Biodiversity: Simon et al. (2010) argue that orchards contribute to biodiversity, relative to other arable systems, because of their permanency and multi-strata design. However even organic orchard systems can receive high levels of pesticide application (Katayama et al. 2019). The biodiversity effects of planting tree crops, for example coffee or oil palm, on existing primary forest land is negative (Philpott et al. 2008; Fitzherbert et al. 2008).

Yield: the effect of tree crops on yield is dependent on the specific perennial crop and the baseline arable crop. For example a modelling study in Rwanda (Bidogeza et al. 2015) indicated that bananas increased the calorie production and reduced the protein production relative to maize.

Other environmental: tropical tree crops will increase above-ground carbon storage relative to arable systems (Table 10). Kim et al. (2016) report that a plantation of tropical staple trees did not have a significant effect on nitrous oxide emissions (Established but incomplete).

Economic: a study in Rwanda (Bidogeza et al. 2015) indicated that bananas resulted in greater margins than maize, but that they also required greater labour input and investment.

4.3.4 Tree-intercropping

Tree-intercropping, also known as silvoarable agroforestry and alley cropping, refers to the integration of trees with arable crops.

Soil carbon: there is evidence that tree intercropping systems increases soil carbon levels relative to conventional arable cropping, primarily in the uncultivated areas next to the trees (Established but incomplete) (Table 11 and Table C.4 in the Appendix).

Table 11. Impacts of tree intercropping (TI) relative to arable cropping (AC)

Statement	Confidence	Effect
Soil carbon: TI increases soil carbon relative to arable cropping (AC)	Established but incomplete	Benefit
Biodiversity: TI increases biodiversity relative to AC	Well established	Benefit
Yield: High tree density TI decreases arable yields compared to AC	Well established	Disadvantage
Low tree density TI may result in similar crop yields compared to AC	Established but incomplete	Similar
Other environmental: TI increases above-ground carbon relative to AC	Well established	Benefit
TI reduces soil erosion losses relative to AC	Well established	Benefit
TI and AC results in similar GHG emissions	Unresolved	
TI reduces soil nitrate losses relative to AC	Well established	Benefit
Economic: TI increases labour and management costs relative to AC, assuming continued arable production	Established	Disadvantage
TI can increase or decrease farm profitability relative to AC	Established but incomplete	Similar
TI can result in greater societal values than AC	Established but incomplete	Benefit
References for tree intercropping: Aertsens et al. (2013); Asbjornsen et al. (2013); Garcia de Jalon et al. (2018a); Garcia de Jalon et al (2018b); Kanzler et al. (2018); Kim et al. (2016); Lin et al (2017); Thevathasan et al. (2016); Torralba et al. (2016); Tuomisto et al. (2013)		

Biodiversity: a review of European tree intercropping studies has indicated a positive effect on biodiversity relative to arable cropping (Well established); we were unable to find biodiversity studies on tropical intercropping systems as opposed to multistrata systems.

Yield: there is a wide range of tree-intercropping systems: those with closely-spaced trees will eventually reduce understory crop yields as the tree canopy develops (Well established); however some widely-spaced arrangements where, for example, the arable crop benefits from reduced wind speeds (e.g. Kanzler et al. 2018) may sustain yields (Established but incomplete) (Table 11).

Other environmental: there is strong evidence that tree intercropping increases carbon storage in above- and below-ground woody tissues (Well established). There is mixed evidence as to whether tree-intercropping, relative to arable cropping, reduces net greenhouse gas emissions, as CO_2 emissions generally decrease, but N_2O emissions can increase (Kim et al. 2016). There is modelled and field evidence of reduced soil erosion losses (Well established) relative to arable cropping.

Economic: tree-intercropping typically results in greater labour and management costs than conventional arable cropping, assuming continued arable production (Well established). The relative financial profitability of the system depends partly on the financial return from the tree component ranging from negative (Garcia de Jalon et al. 2018b) to positive effects (Graves et al. 2007). The inclusion of market values for the environmental benefits of such systems typically means that the societal benefit of such systems can exceed that of arable cropping (Established but incomplete).

4.3.5 Multistrata agroforestry and permaculture

Soil carbon: a study in Uganda indicates higher soil carbon levels under banana agroforestry than banana monocultures (Zake et al. 2015) (Established but incomplete) (Table 12).

Biodiversity: a meta-analysis by De Beenhouwer et al. (2013) indicates a positive benefit on biodiversity of multistrata agroforestry compared to monoculture plantations.

Yield: the choice of the counterfactual is important when considering the yield of multistrata agroforestry. Whitefield (2011) writes "there's little doubt that well-designed permaculture systems can yield at least as much as conventional high-input systems", but he does not provide quantified evidence. In some situations, multistrata agroforestry will result in a lower crop yield of a specific crop than a monoculture, but total crop production can be higher (Niether et al. 2019).

Table 12. Impacts of multistrata agroforestry (MA) relative to a perennial monoculture (PM)

Statement	Confidence	Effect
Soil carbon: MA relative to PM increases soil carbon	Established but incomplete	Benefit
Biodiversity: MA increases biodiversity relative to PM	Well established	Benefit
Yield: MA, relative to monocultures, can reduce yields of the specified crop, but increase total yield	Unresolved	Variable
Other environmental: MA, relative to PM, increases above ground carbon	Established but incomplete	Benefit
Economic: MA, relative to PM anticipated to increase labour requirements MA, relative to PM, increases farm profitability	Inconclusive Inconclusive	
References: Dal Sasso et al (2012); De Beenhouwer et al. (2013); Guo and Gifford (2002); Kim et al. (2016); Niether et al. (2019); Ortiz-Rodriguez et al. (2016); Santos et al. (2019); Zake et al. (2015)		

Other environmental: multistrata systems increase above-ground carbon storage relative to monoculture systems (e.g. Niether et al. 2019).

Economic: it is anticipated that multistrata systems will increase labour demands relative to monoculture systems, but this and the effect on profitability were unresolved by our literature review.

4.3.6 Silvopasture

Soil carbon: The overall effect of integrating trees on grassland in a silvopastoral system on below-ground carbon ranges from similar (Upson et al. 2016) to positive effects (Seddaiu et al. 2018) (Established but incomplete) (See Table C.6 in the Appendix and Table 13).

Biodiversity: a European meta-analysis (Torralba et al. 2016) indicates a positive effect of integrating trees on grassland on biodiversity (Established)

Yield: the effect of trees on pasture production depends to a large extent on the number of trees per hectare. High tree densities can supress grass yields, but low densities can enhance production, and can often provide additional fodder. The impact can also be affected by whether the grass is fertilised or not; with the effect of the trees likely to be more positive where the grass is not fertilised (Moreno Marcos et al. 2007).

Other environmental: integrating trees on grassland increases above-ground carbon storage and reduces soil erosion (Torralba et al. 2016) (Well established).

Animal welfare: stakeholders perceive that silvopasture systems improve animal welfare (Garcia de Jalon et al. 2018a).

Economic: the inclusion of trees tends to increase management and labour costs (Well established). The net effect of such systems on farm profitability is unresolved.

Table 13. Statements related to silvopasture (SP) relative to grassland

Statement	Confidence	Effect
Soil carbon: SP relative to grassland results in similar or increased below-ground carbon	Established but incomplete	Benefit
Biodiversity: SP relative to grassland increases biodiversity	Well established	Benefit
Yield: the effect of SP on grassland yields depends on the tree density	Established	Variable
Welfare: SP relative to grassland increases livestock welfare	Established but incomplete	Benefit
Other environmental: SP relative to grassland increases above-ground carbon SP relative to grassland reduces soil erosion	Well established Well established	Benefit Benefit
Economic: SP relative to grassland increases farm labour SP relative to grassland increases farm profitability	Well established Unresolved	Disadvantage
References: Aertsens et al. (2013); Costa et al. (2018); Garcia de Jalon et al. (2018a); Seddaiu et al. (2018); Moreno Marcos et al. (2007); Torralba et al. (2016), Upson et al. (2016)		

4.3.7 Multi-paddock grazing

Soil carbon: multi-paddock systems can result in similar (Sanderman et al. 2018) or increased soil carbon (Teague et al. 2011) compared to continuous grazing (Established but incomplete) (Table 14 and Table C.7). However the effects of grazing system are likely to be confounded by the effects of stocking rate and grazing intensity (Abdallah et al. 2018).

Biodiversity: high, rather than low, stocking rates can reduce plant diversity (Hawkins 2017), but we did not find any evidence of a particular effect of grazing system on plant biodiversity (Inconclusive).

Yield: In a global meta-analysis, Hawkins (2017) reports that multi-paddock and continuously-grazed systems result in similar grass yields. In a detailed study, Nordborg (2016) reports that there is no review study that demonstrates the grass or livestock productivity benefits of holistic grazing relative to conventional or continuous grazing. However Teague et al. (2016) argues that in practice farmers practising multi-paddock or organic systems can achieve better results than observed on experimental stations (e.g. Briske et al. 2008) by adapting actual management to conditions. In some situations, stocking rates may be higher in multi-paddock systems (Badgery et al. 2017).

Other environmental: on some sites, multi-paddock systems have been shown to increase the infiltration of water (Teague et al. 2010). Methods to increase the infiltration of water into the soil (Teague 2018), including the use of contour ripping along keylines can also help control and divert runoff (Duncan 2016).

Economic: multi-paddock systems require increased fencing costs and provision of water sources. However the increased interaction between the livestock manager and the livestock whilst incurring a cost can also improve livestock husbandry.

Table 14. Statements related to multi-paddock grazing (MPG) systems

Statement	Confidence	Effect
Soil carbon: MPG relative to continuous grazing results in similar or increased soil organic matter	Established but incomplete	Benefit
Biodiversity: effect of MPG, relative to continuous grazing	Inconclusive	
Yield: MPG relative to conventional grazing results in similar grass productivity	Established	Similar
Other environmental: MPG relative to continuous grazing can increase infiltration rates	Established but incomplete	Benefit
Economic: MPG increases fencing and management costs relative to continuous grazing	Established but incomplete	Disadvantage
References: Badgery et al. (2017); Chen and Shi (2018); Cox et al. (2017); Derner and Hart (2007); Hawkins (2017); Heitschmidt et al. (1982); Mudongo et al. (2016); Park et al (2017); Sanderman et al. (2015); Sanderman et al (2015); Teague et al. (2010); Teague et al. (2011); Wang et al. (2016).		

4.3.8 Organic livestock systems

Soil carbon: a meta-analysis by Grauver et al. (2019) indicates that adding organic amendments to soil increases soil carbon. Kidd et al (2015) also showed that the addition of farm yard manure can increase the soil carbon of well-fertilized grassland. Organic systems typically use a higher level of legumes and the addition of legumes generally increases soil carbon (Table 15 and Table C.8).

Table 15. Statements related to organic livestock (OL) relative non organic livestock (non-OL) systems

Statement	Confidence	Effect
Soil carbon: Adding organic amendments increases soil carbon Adding legumes increases soil carbon	Well established Well established	Benefit Benefit
Biodiversity: Adding organic amendments had no effect on biodiversity	Well established	Similar
Yield: OL with the addition of organic amendments can increase the grass yield of unfertilised rangeland OL with the addition of organic amendments can reduce, not affect, or increase the grass yield of fertilised grassland	Well-established Unresolved	Benefit Variable
Other environment: adding organic amendments reduces runoff Adding org amendments increases nitrate concentrations	Well established Well established	Benefit Disadvantage
Economic: OL reduces energy use compared to non-OL systems OL reduces profitability if there is no price premium OL increases profitability if there is a price premium	Established but incomplete Inconclusive Inconclusive	Benefit
References: Clarke and Tilman (2017); Conant et al. (2001); Dalgaard (2013); Gomiero et al. (2001); Hawkins (2017); Mueller et al. (2014); Gravuer et al. (2019); Topp et al. (2007).		

Biodiversity: in the meta-analysis by Grauver et al. (2019) adding organic amendments resulted in similar levels of native plant communities.
Yield: the effect of organic livestock systems depends on the counterfactual. In rangeland systems receiving no fertilizer adding organic amendments such as farmyard manure will increase grass yields (Grauver et al. 2019). However if the existing system involves grassland receiving synthetic fertiliser, moving to an organic system can result in lower yields (Mueller et al. 2014) or higher yields (Kidd et al. 2015) depending in part on the current rate of fertiliser application (Unresolved).
Other environmental: adding organic amendments can reduce runoff, but can increase the nitrate concentrations of runoff (Grauver et al. 2019).
Economic: organic, compared to non-organic, systems generally result in reduce energy use per unit of food (Gomiero et al. 2001). In the absence of specific literature on profitability, we anticipate that organic livestock shows similar profitability characteristics as organic crop production, where profitability depends on a price premium. For example, Duncan (2016) reports that a regenerative agricultural system at Taranaki Farm in Australia depends on direct relationships with consumers, and associated premium sale prices.

4.3.9 Rewilding and land abandonment from agriculture

In this report, rewilding is defined in terms of naturalistic grazing with relatively passive management. The abandonment of agricultural land may occur either due to changes in economic conditions or changes in soil conditions making it unsuitable for cropping (IPBES 2018a).
Soil carbon: it is generally considered that rewilding and land abandonment results in increased soil carbon due to the lack of tillage and greater coverage of perennial plants (Lasanta et al. 2015).
Biodiversity: the effect of rewilding and land abandonment on biodiversity depends on the counterfactual (Queiroz et al. 2014). Abandonment of extensive grazing areas and the establishment of closed forest can reduce long-term biodiversity (Rey Benayas et al. 2007; Lasanta et al. 2015), as well as creating problems with invasive species (Corlett 2016). By contrast including large herbivores in rewilding schemes on agricultural land can prevent canopy closure and enhance biodiversity (Ceausu et al. 2015).

Table 16. Impacts of rewilding and land abandonment relative to conventional crop or grazing system

Statement	Confidence	Effect
Soil carbon: increased by perennial relative to non-perennial vegetation	Well established	Benefit
Biodiversity:		
Abandonment of extensive grazing can reduce biodiversity	Established but incomplete	Disadvantage
Rewilding of intensive arable can increase biodiversity	Established but incomplete	Benefit
Rewilding can increase presence of invasive species	Established but incomplete	Disadvantage
Yields: rewilding reduces food production relative to conventional crop or grazing	Well established	Disadvantage
Other environmental: increased perennial woody vegetation increases above ground carbon	Well established	Benefit
Animal welfare impact of rewilding is debated	Inconclusive	
Economic cost: of restoration has not been reviewed	Inconclusive	
References: Ceaușu et al. (2015); Cerqueira et al. 2015; Conant et al. (2001); Corlett (2016); Guo and Gifford (2002); Lasanta et al. (2015); McLauchlan (2004); Rey Benayas et al. (2007); Silver et al. (2000); Smiraglia et al. (2016); Spencer (2017); VandenBygaart et al. (2003)		

Yield: food production is reduced through rewilding and agricultural abandonment (Smiraglia et al. 2016; Cerqueira et al. 2015), although if the land is already marginal the absolute effect on food production may be small. The Knepp rewilding project across 1100 ha in lowland UK annually results in about 75 tonnes of high value beef, pork and venison (Spencer 2017). Whilst the high value may make the system profitable, the quantity of meat is only about a tenth of that achieved, for example, by typical lowland sheep production (Redman 2018).

Animal welfare: an important topic related to rewilding is animal welfare. There is a need to establish the extent to which it is necessary to protect animals from "hunger, thirst, discomfort, pain, injury, and disease" (Lorimer et al. 2015).

Other environmental: rewilding and land abandonment will generally increase the level of woody perennials and hence above-ground carbon storage.

Economic: land abandonment from agriculture can be inexpensive. Rewilding schemes are generally less labour intensive than agricultural production but may require up-front investment in terms of fencing (Inconclusive). Rewilding may encourage other non-agricultural sources of income.

4.4 Conclusions

Each of the nine selected regenerative systems demonstrates **positive impacts in terms of increased soil carbon and/or on-farm biodiversity** (Table 8) relative to the stated baseline. The benefits in terms of soil carbon are due to increased crop cover, reduced cultivation, and the addition of soil amendments. The biodiversity benefits are derived from an increased diversity of crops, reduced cultivation, and/or reduced use of pesticides and herbicides.

The impacts on yield and profitability depend on the system and the assumed baseline. The results are compatible with the observation by Struik and Kuyper (2017) that there may be benefits from the intensification of low-input agriculture, as may be found in Africa, and the de-intensification of industrial agriculture in developed markets. The main responses are outlined below.

Conservation agriculture: particularly in drier environments, similar crop yields as from tillage systems, combined with lower machinery and labour costs make the practice financially attractive. The reduced machinery costs can also make the system attractive if there are small yield penalties. The risk of a ban on the use of glyphosate in some countries also needs to be considered.

Organic crop production: on farms where there is currently no fertiliser use, making use of organic amendments (which still incur some costs) can increase crop yields. On farms, where synthetic fertilizers are used, a move to certified organic production will lead to yield decreases of between 8 and 52%, but Crowder and Reganold (2015) report a typical price premium of 25% is sufficient to make most organic systems profitable.

Tree crops: growing perennial crops on arable land can increase food production and above ground carbon storage. However care needs to be taken to prevent expansion into forests and the associated negative effects on biodiversity and carbon.

Tree intercropping: high tree densities will eventually result in lower understorey crop yields as the tree develop, but low tree densities may result in similar yields. The financial attraction of the practice is increased if the tree can also produce financially viable products.

Multistrata agroforestry may not offer yield benefits compared to monoculture permanent crop production under well-fertilized conditions, but it can still increase total food production and it can offer yield benefits under less-optimal environments.

Silvopasture grass yields, and thereby livestock production, can be maintained where the tree density is not excessive, and the system can offer animal welfare benefits.

Multi-paddock system experiments have not demonstrated a grass yield benefit compared to continuous grazing, but the increased management options can allow greater stocking densities and adaptive management.

Organic livestock systems because of the recycling of livestock urine and dung, can sustain similar grass yields to some fertilized grassland systems. Adding organic amendments such as farm yard manure (which will incur a cost) can substantially increase grass yields where there is no fertilizer use.

Rewilding and agricultural land abandonment: generally increases soil carbon and can increase biodiversity. Food production will typically be very low, but some areas may have been producing little food before abandonment.

5 Scaling of regenerative agriculture

5.1 Introduction

This section considers the current extent of the regenerative agricultural systems and the current rates of expansion. Conservation agriculture, regenerative organic agriculture, tree crops, tree intercropping, and multistrata agroforestry are assumed to occur on cropland, and silvopasture and multi-paddock and organic grazing management occurs on grassland (Figure 4). The study also included rewilding and abandoned agricultural land, which may revert in part to forest.

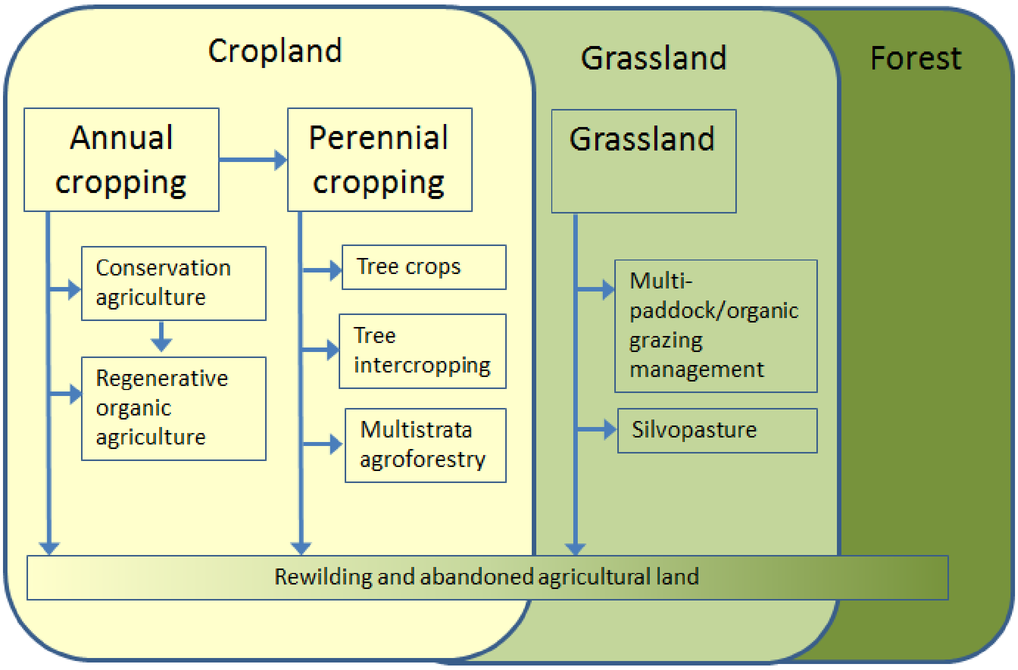

Figure 4. The potential context for the selected regenerative farming systems

5.2 Estimates of current and potential areas

Estimates of the current and potential areas of the selected regenerative land management systems are difficult to find. Some estimates of the current area and the plausible area for 2050 are provided in Table 17, and explanations are provided in the text. In the absence of detailed information, it is assumed that the areas of conservation agriculture; regenerative organic agriculture; tree crops; organic grazing management; and rewilding and agricultural land abandonment are largely mutually exclusive. However we can assume some overlap of agroforestry systems. As our estimate of agroforestry is based on the 15% of agricultural land which has greater than 30% tree cover, to reduce the level of double counting in our area calculations, we assumed that 15% of the area of regenerative organic agriculture, tree crops, and multi-paddock areas were agroforestry (Figure 5).

Table 17. Estimates of the current extent of selected regenerative agriculture systems and a plausible area for 2050

Innovation	Base year	Current area (Mha)	Plausible area in 2050 (Mha)[a]	Key references
Conservation agriculture	2015	180	550	Kassam et al. (2018)
Regenerative organic agriculture	2017	12	45	Willer and Lernoud (2019)
Tree crops	2017	158	237	FAOSTAT (2019)
Tree intercropping[b] Multistrata agroforestry[b] Silvopasture[b]	2010	324	428	Zomer et al. (2014)
Organic grazing management	2017	48	221	Willer and Lernoud (2019)
Abandoned land from agriculture	2016	0[c]	377	FAOSTAT (2019)

[a]: Based on extrapolation of current rates of expansion

[b]: Note that in Figure 5, the assumption is that 15% of the regenerative organic agriculture, tree crops, and organic grazing management could also be termed agroforestry

[c]: Baseline of zero assumed for 2016

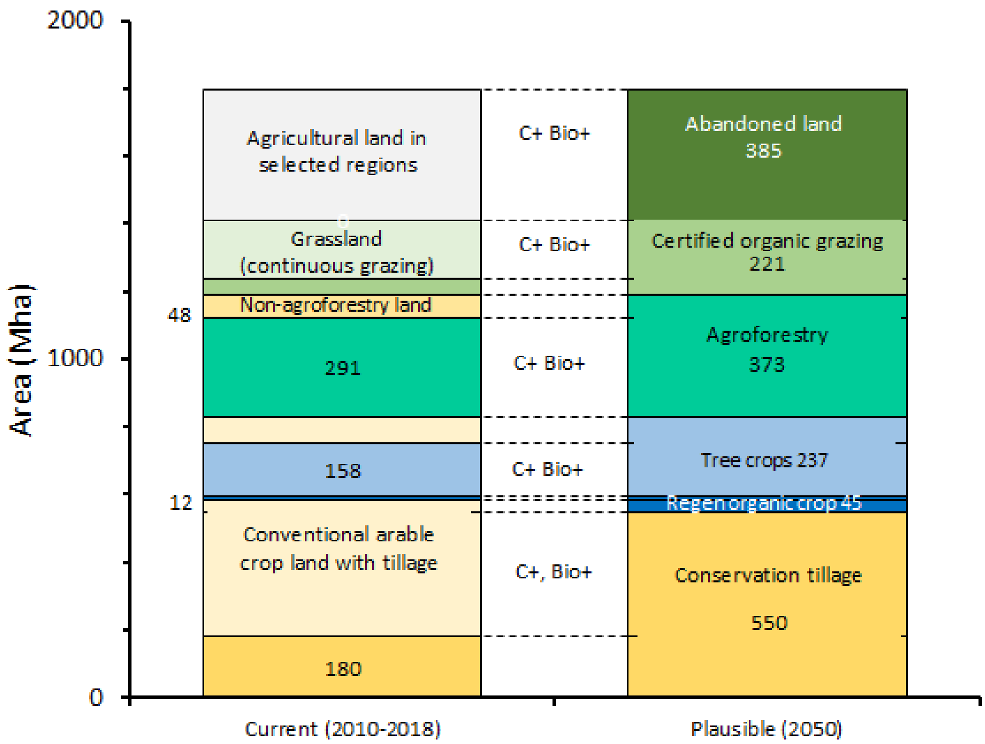

Figure 5. Estimates of the current global extent of selected regenerative agriculture systems (tree intercropping, multistrata agroforestry and silvopasture are summed as agroforestry) and a plausible area for 2050. Conversion of conventional arable cropping, non-agroforestry agricultural land, continuously-grazed grassland to these systems will tend to increase carbon storage and biodiversity. Although not indicated, 15% of the indicated regenerative organic crop production, tree crop, and multi-paddock and organic grass systems could also be defined as agroforestry. The increase in abandoned agricultural land is limited to estimates North and Central America, Western and Southern Europe, North Africa, and Oceania.

5.2.1 Conservation agriculture

Kassam et al. (2018) report that the global area of conservation agriculture increased from 106 Mha in 2008 to 180 Mha in 2015, equivalent to an annual increase of 10.6 Mha per year. Assuming a constant rate of increase, this would imply an area of 550 Mha by 2050. The value of 180 Mha (for 2015) is higher than the value of 72 Mha assumed by Drawdown (2017) and Friedrich et al. (2012) for 2003, primarily because of the more recent base year.

5.2.2 Organic arable production

Willer and Lernoud (2019) report a global area of certified organic arable agriculture in 2017 of 12.1 Mha. This is lower than the estimate of 44 Mha by Drawdown (2017) who reported the area of all certified organic agriculture. The area of organic arable agriculture increased from 8.0 Mha in 2013 (Willer and Lernoud 2016) to 12.1 Mha in 2017. Assuming an annual increase of 1 Mha per year, the extrapolated area in 2050 would be 45 Mha.

5.2.3 Tree crops

It is argued that global fruit and nut production needs to increase to provide healthy diets (Whitmee et al. 2015). Tree crops include fruits (56 Mha), nuts (10 Mha), oil trees (41 Mha) and species such as cloves, coffee, cocoa, rubber and tea (33 Mha). Using FAOSTAT (2019) data, the total global area of tree crops in 2017 was 158.2 Mha (Appendix D). This has increased from 141.4 Mha in 2010 equating to an annual increase of 2.4 Mha. Assuming a linear increase would suggest 237.4 Mha by 2040. Willer and Lernoud (2019) reported an area of certified organic permanent crops of 4.8 Mha in 2017.

5.2.4 Tree intercropping, multistrata agroforestry and silvopasture

We were unable to find a rigorous global assessment of the area of tree-intercropping, and multistrata and silvopasture agroforestry, although there are new global initiatives to estimate the area of trees outside forests (de Foresta et al. 2013). Nair (2012) estimates global areas of tree-intercropping (700 Mha), protective trees (300 Mha), multistrata agroforestry (100 Mha) and silvopasture (450 Mha that have been widely cited (e.g. Lorenz and Lal 2014). However Nair (2012) indicated that these were arbitrary and potential values. Shi et al. (2018) quotes a global area of alley cropping of 604 Mha.

Zomer et al. (2014) completed a global analysis of tree cover on agricultural land (including cropland, grassland, permanent crops, and areas of cropland mosaic). The area of agricultural land classified as "agroforestry" in this way was 324 Mha, 515 Mha and 965 Mha assuming tree covers of more than 30%, 20% and 10% respectively (Table 18). FAO (2019) assumed a global agroforestry area of 515 Mha based on the 20% value (2008-2010). Den Herder et al. (2017) calculated an area of agroforestry in the European Union of 15 Mha which is of the same order of magnitude as the >30% tree cover value for Europe of 28 Mha. This suggests that the 30% value may be an appropriate surrogate value for the area of agroforestry in the absence of other information. In the absence of other information we have included the more conservative >30% tree-cover value of 324 Mha in Table 17.

Table 18. Land area under agroforestry (2008–2010) and trends (2000–2010), by region (after Zomer et al. 2014)

	Total agricultural area (Mha)	Area with >30% tree cover (Mha)	Area with >20% tree cover (Mha)	Area with >10% tree cover (Mha)
North America	207	30	51	86
Central America	27	14	20	25
South America	389	75	129	260
Europe	230	28	49	110
North Africa/Western Asia	114	4	7	13
Sub-Saharan Africa	396	35	58	114
Northern and Central Asia	247	9	21	58
South Asia	183	8	16	49
South-East Asia	165	84	103	129
East Asia	180	23	42	91
Oceania	79	13	19	30
Total	2218	324	515	965
Proportion of total (%)		14.6	23.3	43.5

Zomer et al. (2014) report that the area of agricultural land with >30% tree cover increased from 298 Mha in 2000 to 324 Mha in 2010, equivalent to 2.6 Mha per year. An expansion of 2.6 Mha per year from 2010 to 2050 would imply an increase from 324 Mha in 2010 to 428 Mha in 2050. Some of this increase will be provided by the increase in tree crops and organic systems. Nair (2012) considered that the high labour demand would mean that the area of multistrata agroforestry "is not likely to increase in the near future". By contrast an expansion of integrated crop-livestock-forest systems is planned in Brazil (Box 2). Some of the expansion in agroforestry may also occur as part of the land restoration pledged by countries as part of the Bonn Challenge (Dave et al. 2017; IUCN, 2019).

Box 2: Integrated Crop-livestock-Forest Systems: third wave of regenerative agriculture in Brazil
Between 1977 and 2014, the cultivated area in Brazil increased from 37 to 55 million ha, but much of the land used for crop production in the Cerrado area of Brazil resulted in degraded soils. The first innovation was the introduction of zero-tillage to increase soil carbon levels. The second innovation was the integration of a grass rotation into crop production. In existing areas of pasture production including a crop allowed the recovery of pasture, and the integration of livestock in crop areas increased soil organic matter levels. The third wave was to incorporate trees into the system (Macedo and de Araújo, 2014). In 2015, the Brazilian Ministry of Agriculture announced that there was a target, and associated credit support, for 4 Mha to be in integrated crop-livestock-forest systems by 2020.

5.2.5 Multi-paddock and organic grazing

Drawdown (2017) assumed an area for multi-paddock grazing of 79 Mha in 2014, which could plausibly increase to 448 Mha by 2050. The area of certified organic grassland agriculture increased from 27 Mha in 2013 (Willer and Lernoud 2016) to 48 Mha in 2017 (Willer and Lernoud 2019). Lovins (2016) also reports that holistic grazing management is practiced on more than 16 Mha. For this study, the area estimate is derived from the area of certified organic grassland. The 21 Mha increase in organic grassland from 2013 to 2017 implies an annual increase in certified organic grassland of 5.25 Mha/year. Hence a pro-rata increase to 2050 would be 221 Mha.

5.2.6 Rewilding and agricultural land abandonment

Between 1961 and 2011, the area of land used for agriculture in Western Europe, Southern Europe, North America, and Oceania decreased by 379 Mha (Li and Li 2017). Some of the decline is due to urban expansion and some due to land abandonment. Using values from FAOSTAT (2019), the regions showing decline in agricultural land between 2010 and 2016 (excluding reductions due to urban expansion) included North and Central America and the Caribbean (-0.46 Mha/year), Western and Southern Europe (-0.72 Mha/year), Oceania (-4.71 Mha/year), and North Africa (-5.19 Mha/year). Assuming a similar linear decline for the next 34 years, would result in 377 Mha of rewilded or abandoned agricultural land between 2016 and 2050.

5.3 Conclusions

The estimates of areas of regenerative agriculture systems in terms of: conservation agriculture, organic systems, tree crops, agroforestry, multi-paddock grassland management, and rewilding areas suggests that the area of each seems to be increasing. The 2015 area of conservation agriculture (180 Mha) is substantial and it is expanding by about 11 Mha per year. The 2017 area of certified organic systems is 65 Mha (48 Mha grassland; 5 Mha permanent crops; 12 Mha cropland), with an extrapolation of the growth rate from 2014 to 2017 resulting in 45 Mha of certified organic cropland and 221 Mha of organic grassland by 2050. The 2017 area of tree crops is 158 Mha, with a current expansion rate of 2.4 Mha per year. There is no robust estimate of the global area of agroforestry (silvopasture, multistrata, and tree-intercropping), but in Europe the area of agroforestry expressed as a proportion of agricultural land (8.8%) is comparable to 12.2% of the area of agricultural land with greater than 30% tree cover reported by Zomer et al. (2014). The research by Zomer et al. suggests that the area of agricultural land with greater than 30% tree cover is 324 Mha, increasing by 2.6 Mha per year. This increase is likely to include some of the previously mentioned increase in organic crop and grassland and tree crops. The fifth area relates to rewilding and agricultural land abandonment, primarily in Northern America, Western and Southern Europe, and Oceania, with current rates releasing 377 Mha between 2016 and 2050. The above expansion rates are based on simple linear extrapolations of current values. It could be argued that the rates of expansion could decrease because of diminishing returns as the preferred areas have already been converted, or increase if the drivers for conversion become stronger.

6 Enabling and promoting regenerative agriculture

6.1 Introduction

Implementing regenerative systems will make a very large contribution to the greening of agriculture (Pearson 2007). Codur and Watson (2018) also argue that there is a growing coalition of decision-makers, farmers, scientists, and consumers that are supporting its wider adoption. This section identifies some of the means for enabling and promoting regenerative agriculture from the perspective of four types of stakeholder: 1) policy makers, 2) farmers and advisors, 3) researchers, and 4) consumers and those involved in the food chain.

There are many entry points to promote regenerative agriculture ranging from the support of global frameworks, to national and regional policies, and local action (Figure 6a). Top-down approaches include engagement with global agreements to improve environmental health, such as the Convention on Biological Diversity, the Ramsar and Bonn Conventions, and the Sustainable Development Goals. In the European Union, these have been translated into policy through EU Directives which are then translated into national legislation and measures (Figure 6b). Bottom-up approaches include farmers implementing and benefiting from regenerative agriculture on their farms. Each approach is needed.

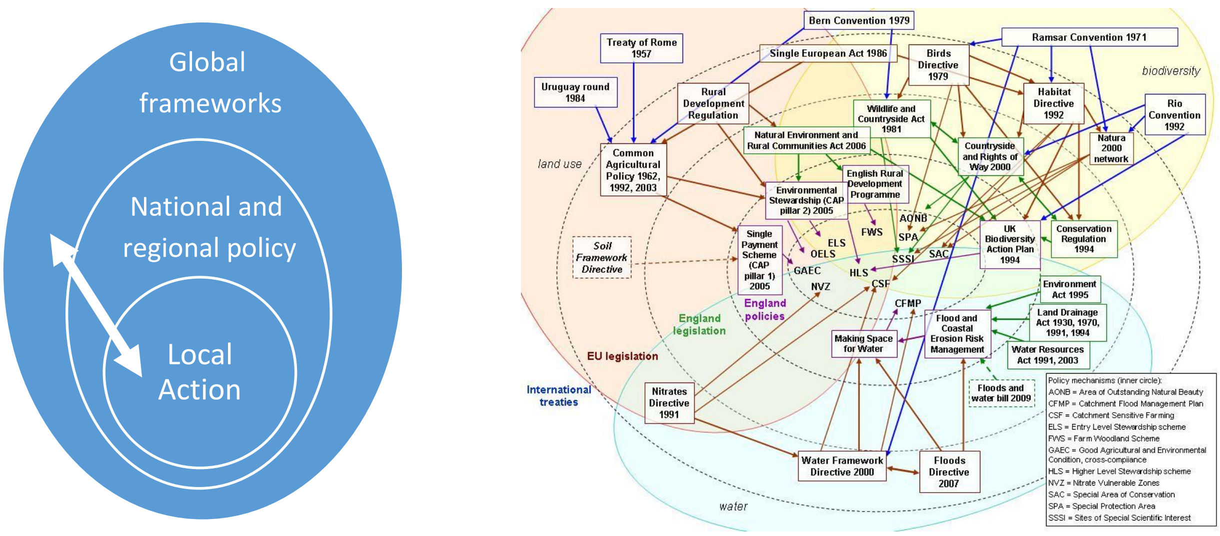

Figure 6. Promoting regenerative agriculture involves the interaction of local action, national and regional policy and global frameworks. Whilst a) the theory may be simple, b) the practice can be complicated (adapted from Morris et al. 2009).

6.2 Recognising the role of regenerative agriculture in policy

Policy makers can help facilitate regenerative agriculture through international and national incentives and through regulation. In terms of incentives, there is a need to highlight how regenerative agriculture can contribute to existing international policies that have been developed to reduce the negative impacts of agriculture on biodiversity, the environment, and people.

International initiatives include "4 per 1000" (Box 3) and the recognition of regenerative agriculture practices and systems in international conventions and in assessments of sustainable agriculture (FAO 2014b). For example, FAO (2019) have recently produced a detailed report on the state of the world's biodiversity for food and agriculture that highlights the positive role of agroforestry. The United Nations (2019) has also designated 2021-2030 as the Decade on Ecosystem Restoration, based on well-established evidence for the loss of biodiversity, natural capital, and the ecosystem services which flow from them (IPBES 2018a; 2018b, Pandit et al. 2018). Studies such as by Wolff et al. (2018) have examined the possibility of protecting 28% of Earth's land resource with the highest biodiversity and carbon storage, compared to a value of 15% in 2018 (FAOSTAT 2019). Springmann et al. (2018) also describe the use of a planetary boundary approach to address the interactions between land use and the demand for and the production of food. The World Bank (2012) has reported studies on the public and private costs and benefits of a range of methods to increase carbon storage in soils.

Box 3: The "4 per 1000" initiative

The "4 per 1000" Initiative (2016) was launched by France in December 2015 at the Paris Climate Conference. The aim is to increase the mean level of soil carbon level in the top 30-40 cm of soil by 0.4%, or 4‰ per year over 10 years. The initiative focuses on conservation tillage, intercropping, agroforestry, improved pasture management, farmland restoration, and the improved management of water and fertilisers.

Government initiatives can also be taken at a national level. In the UK, the recent 25 year plan to improve the environment emphasises measures such as ensuring a net biodiversity gain from housing and a continued reduction of greenhouse gas emissions and agro-chemicals from agriculture. Further commitments include paying farmers for public goods, particularly environmental enhancement through the regeneration of natural capital whilst at the same time increasing effectiveness of the "polluter pays" principle. In India, the government is supporting organic agriculture through the launch of the Paramparagat Krishi Vikas Yojana (PKVY) programme in 2015.

Policy makers can also encourage regenerative agriculture through regulation. This can include the prohibition of the harvest of forested areas and draining of wetlands. Kremen (2015) argues that in developing countries, there can be tendency for it to be easier to expand agriculture into unprotected forests rather than already cleared land because of the lower transaction costs. Governments can also prohibit certain farm practices e.g. removal of hedges, and certain pesticides e.g. neonicotinoids, and requirements to have biodiversity enhancement practices on a certain proportion of a farm (HM Government 2018). One effect of pesticide restrictions is that it forces the convergence of the impact of non-organic systems with those of organic farming.

6.3 Enabling farmers

Some regenerative farm practices have low investment costs which mean that resource-poor farmers can often initiate such practices "from within" (Kamenetzky and Maybury 1989). For example Brown (2016) undertook regenerative agriculture on his farm without government subsidies and support, although such individuals may be an exception. The relatively low cost of some regenerative approaches is an advantage as Pretty (1995) argues that only low-cost technologies and practices can be applied on a scale wide enough to improve the livelihoods of some 2 billion people. However some practices such as establishing tree crops and some agroforestry systems do require significant upfront investment and it can take substantial time before the tree crops provide a return on investment. In such situations, government or social investment support programmes can play a pivotal role.

Most of the regenerative systems we reviewed require increased labour inputs, knowledge and skills (Pearson 2007). Jayne et al. (2019) argue that the highly localised and knowledge intensive focus of regenerative types of agriculture requires massive increases in farm-level research and extension systems. Sherwood and Uphoff (2000) also recommend the participation of stakeholders in a dynamic "learning process" to support improvements in soil health. Likewise extension workers should be "facilitators aiming to transmit knowledge and ways of learning rather than technologies" (Pretty 1995 page 40). The most appropriate solution will depend on the context (Box 4).

Box 4: Analogy between the choice of farm systems and people choosing diets

The most appropriate agricultural systems for a farm, like the most appropriate diet for an individual, are context dependent. Some farms, particularly in less-developed countries, are under-resourced and "undernourished" and will benefit from additional inputs. By contrast in developed countries, some farms are "overweight" and the intake of fewer inputs would provide health benefits. In this latter case, a farmer could choose to self-manage a flexitarian approach or follow an externally accredited "diet and fitness programme" with regular support and validation from a local organisation. There are also opportunities for government and business to provide the resources and tools to help farmers make healthy choices.

In a review of low external input technologies for maintaining soil fertility (such as intercropping, alley cropping, cover crops and green manure, biomass transfer techniques, compost, animal manure, and improved fallows), Graves et al. (2004) found that such approaches were more likely to be adopted if they addressed the needs, challenges and worked within the resource constraints identified by farmers. This is because new technologies can bring challenges that farmers cannot always cope with. For example, Brodd and Osanius (2002) noted that farmers could not adopt alley cropping even when aware of its ability to reduce soil erosion because of their lack of labour and capital. Start-up costs and long-term benefit horizons were noted to be a challenge for farmers adopting alley cropping (Nelson and Cramb 1998; Carter 1995). In Ghana, farmers resisted use of manure for fertiliser as they felt it was old-fashioned (Kiff et al. 1997) or required new knowledge and interest in livestock management that they were reluctant to develop (Dickson and Benneh 1995). Sereke et al. (2017) found that farmers in Switzerland were unwilling to adopt agroforestry because they feared reputational damage; whereas Kliejn et al. (2019) reports that some farmers may be motivated to take up regenerative practices to enhance their reputation.

Graves et al. (2004) concluded that a key challenge for those involved in developing new technologies for farmers was to appreciate that the technology needed to operate within and be facilitated by existing biophysical, social, economic, and cultural contexts. For example, Swinkels and Frankel (1997) found that in Kenya, adoption of alley cropping was higher where farmers had off-farm sources of income, relatively large farms and were cash cropping. Security of tenure and long-term access to land was also found to favour investment by farmers in long-term technologies such as alley cropping. In this respect, Graves et al. (2004) suggested that technologies that could address issues in terms that were important to farmers, such as reducing labour, easing cultivation, decreasing risk, as well as increasing yield, had a greater chance of being adopted. They also suggested that such technologies would not suit all farmers, but that the solutions developed would need to be flexible, fitting biophysical, social, economic, and culture at local and perhaps even farm scale.

Pannel (1999) has suggested that where a new technology is markedly different to an existing technology four conditions are necessary for adoption. These are firstly that the farmer must be aware that there are alternative technologies available, secondly believe that the technologies can be trialled, thirdly believe that they are worth trialling, and fourthly believe that they satisfies objectives, particularly for profit. Graves et al. (2004) note that whilst these conditions may be readily observed for short-term technologies, they are more difficult to achieve with long term technologies such as agroforestry where benefits may only be observed over a long period of time and are difficult to demonstrate in the short-term. In some circumstances, voluntary and regulatory mechanisms such as payments for ecosystem services, subsidies, tax relief, cross compliance, compulsory adoption through government strategic plans, penalties for non-adoption, or public acquisition of land could be needed.

6.4 Research and initiatives to improve regenerative systems

Röös et al. (2018) provide a good review on the importance of research to enhance the productivity of organic agriculture, such as developing breeds and varietal mixtures suited for organic production. They also argue that the organic movement should sometimes be flexible; for example should it allow the use of mineral nitrogen produced using renewable energy sources?

One of the constraints on organic systems in developed countries is the high labour costs associated with, for example, weed control. Farm work schemes, such as WWOOF, can provide farmers with access to labour and such schemes can also help to promote and exchange the flow of knowledge and information. Some of the labour constraints may be overcome by investment in new technologies; for example semi-robotic mechanical weeders with sensors can help reduce the labour requirements for the intra-row weeding of row-crop systems (Pérez-Ruíz et al. 2014). Such systems could improve the viability of organic systems.

National and international funding on research projects related to regenerative agricultural practices can also help to support innovation, create extension materials and bring stakeholders together (Burgess and Rosati 2018). Organisations and groupings such as the Regen Network (2018) and Terra-Genesis (Solviev and Landua 2016), which offer design or data handling services, can also support regenerative practices.

6.5 Consumers and product premiums

Market-driven processes are an important enabler of adoption (Kliejn et al. 2019), and regenerative agriculture can learn from successes with the promotion of organic farming. In their comprehensive study, Crowder and Reganold (2015) indicate an organic premium of only 5-7% is typically sufficient for organic profits to match conventional profits. This premium requires a consumer demand. Awareness of organic products as a potentially healthier and less environmentally damaging approach to farming can be generated by consumer pressure and the press. Although the cause and effect relationship is confounded, consumers in Europe who buy organic are more likely to have a healthier diet than other consumers (Röös et al. 2018). In some countries, a demand for organic products has been increased by the action of local governments to supply organic food in schools (e.g. Organic Centre Wales; Conscious Kitchen in the USA). An interest in organic farming can also be promoted through courses ranging from a few days (e.g. The Kindling Trust) to MSc courses in organic agriculture (e.g. Newcastle and SRUC).

An important method to capture the added value of regenerative or organic products is for farmers to directly engage with consumers. For example, schemes such as organic box schemes and pop-up markets that have helped organic farmers to capture a greater share of the value of the products they produce.

Defries et al. (2017) in a recent meta-analysis also identified the positive effect of certification programmes particularly in terms of conserving habitats and increasing on-farm revenue. Certification schemes can allow consumers to purchase food products with the knowledge that they have been produced to particular standards and values. This is the vision behind the regenerative organic agriculture certification scheme in the USA run by the Regenerative Organic Alliance (Rodale Institute 2018). The scheme builds on USDAs certified organic standard as a baseline and adds three pillars relating to soil health, animal welfare, and social fairness. Any price premium achieved from certification will need to cover the additional practice crops and the administrative costs of the certification scheme.

6.6 Conclusions

Policy makers, farmers, researchers and funding agencies, and consumers and those in the supply chain all have a role in enabling regenerative agriculture. As detailed by FAO (2019), the good news is that many regenerative systems can be profitable, can sequester carbon, and can enhance biodiversity, and in many cases such systems are being more widely adopted.

7 References

4 per 1000 Initiative (2016) Join the 4 per 1000 Initiative. https://www.4p1000.org/sites/default/files/content/en-4pour1000-8pages.pdf

Abdalla M, Hastings A, Chadwick DR, Jones DL, Evans CD, Jones MB, Rees RM, Smith P (2018) Critical review of the impacts of grazing intensity on soil organic carbon storage and other soil quality indicators in extensively managed grasslands. Agriculture, Ecosystems and Environment 253, 62–81.

Abeliotis K, Detsis V, Pappia C (2013) Life cycle assessment of bean production in the Prespa National Park, Greece. Journal of Cleaner Production 41, 89-96.

Aertsens J, De Nocker L, Gobin A (2013) Valuing the carbon sequestration potential for European agriculture. Land Use Policy 31, 584– 594.

Alkemade R, van Oorschot M, Miles L, Nellemann C, Bakkenes M, ten Brink B (2009) GLOBIO3: A framework to investigate options for reducing global terrestrial biodiversity loss. Ecosystems 12: 374-390.

Altieri MA (1999) The ecological role of biodiversity in agroecosystems. Agriculture, Ecosystems and Environment 74, 19-31.

Aguilera E, Lassaletta L, Gattinger A, Gimenoe BS (2013) Managing soil carbon for climate change mitigation and adaptation in Mediterranean cropping systems: a metaanalysis. Agriculture, Ecosystems and Environment 168, 25–36.

Alluvione F, Halvorson AD, Del Grosso SJ (2009) Nitrogen, tillage, and crop rotation effects on carbon dioxide and methane fluxes from irrigated cropping systems. Journal of Environmental Quality 38, 2023–2033.

Asbjornsen H, Hernandez-Santana V, Liebman M, Bayala J, Chen J, Helmers M, Ong CK, Schulte LA (2013) Targeting perennial vegetation in agricultural landscapes for enhancing ecosystem services. Renewable Agriculture and Food Systems 29, 101–125.

Balmford B, Green RE, Onial M, Phalan B, Balmford A (2018) How imperfect can land sparing be before land sharing is more favourable for wild species? Journal of Applied Ecology 56, 73-84.

Bayer C, Gomes J, Zanatta JA, Vieira FCB, de Cássia Piccolo M, Dieckow J, Six J (2015) Soil nitrous oxide emissions as affected by long-term tillage, cropping systems and nitrogen fertilization in Southern Brazil. Soil & Tillage Research 146, 213–222.

Bengtsson J, Ahnstrom J, Weibull A-C (2005) The effects of organic agriculture on biodiversity and abundance: a meta-analysis. Journal of Applied Ecology 42, 261–269.

Berazneva J, Lee DR (2013) Explaining the African food riots of 2007–2008: An empirical analysis. Food Policy 39, 28-39.

Bidogeza JC, Berentsen PBM, De Graaff J, Oude Lansink AGJM (2015) Bio-economic modelling of the influence of family planning, land consolidation and soil erosion on farm production and food security in Rwanda. Journal of Development and Agricultural Economics 7, 204-221.

Blanco-Canqui H, Lal R (2008) No-tillage and soil-profile carbon sequestration: an on-farm assessment. SSSAJ, 72, 693-701.

Burgess PJ, Rosati A (2018) Advances in European agroforestry: results from the AGFORWARD project. *Agroforestry Systems* 92, 801–810. https://doi.org/10.1007/s10457-018-0261-3

Briske D, Derner J, Brown J, Fuhlendorf S, Teague R, Gillen B, Ash A, Havstad K, Willms W (2008). Benefits of rotational grazing on rangelands: an evaluation of the experimental evidence. Rangeland Ecology and Management 61, 3-17.

Brodd P, Osanius M (2002) Erosion and land use at plot and catchment levels - a case study in 1 northern Vietnam. Minor Field Studies International Office, Swedish University of Agricultural 2 Sciences, Uppsala, Sweden. 62 pp.

Brown G (2016) Regeneration of Our Lands: A Producer's Perspective. TEDxGrandForks. https://www.youtube.com/watch?v=QfTZ0rnowcc

Brown LR (2005) Outgrowing the Earth: The Food Security Challenge in an Age of Falling Water Tables and Rising Temperatures. New York: WW Norton & Co.

Brown LR (2012) Supporting Data for Chapter 3: Moving Up the Food Chain. Full Planet, Empty Plates: The New Geopolitics of Food Scarcity (New York: W.W. Norton & Company, 2012). http://www.earth-policy.org/datacenter/pdf/book_fpep_ch3_all.pdf

California State University (2017) What is Regenerative Agriculture? https://www.csuchico.edu/regenerativeagriculture/_assets/documents/ra101-reg-ag-definition.pdf

Carter J (1995) Alley farming: Have resource-poor farmers benefited? Natural Resources 17 Perspectives No. 3. Overseas Development Institute, London.

Ceaușu S, Hofmann M, Navarro LM, Carver S, Verburg PH, Pereira HM (2015) Mapping opportunities and challenges for rewilding in Europe. Conservation Biology 29, 1017–1027.

Cerqueira Y, Navarro lM, Maes J, Marta-Pedroso C, Honrado JP, and Henrique M. Pereira HM (2012) Ecosystem services: the opportunities of rewilding in Europe. In: Pereira HM, Navarro LM (Eds) Rewilding European Landscapes 47-64. Springer

Chang J, Ciais P, Herrero M, Havlik P, Campioli M, Zhang X, Bai Y, Viovy N, Joiner J, Wang X, Peng S, Yue C, Piao S, Wang T, Hauglustaine DA, Soussana J-F, Peregon A, Kosykh N, Nironycheva-Tokareva N (2016) Combining livestock production information in a process-based vegetation model to reconstruct the history of grassland management. Biogeosciences, 13, 3757–3776.

Clark M, Tilman D (2017) Comparative analysis of environmental impacts of agricultural production systems, agricultural input efficiency, and food choice. Environmental Research Letters 12, 064016.

Codur A, Watson J (2018) Climate smart or regenerative agriculture? Defining climate policies based on soil health. Global Development and Environment Institute, Tufts University. Climate Policy Brief No. 9 April 2018. http://www.ase.tufts.edu/gdae/Pubs/climate/ClimatePolicyBrief9.pdf

Conant RT, Paustian K, Elliott ET (2001) Grassland management and conversion into grassland: effects on soil carbon. Ecological Applications 11, 343-355.

Connor DJ (2018) Organic agriculture and food security: A decade of unreason finally implodes. Field Crops Research 225, 128-129.

Convention on Biological Diversity (2010) Strategic Plan for Biodiversity 2011-2020: Provisional technical rationale, possible indicators and suggested milestone for the Aichi Biodiversity Targets. https://www.cbd.int/doc/meetings/cop/cop-10/official/cop-10-27-add1-en.pdf

Cooper J, Baranski M, Stewart G, Nobel-de Lange M, Bàrberi P, Fließbach A, Peigné J, Berner A, Brock C, Casagrande M, Crowley O, David C, De Vliegher A, Döring TF, Dupont A, Entz M, Grosse M, Haase T, Halde C, Hammerl V, Huiting H, Leithold G, Messmer M, Schloter M, Sukkel W, van der Heijden MGA, Willekens K, Wittwer R, Mäder P (2016) Shallow non-inversion tillage in organic farming maintains crop yields and increases soil C stocks: a meta-analysis. Agronomy for Sustainable Development 36, 22.

Corlett RT (2016) Restoration, reintroduction, and rewilding in a changing world. Trends in Ecology & Evolution, 31, 453-462.

Costa MP, Schoeneboom JC, Oliveria SA, Vinas RS, de Medeiros GA (2018) A socio-eco-efficiency analysis of integrated and non-integrated crop-livestock-forestry systems in the Brazilian Cerrado based on LCA. Journal of Cleaner Production 171, 1460-1471.

Crowder DW, Reganold JP (2015) Financial competitiveness of organic agriculture on a global scale. PNAS 112, 7611-7616.

Dalgaard T (2013) Energy balance comparisons of organic and conventional farming systems and potentials for mitigation of fossil resource use. Presentation at International Conference on Organic Farming Systems as a Driver for Change. NJF seminar 461, 21-23 Aug 2013, Vingsted, Denmark http://orgprints.org/23561/2/23561p.pdf

Dal Sasso P, Ruggiero G, Ottolino MA, Verdiani G (2012) The role of agroforestry areas of the province of Bari in the absorption of carbon dioxide. Journal of Agricultural Engineering 2012, 9-14.

Dave R, Saint-Laurent C, Moraes M, Simonit S, Raes L, Karangwa C (2017) Bonn Challenge Barometer of Progress: Spotlight Report 2017. Gland, Switzerland: IUCN, 36pp https://portals.iucn.org/library/sites/library/files/documents/2017-060.pdf

De Beenhouwer M, Aerts R, Honnay O (2013) A global meta-analysis of the biodiversity and ecosystem service benefits of coffee and cacao agroforestry. Agriculture, Ecosystems and Environment 175, 1–7.

de Foresta H, Somarriba E, Temu A, Boulanger D, Feuilly H, Gauthier M (2013) Towards the Assessment of Trees outside Forests: A Thematic Report prepared in the framework of the Global Forest Resources Assessment. Forest Resources Assessment Working Paper 183 FAO: Rome.

DeFries RS, Fanzo J, Mondal P, Remans R, Wood SA (2017) Is voluntary certification of tropical agricultural commodities achieving sustainability goals for small-scale producers? A review of the evidence. Environmental Research Letters 12, 033001.

den Herder M, Moreno G, Mosquera-Losada RM, Palma JHN, Sidiropoulou A, Santiago Freijanes JJ, Crous-Duran J, Paulo JA., Tomé M, Pantera A, Papanastasis VP, Mantzanas K, Pachana P, Papadopoulos A, Plieninger T, Burgess PJ (2017) . Current extent and stratification of agroforestry in the European Union. Agriculture, Ecosystems and Environment 241, 121–132.

Dickson KB, Benneh G (1995) A New Geography of Ghana. Longman: Harlow.

Diop AM (1999) Sustainable agriculture: new paradigms and old practices? Increased production with management of organic inputs in Senegal. Environment, Development and Sustainability 1, 285–296.

Doran JW (1980) Soil microbial and biochemical changes associated with reduced tillage. Soil Science Society of America Journal 44, 765-771.

Drawdown (2017) Drawdown: The Most Comprehensive Plan ever proposed to reverse Global Warming. Penguin Books. [An online version also provides technical summaries] https://www.drawdown.org/solutions/food

Drinkwater LE, Wagoner P, Sarrantonio M (1998) Legume-based cropping systems have reduced carbon and nitrogen losses. Nature 396, 262-265.

Duncan T (2016) Chapter 4.3 - Case Study: Taranaki Farm Regenerative Agriculture. Pathways to Integrated Ecological Farming. In: Chabay I, Frick M, Helgeson J (Eds) Land Restoration: Reclaiming Landscapes for a Sustainable Future, 271-287. Academic Press.

Ellen Macarthur Foundation and SYSTEMIQ (2017) Achieving “Growth Within”. Ellen Macarthur Foundation.

Elshout PMF, van Zelm R, Karuppiah R, Laurenzi IJ, Huijbregts MAJ (2014) A spatially explicit data-driven approach to assess the effect of agricultural land occupation on species groups. International Journal of Life Cycle Assessment 19, 758–769.

Erb KH, Gaube V, Krausmann F, Plutzar C, Bondeau A, Haberl H (2007) A comprehensive global 5 min resolution land-use data set for the year 2000 consistent with national census data. Journal of Land Use Science 2, 191-224.

Ekroos J, Ödman AM, Andersson GKS, Birkhofer K, Herbertsson L, Klatt BK, Olsson O, Olsson PA, Persson AS, Honor C. Prentice HC, Rundlöf M, Smith HG (2016) Sparing land for biodiversity at multiple spatial scales. Frontiers in Ecology and Evolution 3, 145.

Elevitch CR, Mazaroli DK, Ragone D (2018) Agroforestry standards for regenerative agriculture. Sustainability 10, 3337.

Erb K-H, Haberl H, Plutzar C (2012a) Dependency of global primary bioenergy crop potentials in 2050 on food systems, yields, biodiversity conservation and political stability. Energy Policy 47, 260–269.

FAO (2006) World Agriculture: Towards 2030/2050. Prospects for Food, Nutrition, Agriculture and Major Commodity Groups, Food and Agriculture Organization of the United Nations, Global Perspective Studies Unit. Global Perspective Studies Unit, Food and Agriculture Organization of the United Nations, Rome, June 2006.

FAO (2011) Global food losses and food waste – Extent, causes and prevention. Rome. http://www.fao.org/3/a-i2697e.pdf

FAO (2012) World Agriculture towards 2030/2050: The 2012 Revision. Global Perspective Studies Team. ESA Working Paper No. 12-03 June 2012. http://www.fao.org/3/a-ap106e.pdf

FAO (2014a) Building a common vision for sustainable food and agriculture: Principles and approaches. http://www.fao.org/3/a-i3940e.pdf

FAO (2014) SAFA Sustainability Assessment of Food and Agriculture Systems Guidelines Version 3.0. http://www.fao.org/3/a-i3957e.pdf. Rome: FAO.

FAO (2019) The State of the World's Biodiversity for Food and Agriculture (Eds. Bélanger J, Pilling D). FAO Commission on Genetic Resources for Food and Agriculture Assessments. Rome. 572 pp. http://www.fao.org/3/CA3129EN/CA3129EN.pdf

FAO & WHO (1999) Guidelines for the Production, Processing, Labelling and Marketing of Organically Produced Foods. Rome: FAO. (available at www.fao.org/input/download/standards/360/cxg_032e.pdf

FAOSTAT (2019) Food and Agriculture Data. http://www.fao.org/faostat/en/

Fernandez EMA (2016) The Influence of Management Practices on the Greenhouse Gas Balance of Mediterranean Cropping Systems. Identifying the Climate Change Mitigation Potential through Quantitative Review and Life Cycle Assessment. PhD Thesis. Universidad Pablo de Olavide. https://rio.upo.es/xmlui/handle/10433/3712

Fitzherbert EB, Struebig MJ, Morel A, Danielsen F, Carsten A. Brühl CA, Donald PF, Phalan B How will oil palm expansion affect biodiversity? (2008) Trends in Ecology and Evolution 23, 538-545.

Flynn HC, Canals LMI, Keller E, King H, Sim S, Hastings A, Wang S, Smith P (2012) Quantifying global greenhouse gas emissions from land-use change for crop production. Global Change Biology 18, 1622–1635.

Foresight (2011) The Future of Food and Farming Final Project Report. The Government Office for Science, London.

Foster F, Lunn J (2007) 40th Anniversary Briefing Paper: Food availability and our changing diet British Nutrition Foundation Nutrition Bulletin, 32, 187–249.

Francis CA, Harwood RR, Parr JF (1986) The potential for regenerative agriculture in the developing world. American Journal of Alternative Agriculture 1, 65-74.

Friedrich T, Derpsch R, Kassam A (2012) Overview of the global spread of conservation agriculture. Field Actions Science Reports, Special Issue 6 (2012); https://journals.openedition.org/factsreports/1941

García de Jalón S, Burgess PJ, Graves A, Moreno G, McAdam J, Pottier E, Novak S, Bondesan V, Mosquera-Losada MR, Crous-Durán J, Palma JHN, Paulo JA, Oliveira TS, Cirou E, Hannachi Y, Pantera A, Wartelle R, Kay S, Malignier N, Van Lerberghe P, Tsonkova P, Mirck J, Rois M, Kongsted AG, Thenail C, Luske B, Berg S, Gosme M, Vityi A (2018a) How is agroforestry perceived in Europe? An assessment of positive and negative aspects among stakeholders. Agroforestry Systems 92, 829–848.

García de Jalón S, Graves A, Palma JHN, Williams A, Upson MA, Burgess PJ (2018b) Modelling and valuing the environmental impacts of arable, forestry and agroforestry systems: a case study. Agroforestry Systems 92, 1059–1073.

Garnett T, Appleby MC, Balmford A, Bateman IJ, Benton TG, Bloomer P, Burlingame B, Dawkins M, Dolan L, Fraser D, Herrero M, Hoffmann I, Smith P, Thornton PK, Toulmin C, Vermeulen SJ, Godfray HCJ (2013) Sustainable intensification in agriculture: premises and policies. Science 341, 33.

General Mills (2018) Introduction to the General Mills Regenerative Agriculture Scorecard. https://www.annies.com/wp-content/uploads/2018/03/GM_Regenerative_Agriculture_Scorecard.pdf

Giannitsopoulos M, Burgess PJ, Rickson RJ (2019) Effects of conservation tillage systems on soil physical changes and crop yields in a wheat-oilseed rape rotation. Journal of Soil and Water Conservation 73, 231-242.

Godfray HCJ, Garnett T (2014) Food security and sustainable intensification. Philosophical Transactions of the Royal Society B 369: 20120273. http://dx.doi.org/10.1098/rstb.2012.0273

Grau R, Kuemmerle T, Macchi L (2013) Beyond 'land sparing versus land sharing': environmental heterogeneity, globalization and the balance between agricultural production and nature conservation. Current Opinion in Environmental Sustainability 5, 477-483.

Graves A, Matthews R, Waldie K (2004) Low external input technologies for livelihood improvement in subsistence agriculture. Advances in Agronomy: 82:473-555.

Graves AR, Burgess PJ, Palma JHN, Herzog F, Moreno G, Bertomeu M, Dupraz C, Liagre F, Keesman K, van der Werf W, Koeffeman de Nooy A, van den Briel JP (2007) Development and application of bio-economic modelling to compare silvoarable, arable and forestry systems in three European countries. Ecological Engineering 29, 434-449.

Gravuer K, Gennet S, Throop HL (2019) Organic amendment additions to rangelands: A meta-analysis of multiple ecosystem outcomes. Global change Biology. Available on-line: DOI: 10.1111/gcb.14535

Greenland DJ, Gregory PJ, Nye PH (1997) Introduction and Conclusions In (Eds. Greenland DJ, Gregory PJ, Nye PH) Land Resources: on the Edge of the Malthuisan Precipice 1-7. The Royal Society and CAB International.

Guo B, Gifford RM (2002) Soil carbon stocks and land use change: a meta-analysis. Global Change Biology 8, 345-360.

Gomiero T, Pimentel D, Paoletti MG (2011) Environmental impact of different agricultural management practices: conventional vs. organic agriculture. Critical Reviews in Plant Sciences, 30:1-2, 95-124, DOI: 10.1080/07352689.2011.554355

Haddaway NR, Hedlund K, Jackson LE, Kätterer T, Lugato E, Thomsen IK, Jørgensen HB, Isberg PE (2017) How does tillage intensity affect soil organic carbon? A systematic review. Environmental Evidence 6, 30.

Han P, Zhang W, Wang G, Sun W, Huang Y (2016) Changes in soil organic carbon in croplands subjected to fertilizer management: a global meta-analysis. Scientific Reports 6, 27199.

Hawkins HJ (2017) A global assessment of Holistic Planned Grazing™ compared with season-long, continuous grazing: meta-analysis findings, African Journal of Range & Forage Science 34, 65-75.

Hijbeek R, van Ittersum MK, ten Berge HFM, Gort G, Spiegel H, Whitmore AP (2017) Do organic inputs matter – a meta-analysis of additional yield effects for arable crops in Europe. Plant and Soil 411, 293-303.

Hobbs R et al (2014) Managing the whole landscape: historical, hybrid and novel ecosystems. Frontiers in Ecology and Environment. 12, 557 – 564.

Holmgren D (2002) Permaculture: Principles and pathways beyond sustainability. Hepburn, Vic: Holmgren Design Services.

Houghton RA (1999) The annual net flux of carbon to the atmosphere from changes in land use 1850–1990, Tellus B: Chemical and Physical Meteorology, 51, 298-313.

Huggins DR, Reganold JP (2008) No-till: the quiet revolution. Scientific American 299, 70–77.

Hurtt G, Chini L, Frolking S, Betts R, Feddema J, Fischer G, Fisk J, Hibbard K, Houghton R, Janetos A, Jones C, Kindermann G, Kinoshita T, Klein Goldewijk K, Riahi K, Shevliakova E, Smith S, Stehfest E, Thomson A, Thornton P, van Vuuren D, Wang Y (2011) Harmonization of land-use scenarios for the period 1500 – 2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands. Climatic Change 109, 117 – 161.

Hutchinson JJ, Campbell CA, Desjardins RL (2007) Some perspectives on carbon sequestration in agriculture. Agricultural and Forest Meteorology 142, 288–302.

HM Government (2018) A Green Future: Our 25 Year Plan to Improve the Environment. www.gov.uk/government/publications.

IPBES (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services) (2017) Progress report on the guide on the production of assessments (deliverable 2 (a)). 3 February 2017.

IPBES (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services) (2018a) Summary for Policymakers of the Assessment Report on Land Degradation and Restoration of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Bonn, Germany: IPBES Secretariat.

IPBES (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem) (2018b) Summary for policymakers of the regional assessment report on biodiversity and ecosystem services for Europe and Central Asia of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. IPBES secretariat, Bonn, Germany. 48 pp.

Intergovernmental Panel on Climate Change (IPCC) (2014) WGII AR5 Chapter 7 https://www.ipcc.ch/site/assets/uploads/2018/02/WGIIAR5-Chap7_FINAL.pdf

Inwood M (2012) Sustainable and Regenerative Agriculture: Farming in a world of finite resources. Accessed 18 December 2018. http://nuffieldinternational.org/live/Report/AU/2011/michael-inwood

IUCN (2019) The Bonn Challenge. http://www.bonnchallenge.org/

Jayne TS, Snapp S, Place F, Sitko N (2019) Sustainable agricultural intensification in an era of rural transformation in Africa. Global Food Security 20, 105–113.

Kamenetzky M, Maybury RH (1989) Agriculture in harmony with nature. Science and Public Policy 16, 73-82.

Kanzler M, Böhm C, Mirck J, Schmitt D, Veste M (2018) Microclimate effects on evaporation and winter wheat (*Triticum aestivum* L.) yield within a temperate agroforestry system. Agroforestry Systems. Available on-line: https://doi.org/10.1007/s10457-018-0289-4

Kassam A, Fredrich T, Shaxon F, Pretty J (2009) The spread of conservation agriculture: justification, sustainability and uptake. International Journal of Agricultural Sustainability 7, 252-320.

Kassam A, Friedrich T, Derpsch R (2019) Global spread of Conservation Agriculture, International Journal of Environmental Studies, 76:1, 29-51, DOI: 10.1080/00207233.2018.1494927

Katayama N, Bouam I, Koshida C, Babaa YG (2019) Biodiversity and yield under different land-use types in orchard/vineyard landscapes: A meta-analysis. Biological Conservation 229, 125-133.

Khan SA, Mulvaney RL, Ellsworth TR, Boast CW (2007) The myth of nitrogen fertilization for soil carbon sequestration. Journal of Environmental Quality 36, 1821–1832.

Kiff E, Chan MK, Jackson D (1997) Integrated Food Crop Systems Project, Ghana: 12 Development and Promotion of Improved Techniques of Water and Soil Fertility Management 13 for the Sustainable Production of Crops on Land in the Humid Forest Belt. (Inception Report). 14 Report No. R6789 AO683. Natural Resources Institute, London.

Kidd J, Manning P, Simkin J, Peacock S, Stockdale E (2017) Impacts of 120 years of fertilizer addition on a temperate grassland ecosystem. PLoS ONE 12(3): e0174632.

Kim D, Kirschbaum MUF, Beedy TL (2016) Carbon sequestration and net emissions of CH_4 and N_2O under agroforestry: Synthesizing available data and suggestions for future studies. Agriculture, Ecosystems and Environment 226, 65–78.

Kleijn D, Bommarco R, Fijen TPM, Garibaldi LA, Potts SG, van der Putten WH (2019) Ecological intensification: bridging the gap between science and practice. Trends in Ecology & Evolution 34, 154-166.

Knudsen MT (2011) Environmental assessment of imported organic products. Focusing on orange juice from Brazil and soybeans from China. Department of Agriculture and Ecology, Faculty of Life Sciences, University of Copenhagen, Denmark. 146 pp.

Korsaeth A (2012) N, P, and K budgets and changes in selected topsoil nutrients over 10 years in a long-term experiment with conventional and organic crop rotations. Applied and Environmental Soil Science 2012(1) DOI: 10.1155/2012/53958

Kotiaho JS, ten Brink B, Harris JA (2016) Land use: A global baseline for ecosystem recovery. Nature 532, 37. doi:10.1038/532037c

Kramer SB, Reganold JP, Glover JD, Bohannan BJM, Mooney HA (2006) Reduced nitrate leaching and enhanced denitrifier activity and efficiency in organically fertilized soils. PNAS 103: 4522–4527.

Krausmann F, Erb K-H, Gingrich S, Lauk C, Haberl H (2008) Global patterns of socioeconomic biomass flows in the year 2000: A comprehensive assessment of supply, consumption and constraints. Ecological Economics, 65, 471–487.

Kremen C, Iles A, Bacon C (2012) Diversified farming systems: an agroecological, systems-based alternative to modern industrial agriculture. Ecology and Society 17, 44.

Kremen CE (2015) Reframing the land-sparing/land-sharing debate for biodiversity conservation. Annals of the New York Academy of Sciences 1355, 52-76.

Lal R (2009) Managing soil carbon for protecting climate and advancing food security. In: Proceedings of the International Conference on Organic Agriculture and Climate Change. 28-29 September 2009, Sofia, Bulgaria.

LaCanne CE, Lundgren JG (2018) Regenerative agriculture: merging farming and natural resource conservation profitably. PeerJ 6:e4428; DOI 10.7717/peerj.4428

Lasanta T, Nadal-Romero E, Arnaez J (2015) Managing abandoned farmland to control the impact of re-vegetation on the environment.The state of the art in Europe. Environmental Science and Policy 52, 99-109.

Lesur-Dumoulin C, Malézieux E, Ben-Ari T, Langlais C, Makowski D (2017) Lower average yields but similar yield variability in organic versus conventional horticulture. A meta-analysis. Agronomy for Sustainable Development 37, 45.

Li S, Li X (2017) Global understanding of farmland abandonment: A review and prospects. Journal of Geographical Sciences, 27, 1123- 1150.

Lichtenberg EM, Kennedy CM, Kremen C, Batary P, Berendse F, Bommarco R, Bosque-Perez NA, Carvalheiro LG, Snyder WE, Williams NM, Winfree R, Klatt BK, Astrom S, Benjamin F, Brittain C, Chaplin-Kramer R, Clough Y, Danforth B, Diekotter T, Eigenbrode SD, Ekroos J, Elle E, Freitas BM, Fukuda Y, Gaines-Day HR, Grab H, Gratton C, Holzschuh A, Isaacs R, Isaia M, Jha S, Jonason D, Jones VP, Klein A-M, Krauss J, Letourneau DK, Macfadyen S, Mallinger RE, Martin EA, Martinez E, Memmott J, Morandin L, Neame L, Otieno M, Park MG, Pfiffner L, Pocock MJO, Ponce C, Potts SG, Poveda K, Ramos M, Rosenheim JA, Rundlof M, Sardinas H, Saunders ME, Schon NL, Sciligo AR, Sidhu CS, Steffan-Dewenter I, Tscharntke T, Vesely M, Weisser WW, Julianna K. Wilson JK, Crowde DW (2017) A global synthesis of the effects of diversified farming systems on arthropod diversity within fields and across agricultural landscapes. Global Change Biology 23, 4946–4957.

Lin HC, Hülsbergen KJ (2017) A new method for analysing agricultural land-use efficiency, and its application in organic and conventional farming systems in southern Germany. European Journal of Agronomy 83, 15-27.

Lin HC, Huber JA, Gerl G, Hülsbergen KJ (2017) Effects of changing farm management and farm structure on energy balance and energy-use efficiency—A case study of organic and conventional farming systems in southern Germany. European Journal of Agronomy 82, 242–253.

Loos J, von Wehrden H (2018) Beyond biodiversity conservation: land sharing constitutes sustainable agriculture in European cultural landscapes. Sustainability 10, 1395.

Lorenz K, Lal R (2014) Soil organic carbon sequestration in agroforestry systems. A review. Agronomy for Sustainable Development 34, 443–454.

Lorimer J, Sandom C, Jepson P, Doughty C, Barau M, Kirby K (2015) Rewilding: Science, Practice and Politics. Annual Review of Environmental Resources 40:8.1-8.24.

Lovins L.H. (2016) The circular economy of soil. In: Ellen MacArthur Foundation (Eds). A New Dynamic 2: Effective Systems in a Circular Economy. 87-105. Isles of Wight: Ellen MacArthur Foundation.

Macedo, MCM, de Araújo, AR (2014) Integrated crop and livestock systems as alternative to recover degraded pastures. In: Bungenstab DJ, de Almeida RG (Eds) Integrated Crop-Livestock-Forestry Systems: A Brazilian Experience for Sustainable Farming, 43-63. Brasilia: Embrapa.

Maetens W, Vanmaercke M, Poesen J, Jankauskas B, Jankauskiene G, Ionita I (2012) Effects of land use on annual runoff and soil loss in Europe and the Mediterranean: A meta-analysis of plot data, Progress in Physical Geography 36, 599–653.

Mathew RP, Feng Y, Githinji L, Ankumah R, Balkcom KS (2012) Impact of no-tillage and conventional tillage systems on soil microbial communities. Applied and Environmental Soil Science 2012, Article ID 548620, doi:10.1155/2012/548620

McLauchlan K (2006) The nature and longevity of agricultural impacts on soil carbon and nutrients: a review. Ecosystems 9, 1364-1382.

Metcalfe JP, Cormack WF (2000) Energy Use in Organic Farming Systems. MAFF Project OF0182:

Metay A, Mary B, Arrouays D, Labreuche J, Martin M, Nicolardot B, Germon JC (2009) Effects of reduced or no tillage practices on C sequestration in soils in temperate regions. Canadian Journal of Soil Science 89, 623–634.

McGuire M (2018) Regenerative Agriculture: Solid Principles, Extraordinary Claims. http://csanr.wsu.edu/regen-ag-solid-principles-extraordinary-claims/

Mehrabi Z, Ellis EC, Ramankutty N (2018) The challenge of feeding the world while conserving half the planet. Nature Sustainability 1, 409-412.

Mollison B, Holmgren D (1981) Permaculture One: A Perennial Agriculture for Human Settlements. International Tree Corps Institute, USA.

Mondelaers K, Aertsens J, Huylenbroeck GV (2009) A meta-analysis of the differences in environmental impacts between organic and conventional farming. British Food Journal 111, 1098-1119.

Moreno Marcos G, Obrador JJ, García E, Cubera E, Montero MJ, Pulido F, Dupraz C (2007) Driving competitive and facilitative interactions in oak dehesas through management practices. Agroforestry Systems, 70, 25–40.

Morris J, Posthumus H, Hess T, Gowing D, Rouquette J (2009) Watery land: the management of lowland floodplains in England. In: Winter M, Lobley M (Eds) What is Land for? The Food, Fuel, and Climate Change Debate. Earthscan, London and Washington, 340pp.

Mottet A, de Hann C, Falcucci A, Tempio G, Opio C, Gerber P (2017) Livestock: on our plates or eating at our table? A new analysis of the feed/food debate. Global Food Security 14, 1-8.

Müeller C, De Baan L, Köllner T (2014) Comparing direct land use impacts on biodiversity of conventional and organic milk—based on a Swedish case study. International Journal of Life Cycle Assessment. 19, 52-68.

Mutuo PK, Cadisch G, Albrecht A, Palm CA, Verchot L (2005) Potential of agroforestry for carbon sequestration and mitigation of greenhouse gas emissions from soils in the tropics. Nutrient Cycling in Agroecosystems 71, 43–54

Nair PKR (2012) Climate change mitigation: a low-hanging fruit of agroforestry. In: Nair PKR, Garrity D (Eds) Agroforestry—The Future of Global Land Use, 31–67. Springer: Netherlands.

Navarro LM, Pereira HM (2015) Rewilding abandoned landscapes in Europe. In: Pereira HM, Navarro LM (Eds) Rewilding European Landscapes 3-23. Springer.

Nelson RA, Cramb RA (1998) Economic incentives for farmers in the Philippine uplands to adopt hedgerow intercropping. Journal of Environmental Management 54, 83-100.

Niether W, Schneidewind U, Fuchs M, Schneider M, Armengot L (2019) Below- and aboveground production in cocoa monocultures and agroforestry systems. Science of the Total Environment 657, 558–567.

Nordborg M (2016) Holistic management – a critical review of Allan Savory's grazing method. Swedish University of Agricultural Sciences. https://www.slu.se/globalassets/ew/org/centrb/epok/dokument/holisticmanagement_review.pdf

Ortiz-Rodriguez OO, Villamizar-Gallardo RA, Naranjo-Merino A, Garcia-Caceres G, Castaneda-Galvis M. (2016) Carbon footprint of the Colombian cocoa production. Journal of the Brazilian Association of Agricultural Engineering 36, 260-270.

Oxford English Dictionary (2002) Concise Oxford English Dictionary. Oxford University Press.

Pannel DJ (1999) Social and economic challenges in the development of complex farming systems. Agroforestry Systems 45, 393-409.

Pandit R, Parrota J, Anker Y, Coudel E, Diaz Morejón CF, Harris J, Karlen DL, Kertész Á, Mariño De Posada JL, Ntshotsho Simelane P, Tamin NM, Vieira DLM (2018) Chapter 6: Responses to halt land degradation and to restore degraded land. In: (Eds. Montanarella L, Scholes R, Brainich A) IPBES: The IPBES assessment report on land degradation and restoration. Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem services, Bonn, Germany.

Passianoto CC, Ahrens T, Feigl BJ, Steudler PA, Carmo JB, Melillo JM (2003) Emissions of CO_2, N_2O, and NO in conventional and no-till management practices in Rondônia, Brazil. Biology and Fertility of Soils, 38, 200-208.

Pearson CJ (2007) Regenerative, semiclosed systems: a priority for twenty-first-century agriculture. BioScience 57, 409–418.

Pérez-Ruíz M, Slaughter DC, Fathalla FA, Gliever CJ, Miller BJ (2014) Co-robotic intra-row weed control system. Biosystems Engineering 126, 45-55.

Philpott SM, Arendt WJ, Armbrecht I, Bichier P, Diestch TV, Gordon C, Greenberg R, Perfecto I, Reynoso-Santos R, Soto-Pinto L, Tejeda-Cruz C, Williams-Linera G, Valenzuela J, Zolotoff J (2008) Biodiversity loss in Latin American coffee landscapes: Review of the evidence on ants, birds, and trees. Conservation Biology, 22, 1093–1105.

Pittelkow CM, Linquist BA, Lundya ME, Liang X, van Groenigen KJ, Lee J, van Gestel N, Six J, Rodney T, Venterea RT, van Kessel C (2015) When does no-till yield more? A global meta-analysis. Field Crops Research 183, 156–168.

Parliamentary Office of Science and Technology (post) (2012) Balancing Nature and Agriculture. POST Note 418. POST, London.

Ponisio LC, M'Gonigle LK, Mace KC, Palomino J, de Valpine P, Kremen C (2015) Diversification practices reduce organic to conventional yield gap. Proceedings of the Royal Society B 282, 1396.

Pretty JN (1995) Regenerating Agriculture: Policies and Practice for Sustainability and Self-reliance. Washington DC: Joseph Henry Press.

Pretty J, Benton TG, Bharucha ZP, Dicks LV, Flora CB, Godfray HCJ, Goulson D, Hartley S, Lampkin N, Morris C, Pierzynski G, Prasad PVV, Reganold J, Rockström J, Smith P, Thorne P, Wratten S (2018) Global assessment of agricultural system redesign for sustainable intensification. Nature Sustainability 1, 441–446.

Queiroz C, Beilin R, Folke C, Lindborg R (2014) Farmland abandonment: threat or opportunity for biodiversity conservation? A global review. Frontiers of Ecology and Environment 12(5), 288–296.

Rahmann G (2011) Biodiversity and organic farming: what do we know? Agricultural and Forestry Research 3(61), 189-208

Ramankutty N, Graumlich L, Achard F, Alves D, Chhabra A, DeFries RS, Foley J, Geist H, Houghton RA, Goldewijk KK, Lambin EF, Millington A, Rasmussen K, Reid RS, Turner BL (2006) Chapter 2: Global Land-Cover Change: Recent Progress, Remaining Challenges. DOI: 10.1007/3-540-32202-7_2

Redman G (2018) John Nix Pocketbook for Farm Management for 2019. Leicestershire UK: Agro Business Consultants Ltd. 305 pp.

Rey Benayas JM, Martins A, Nicolau JM, Schulz JJ (2007) Abandonment of agricultural land: an overview of drivers and consequences. CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources 2, 057.

Regen Network (2018) What is Regeneration? Accessed 10 December 2018. https://www.regen.network/

Reguzzonia A (2018) What does the new regenerative organic certification mean for the future of good food? https://civileats.com/2018/03/12/what-does-the-new-regenerative-organic-certification-mean-for-the-future-of-good-food/

Rhodes CJ (2015) Permaculture: Regenerative – not merely sustainable. https://www.resilience.org/stories/2015-11-02/permaculture-regenerative-not-merely-sustainable/

Rhodes CJ (2017) The imperative for regenerative agriculture. Science Progress, 100, 80-129, DOI: https://doi.org/10.3184/003685017X14876775256165

Robertson GP, Eldor AP, Harwood RP (2000) Greenhouse gases in intensive agriculture: contributions of individual gases to the radiative forcing of the atmosphere. Science 289, 1922–1925.

Rodale Institute (2014) Regenerative Organic Agriculture and Climate Change: A down to Earth Solution to Global Warming. Accessed 18 December 2018. 24 pp. https://rodaleinstitute.org/wp-content/uploads/rodale-white-paper.pdf

Rodale Institute (2018) Framework for Regenerative Organic Certification. https://regenorganic.org/wp-content/uploads/2018/08/ROC-Framework-Aug-2018_Pilot-Version.pdf

Roldán A, Salinas-García AJR, Alguacil BMM, Díaz AG, Caravaca F (2004) Changes in soil microbial activity following conservation tillage practices in a sorghum field under subtropical conditions. ISCO 2004 - 13th International Soil Conservation Organisation Conference – Conserving Soil and Water for Society: Sharing Solutions. Brisbane, July 2004.

Röös E, Mie A, Wivstad M, Salomon E, Johansson B, Gunnarsson S, Wallenbeck A, Hoffmann R, Nilsson U, Sundberg C, Watson CA (2018) Risks and opportunities of increasing yields in organic farming. A review. Agronomy for Sustainable Development 38: 14.

RSA (2018) Food, Farming and Countryside Commission: Our Common Ground. Progress Report. https://www.thersa.org/discover/publications-and-articles/reports/food-farming-countryside-commission-our-common-ground

Sala OE, Chapin FS, Armesto JJ, Berlow E, Bloomfield J, Dirzo R, Huber-Sanwald E, Huenneke LF, Jackson RB, Kinzig A, Leemans R, Lodge DM, Mooney HA, Oesterheld M, Poff NL, Sykes MT, Walker BH, Walker M, Wall DH (2000) Global biodiversity scenarios for the year 2100. Science 287, 1770 – 1774.

Sánchez-Bayo F, Wyckhuys KAG (2019) Worldwide decline of the entofauna: a review of its drivers, Biological Conservation 232, 8-27.

Santos PZF, Crouzeilles R, Sansevero JBB (2019) Can agroforestry systems enhance biodiversity and ecosystem service provision in agricultural landscapes? A meta-analysis for the Brazilian Atlantic Forest. Forest Ecology and Management 433, 140–145.

Savory A, Duncan T (2016) Chapter 4.4 - Regenerating agriculture to sustain civilization. In: Chabay I, Frick M, Helgeson J (Eds) Land Restoration: Reclaiming Landscapes for a Sustainable Future, 289-309. Academic Press.

Schmitz PM, Garvert HE (2012) Agro-economic analysis of the use of glyphosate in Germany. Journal fur Kulturpflanzen 64, 150-162.

Seddaiu G, Bagella S, Pilina A, Cappai C, Salis L, Rossetti I, Lai R, Roggero PP (2018) Mediterranean cork oak wooded grasslands: synergies and trade-offs between plant diversity, pasture production and soil carbon. Agroforestry Systems 92, 893-908.

Sereke F, Dobricki M, Wilkes J, Kaeser A, Graves AR, Szerencsits E, Herzog F (2017) Swiss farmers don't adopt agroforestry because they fear for their reputation. Agroforestry Systems 90, 385–394.

Serle O (2017) Regenerative Agriculture. A Soil Health Focus. Nuffield Australia Project No 1307. March 2017. Accessed 18 December 2018. http://nuffieldinternational.org/live/Report/AU/2013/paul-serle

Seufert V, Ramankutty N, Foley JA (2012) Comparing the yields of organic and conventional agriculture. Nature 485, 229.

Shi L, Feng W, Xu J, Kuzyakov Y (2018) Agroforestry systems: Meta-analysis of soil carbon stocks, sequestration processes, and future potentials. Land Degradation and Development 29, 3886–3897.

Sherwood S, Uphoff N (2000) Soil health: research, practice and policy for a more regenerative agriculture. Applied Soil Ecology 15, 85–97.

Simon S, Bouvier J-C, Debras J-F, Sauphanor B (2010) Biodiversity and pest management in orchard systems. A review. Agronomy for Sustainable Development 30, 139–152.

Silver WL, Ostertag R, Lugo AE (2000) The potential for carbon sequestration through reforestation of abandoned tropical agricultural and pasture lands Restoration Ecology 8, 394–407.

Skinner C, Gattinger A, Mueller A, Mäder P, Fließbach A, Stolze M, Ruser R, Niggli U (2014) Greenhouse gas fluxes from agricultural soils under organic and non-organic management – A global meta-analysis. Science of the Total Environment 468-469, 553-563.

Smaje C (2018) Waiting on amber: a note on regenerative agriculture and carbon farming. https://smallfarmfuture.org.uk/2018/03/waiting-on-amber-a-note-on-regenerative-agriculture-and-carbon-farming/

Smiraglia D, Ceccarelli T, Bajocco S, Salvati L, Perini L (2016) Linking trajectories of land change, land degradation processes andecosystem services. Environmental Research 147, 590–600.

Smith LG, Jones PJ, Kirk GJD, Pearce BD, Williams AG (2018) Modelling the production impacts of a widespread conversion to organic agriculture in England and Wales. Land Use Policy 76, 391–404.

Smith P, Powlson DS, Glendining MJ, Smith JU (1998) Preliminary estimates of the potential for carbon mitigation in European soils through no-till farming. Global Change Biology 4, 679-685.

Smith P, Clark H, Dong H, Elsiddig EA, Haberl H, Harper R, House J, Jafari M, et al. (2014) Chapter 11 - Agriculture, forestry and other land use (AFOLU). In: Climate Change 2014: Mitigation of Climate Change. IPCC Working Group III Contribution to AR5. Cambridge University Press. http://pure.iiasa.ac.at/id/eprint/11115/

Smith P, Haberl H, Popp A, Erb K, Lauk C, Harper R, Tubiello FN, de Siqueira Pinto A, Jafari M, Sohi S, Masera O, Böttcher H, Berndes G, Bustamante M, Ahammad H, Clark H, Dong H, Elsiddig EA, Mbow C, Ravindranath NH, Rice CW, Robledo Abad C, Romanovskaya A, Sperling F, Herrero M, House JI, Rose S (2013) How much landbased greenhouse gas mitigation can be achieved without compromising food security and environmental goals? Global Change Biology 19, 2285–2302.

Society for Ecological Restoration (2004) The SER International Primer on Ecological Restoration. SER Washington, DC. https://cdn.ymaws.com/www.ser.org/resource/resmgr/custompages/publications/ser_publications/ser_primer.pdf

Soloviev ER, Landua G (2016) Levels of Regenerative Agriculture. Accessed 18 December 2018. Terra Genesis International. http://www.terra-genesis.com/wp-content/uploads/2017/03/Levels-of-Regenerative-Agriculture-1.pdf

Soulé ME, Noss R (1998) Rewilding and biodiversity. Wild Earth 8, 2–11.

Spencer J (2017) Knepp Castle Estate Wildland Project Conservation Area Audit for VCA. https://static1.squarespace.com/static/595ca91bebbd1a1d0aaab285/t/5a537b1fc830256b61c30b0c/1515420458874/Knepp+Castle+Wildlands+VCA+audit+Report+JWS+12+12+16+%282%29.pdf

Springmann M, Clark M, Mason-D'Croz D, Wiebe K, Bodirsky BL, Lassaletta L, de Vries W, Vermeulen SJ, Herrero M, Carlson KM, Jonell M, Troell M, DeClerck F, Gordon LJ, Zurayk R, Scarborough P, Rayner M, Loken B, Fanzo J, Godfray HCJ, Tilman D, Rockström J, Willett W (2018) Options for keeping the food system within environmental limits. Nature 562, 519–525.

Struik PC, Kuyper TW (2017) Sustainable intensification in agriculture: the richer shade of green. A review. Agronomy for Sustainable Development 37, 39.

Swinkels R, Franzel S (1997) Adoption potential of hedgerow intercropping in maize-based cropping systems in the highlands of western Kenya. 2. Economic and farmers' evaluation. Experimental Agriculture 33, 211-223.

Syers JK (1997) Managing soils for long-term productivity. Philosophical Transactions of the Royal Society London B, 352, 1011-1021.

Teague R, Provenza F, Kreuter U, Steffens T, Barnes M (2016) Multi-paddock grazing on rangelands: Why the perceptual dichotomy between research results and rancher experience? Journal of Environmental Management 128, 699-717.

Teague R, Barnes M (2017) Grazing management that regenerates ecosystem function and grazingland livelihoods, African Journal of Range & Forage Science 34, 77-86.

Teague WR (2018) Forages and Pastures Symposium: Cover crops in livestock production: Whole System Approach: Managing grazing to restore soil health and farm livelihoods, Journal of Animal Science, 96, 1519–1530. https://doi.org/10.1093/jas/skx060

Terra Genesis International (2017) Regenerative Agriculture: A Definition. Accessed 18 December 2018. http://www.terra-genesis.com/wp-content/uploads/2017/03/Regenerative-Agriculture-Definition.pdf

Thevathasan NV, Gordon AM, Wotherspoon A, Graungaard K, Dunfield K, Jeffries D, Heck R, Coleman R, Voroney P (2016) Tree-based intercropping systems: a potential land-use solution for climate change mitigation in Canadian agricultural landscapes. In: Proceedings of the 3rd European Agroforestry Conference 204-207 Montpellier, 23-25 May 2016.

Tilman D, Balzer C, Hill J, Befort BL (2011) Global food demand and the sustainable intensification of agriculture. PNAS 108, 20260–20264.

Toensmeier E (2016) The Carbon Farming Solution: A Global Toolkit of Regenerative Agriculture. White River Junction, Vermont; Chelsea Green Publishing.

Tonitto C, Ricker-Gilbert JE (2016) Nutrient management in African sorghum cropping systems: applying meta-analysis to assess yield and profitability. Agronomy for Sustainable Development 36, 10. https://doi.org/10.1007/s13593-015-0336-8

Torralba M, Fagerholm N, Burgess PJ, Moreno G, Plieninger T (2016) Do European agroforestry systems enhance biodiversity and ecosystem services? A meta-analysis. Agriculture, Ecosystems and Environment 230: 150-161.

Topp CFE, Stockdale EA, Wateson CA, Rees RM (2007) Estimating resource use efficiencies in organic agriculture: a review of budgeting approaches used. Journal of the Science of Food and Agriculture 87. 2782-2790.

Tuomisto HL, Hodge ID, Riordan P, Macdonald DW (2012) Does organic farming reduce environmental impacts? A meta-analysis of European research. Journal of Environmental Management 112, 309-320.

Tuomisto HL, Angileri V, De Camillis C, Loudjani P, Nisini L, Pelletier N, Haastrup P (2013) Final Technical Report: Certification of Low Carbon Farming Practices. JRC Technical Report.

United Nations (2013) Trade and Environment Review 2013, Make Agriculture Truly Sustainable Now for Food Security in a Changing Climate. https://unctad.org/en/publicationslibrary/ditcted2012d3_en.pdf

United Nations (2015) United Nations Sustainable Development Goals. https://www.un.org/sustainabledevelopment/sustainable-development-goals/

United Nations (2017) World Population Prospects 2017. https://population.un.org/wpp/DataQuery/

United Nations (2019) United Nations Decade on Ecosystem Restoration (2021-2030), adopted by the 73rd session of the General Assembly 1st March 2019, Document A/RES/73/284.

VandenBygaart AJ, Gregorich EG, Angers DA (2003) Influence of agricultural management on soil organic carbon: A compendium and assessment of Canadian studies. Canadian Journal of Soil Science 83, 363–380.

van Groenigen JW, van Kessel C, Hungate BA, Oenema O, Powlson DS, van Groenigen KJ (2017) Sequestering soil organic carbon: a nitrogen dilemma. Environmental Science & Technology 51, 4738–4739. doi: 10.1021/acs.est.7b01427.

Vicente-Vicente JL, García-Ruiz R, Francaviglia R, Aguilera E, Smith P (2016) Soil carbon sequestration rates under Mediterranean woody crops using recommended management practices: A meta-analysis. Agriculture, Ecosystems and Environment 235, 204–214.

Vlek PLG, Kühne FR, Denich M (1997) Nutrient resources for crop production in the tropics. Philosophical Transactions of the Royal Society London B, 352, 975-985.

West TO, Post WM (2002) Soil organic carbon sequestration rates by tillage and crop rotation: a global data analysis. Soil Science Society of America Journal 66, 1930-1946.

Whitefield P (2011) The Earth Care Manual: A Permaculture Handbook for Britain and other Temperate Climates. Hampshire: Permanent Publications.

Whitmee S, Haines A, Beyrer C, Boltz F, Capon AG, Ferreira de Souza Dias B, Ezeh A, Frumkin H, Gong P, Head P, Horton R, Mace GM, Marten R, Myers SS, Nishtar S, Osofsky SA, Pattanayak SK, Pongsiri MJ, Romanelli C, Soucat A, Vega J, Yach D (2015) Safeguarding human health in the Anthropocene epoch: report of The Rockefeller Foundation–Lancet Commission on planetary health. The Lancet 386, 1973-2028.

Willer H, Lernoud J (Eds.) (2016) The World of Organic Agriculture: Statistics and Emerging Trends 2016. Research Institute of Organic Agriculture (FiBL), Frick, and IFOAM – Organics International, Bonn. Retrieved from https://shop.fibl.org/CHde/mwdownloads/download/link/id/747/?ref=1

Willer H, Lernoud J (2019) The World of Organic Agriculture. Statistics and Emerging Trends 2019. Bonn, Germany and Frick, Switzerland: IFOAM & FiBL, p. 354. https://shop.fibl.org/CHen/mwdownloads/download/link/id/1202/?ref=1

Willett W et al. (2019) Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. The Lancet. http://dx.doi.org/10.1016/S0140-6736(18)31788-4

Wilting HC, Schipper AM, Bakkenes M, Meijer JR, Huijbregts MAJ (2017) Quantifying biodiversity losses due to human consumption: a global-scale footprint analysis. Environmental Science and Technology 51, 3298−3306.

Wirsenius S (2003) The biomass metabolism of the food system: a model-based survey of the global and regional turnover of food biomass. Journal of Industrial Ecology, 7, 47–80.

Wirsenius S, Azar C, Berndes G (2010) How much land is needed for global food production under scenarios of dietary changes and livestock productivity increases in 2030? Agricultural Systems, 103, 621–638.

World Bank (2012) Carbon sequestration in Agricultural Soils. 118 pp http://documents.worldbank.org/curated/en/751961468336701332/Carbon-sequestration-in-agricultural-soils

Wolff S, Schrammeijer EA, Schulp CJE, Verburg PH (2018) Meeting global land restoration and protection targets: What would the world look like in 2050? Global Environmental Change 52, 259–272.

Zake J, Pietsch SA, Friedel JK, Zechmeister-Boltenstern S (2015) Can agroforestry improve soil fertility and carbon storage in smallholder banana farming systems? J. Plant Nutr. Soil Sci. 178, 237–249.

Ziesemer J (2007) Energy use in organic food systems. Food and Agriculture Organization of the United Nations, Rome.

Zomer, RJ, Trabucco A, Coe R, Place F, van Noordwijk M, Xu JC (2014) "Trees on Farms: An Update and Reanalysis of Agroforestry's Global Extent and Socio-Ecological Characteristics." World Agroforestry Center Working Paper 179 (2014). http://www.worldagroforestry.org/sea/Publications/files/workingpaper/WP0182-14.pdf

8 Appendices

Appendix A: Papers identified in the Scopus database with "Regenerative Agriculture" in article, abstract or keywords

No	Reference
1	Elevitch et al. (2018) Agroforestry standards for regenerative agriculture. Sustainability 2018, 10, 3337
2	Teague WR (2018) Forages and Pastures Symposium: Cover crops in livestock production: Whole System Approach: Managing grazing to restore soil health and farm livelihoods, Journal of Animal Science, 96, 1519–1530, https://doi.org/10.1093/jas/skx060
3	LaCanne, CE, Lundgren JG (2018) Regenerative agriculture: merging farming and natural resource conservation profitably. PeerJ 6:e4428; DOI 10.7717/peerj.4428
5	Gravuer K, Gennet S, Throop HL (2019). Organic amendment additions to rangelands: A meta-analysis of multiple ecosystem outcomes. Global Change Biology https://doi.org/10.1111/gcb.14535
6	Shelef O, Weisberg PJ, Provenza FD (2017). The value of native plants and local production in an era of global agriculture. Frontiers in Plant Science https://doi.org/10.3389/fpls.2017.02069
7	Teague R, Barnes M (2017) Grazing management that regenerates ecosystem function and grazingland livelihoods, African Journal of Range & Forage Science, 34:2, 77-86, https://doi.org/10.2989/10220119.2017.1334706
8	Rhodes, CJ (2017). The imperative for regenerative agriculture. Science Progress, 100, 80-129, DOI: https://doi.org/10.3184/003685017X14876775256165
9	Carr PM (2017). Guest editorial: conservation tillage for organic farming. Agriculture (Switzerland), 7(3), 19 https://doi.org/10.3390/agriculture7030019
11	Duncan T (2016). Chapter 4.3 - Case Study: Taranaki Farm Regenerative Agriculture. Pathways to Integrated Ecological Farming. In: Chabay I, Frick M, Helgeson J (Eds). Land Restoration: Reclaiming Landscapes for a Sustainable Future, 271-287. Academic Press. https://doi.org/10.1016/B978-0-12-801231-4.00022-7
12	Savory A, Duncan T (2016). Chapter 4.4 - Regenerating Agriculture to Sustain Civilization. In: Chabay I, Frick M, Helgeson J (Eds). Land Restoration: Reclaiming Landscapes for a Sustainable Future, 289-309. Academic Press. https://doi.org/10.1016/B978-0-12-801231-4.00023-9
13	Rhodes C (2012). Feeding and healing the world: through regenerative agriculture and permaculture. Science Progress, 95(4) 345-446. https://doi.org/10.3184/003685012X13504990668392
14	de la Torre Ugarte DG, Hellwinckel CC (2010). The problem is the solution: the role of biofuels in the transition to a regenerative agriculture. Biotechnology in Agriculture and Forestry, 66, 365-384. Springer DOI: 10.1007/978-3-642-13440-1_14
15	Bond AC (2009) Contextual analysis of agroforestry adoption in the buffer zone of Podocarpus National Park, Ecuador. Journal of Sustainable Forestry 28,825-843 https://doi.org/10.1080/10549810902794568
17	Sherwood S, Uphoff N (2000). Soil health: research, practice and policy for a more regenerative agriculture Applied Soil Ecology 15, 85–97.
18	Roberts, B. (2000). NGO leadership success, and growth in Senegal: Lessons from ground level, Urban Anthropology 29(2), 143-180.
19	Diop AM (1999) Sustainable Agriculture: New Paradigms and Old Practices? Increased Production with Management of Organic Inputs in Senegal. Environment, Development and Sustainability 1, 285–296.
20	Keeney D, Vorle W (1998). Bugs in the System: Redesigning the Pesticide Industry for Sustainable Agriculture.
21	Burkhardt, J. (1989). The morality behind sustainability. Journal of Agricultural Ethics 2(2), 113-128.
22	Kamenetzky M, Maybury RH (1989) Agriculture in harmony with nature. Science and Public Policy 16, 73-82. https://doi.org/10.1093/spp/16.2.73
23	Francis CA, Harwood RR, Parr JF (1986). The potential for regenerative agriculture in the developing world. American Journal of Alternative Agriculture 1, 65-74. https://doi.org/10.1017/S0889189300000904

Appendix B: Relating agricultural areas and yields to global demands

The area of grassland required (A_{grass}) required is the product of the global population (P), the proportion wasted (W), the proportion of animal products that is used as food (f_{food}), the demand for animal products as food per person (D_{animal}; kg/person/year), the conversion ratio of the amount of grass required per unit animal product ($cr_{pasture}$), and the mean yield of grassland (Y_{grass}) (Equation 1; Table B.1).

$$A_{grass} = P\,(1/(1-W))\,(\frac{1}{f_{food}})\,\left(D_{animal}\; cr_{pasture}\right)/(Y_{graze}) \qquad \text{Equation 1}$$

Population values (P) are provided by UN (2017). The mean level of waste (W) in 2007 was about 30% of global food grown (FAO 2011).

Table B.1. Factors in the calculation of grassland production in 2000 (derived from Smith et al 2014)

P (million)	W	f_{food}	D_{animal} (kg/capita/yr)	$CR_{pasture}$ kg grass/kg food	Total grass (Million kg)	Y_{grass} (kg/ha)	A_{grass} (million ha)
6150	0.3	0.65	42.3	6.78	3870	1138	3400

The global dry matter of crops required (DM_{crop}) is the sum of the dry matter needed for livestock ($DM_{crop\text{-}livestock}$; Equation 2), for crop-based materials ($DM_{crop\text{-}materials}$; Equation 3), and direct human consumption of crops ($DM_{crop\text{-}food}$; Equation 4)

$$DM_{crop-livestock} = P\,(1/(1-W))\,\left(D_{animal}\; cr_{crop}\right) \qquad \text{Equation 2}$$

$$DM_{crop-materials} = P\; D_{crop-material} \qquad \text{Equation 3}$$

$$DM_{crop-food} = P\; D_{crop} \qquad \text{Equation 4}$$

The values depend on the population (P), the proportion of food wasted (W), the demand of animal products per person (D_{animal}), the conversion ratio of the amount of crop per unit animal product (cr_{crop}), the annual demand per person for crop materials ($D_{crop\text{-}materials}$) and directly-consumed crops ($D_{crop\text{-}food}$). Mean per capita consumption of meat was 42.3 kg/capita in 2000, with a predicted increase to 56 kg/person/year in 2050. The area of cropland A_{crop} required is then the sum of these divided by the mean yield of crop and crop residues (Y_{crop}) (Equation 5), which was equivalent to 4260 kg/ha in 2000 (Table B.2).

$$A_{crop} = \left(DM_{crop-livestock} + DM_{crop-materials} + DM_{crop}\right)/(Y_{crop}) \qquad \text{Equation 5}$$

Table B.2. Factors in the calculation of global crop production in 2000 (derived from Smith et al 2014)

Use of crops	P (million)	W	D (kg/capita/yr)	CR_{crop} kg crop/ kg food	DM (Million kg)	Y_{crop} (kg/ha)	A_{crop} (million ha)
for livestock	6150	0.3	42.3	8.45	3140		
for materials	6150		101		620		
for food directly	6150		289		1780		
Total					5540	4260	1300

Using such calculations it is possible to estimate not just the land and yields required in 2000, but also the land and yields required in previous years, but also in the future. The values in Table B.3 are indicative, but they are useful to demonstrate some of the interactions between population, wastage rates, per capita resource demands, crop and grazing areas, and yields.

Table B.3. Areas of cropland and grazing land in 1900, 1950, 2000 and assumed areas required in 2050 (Derived from Smith et al. 2014 and Krausmann et al. 2008). The scenarios are included for 2050 include a reference value based on FAO (2012) and Smith et al (2014), and one where animal product consumption remains at the 2000 value.

Year	World population[a] (billion)	Level of food waste (%)[b]	Crop-based demand per capita (kg DM/capita/y)[bc]	Animal product-demand (kg DM/capita)[bd]	Crop used for animal production (kg DM/capita)[e]	Cropland area (million ha)[f]	Mean crop and crop residue yield (kg DM/ha)	Demand for grass feed per capita[e] (kg DM)	Assumed harvest of grass (kg DM/ha)[5]	Grazed land area (million ha)[f]	Total managed (million ha)
1900	1.65	30	390	18.6	224	758	1336	277	312	1466	2224
1950	2.50	30	390	18.6	224	1083	1417	277	259	2666	3743
2000	6.15	30	390	42.3	510	**1300**	**4260**	**629**	**1137**	3400	4700
2050 default	*9.77*	*30*	*390*	*[g]56.0*	*675*	*1600*	*[g]6503*	*833*	*2000*	*4070*	*5107*
2050 diet	*9.77*	*30*	*390*	*42.3*	*510*	*1352*	*6503*	*629*	*2000*	*3072*	*4398*

[a]: World population is derived from the UN (2017).

[b]: Values include food waste which is assumed to remain at 30%.

[d]: In 2000: annual crop consumption includes direct consumption of crops (289 kg/capita) and agricultural crop and crop residues for materials and energy (101 kg/capita) = 390 kg/capita. Assumption that crop-based demand per capita is the same in 1900 and 1950 as in 2000.

[d]: Brown (2012) reports that in 1950 global meat production was 45 million tonnes (18 kg/capita). There is no global estimate of meat consumption in 1900, but Brown (2005) reports that meat consumption per capita in the USA was similar in 1909 to that in 1950; hence the same value is used for 1900 and 1950.

[e]: In 2000: 3.14 Gt of crop used for animal-based products divided by 6.15 billion = 510 kg/capita (Smith et al. 2014). 2.94 Pg out of 6.37 Pg of crop-based biomass (46%) is defined as "crop residues" such as straw (Krausmann et al. 2008). 3.87 Gt of pasture-based feed divided by 6.15 billion = 629 kg/capita (Smith et al. 2014). The weight of crop and grass used per weight of animal product output for food (7.01 Pg/0.26 Pg) i.e. 27.0 kg kg^{-1} is high. The weight of animal-derived food per unit crop is 3.14 Pg/0.26 Pg i.e. 12.07 kg kg^{-1}, whilst the weight of animal-derived food per unit grass is 3.87 Pg/0.26 Pg = 14.88 kg kg^{-1}. We applied the same conversion ratios for 1900 and 1950.

[f]: In the literature there is substantial variability in the estimates of cropland and grassland areas. For 2000, Smith et al (2013) quotes the area of cropland of 1300 Mha, yet also quotes the FAO value for cropland in 2011 as 1560 Mha. The area of grazed grassland of 3400 million ha is from Smith et al. (2014). The area of global cropland and grassland in 1900 and 1950 are interpolated from Hurrt et al. (2011). 1900: cropland: 7/12 * 1300; grassland 11/25.5 * 3400; 1950: 10/12 * 1300; grassland 20/25.5 * 3400. In 2050; reference value for grassland and for cropland is 4.07 Gha and 1.60 Gha respectively (Smith et al. 2013).

[g]: The reference case for 2050 is based on Smith et al. (2014) which is similar to the FAO (2006) projections for 2050 and assumes a continuation of on-going trends towards richer diets, considerably higher cropland yields (+52 %) and moderately increased cropland areas (+9 %). FAO (2012) estimates that global meat consumption per capita will increase from 37 kg in 2000 to 49 kg in 2050 (+32%); 42.3 *1.32 = 56. A 40-45% increase in mean crop yields (4.83/3.32) is predicted from 2005 to 2050, so this increase of 52% seems reasonable (FAO, 2012).

Appendix C: Worksheets of evidence

Table C.1. Evidence worksheet for conservation agriculture

Inter-vention (A)	Relative to baseline (B)	Impact	Type of study	Number of studies	Location	Crop yield ratio: A/B	Additional carbon storage	GHG emission ration (A/B)	Bio-diversity	Labour use	Energy use	Reference
CA	v conv. agriculture		Desk-study		Global	1.08	+0.25-0.71 t C/ha/a	-0.23 t CO2eq/ha/a				Drawdown project (2017)
No-till	v conv. tillage	provides similar yields for oilseeds and cotton in most environments	Meta-analysis	74	Global	1.01						Pittelkow et al. 2015
		provides similar yields for legumes in most environments	Meta-analysis	166	Global	1.00						Pittelkow et al. 2015
		provides similar oat and maize yield in dry unirrigated area	Experiment	1	Brazil	1.00						Bayer et al (2015)
		increases soil moisture and thereby crop yields in dry environments	Review	1	Canada							Hutchinson et al (2007).
		reduces yields of root crops in most environments	Meta-analysis	19	Global	0.86						Pittelkow et al. 2015
		reduced yields of maize in most environments	Meta-analysis	224	Global	0.94						Pittelkow et al. 2015
		reduced yields of rice in most environments	Meta-analysis	153	Global	0.96						Pittelkow et al. 2015
		reduced yields of wheat in most environments	Meta-analysis	260	Global	0.97						Pittelkow et al. 2015
						0.97						
No till	v tillage	increases soil carbon in the top 5 cm	Experiment	1	USA		+1% C					Mathew et al (2012)
No till	v conventional tillage	increases soil carbon in the top 25 cm of soil	Review	14	Europe		+0.71% C/yr					Smith et al (1998)
		increases soil carbon in the top 30 cm of soil	Review	1	France		+0.1 t C/ha/yr					Metay et al. (2009)
		increases soil carbon in the surface layer	Experiment	1	USA		+0.3 t C/ha/yr					Robertson et al (2000)
		increases soil carbon in the top 30 cm of soil	Meta-analysis	351	Global		+3.8-4.6 Mg/ha					Haddaway et al (2017)
		increases soil carbon in the top 15 cm of soil	Meta-analysis	93	Global		0.48 t C/ha/yr					West and Post (2012)
No till	v plough tillage	increases soil carbon in the top 10 cm of soil	Field trials	11	United States		Positive					Blanco-Canqui and Lal (2008)
No Till	v conventional tillage	increases soil carbon in the top 20 cm	Experiment	1	USA		+2.8-5.6 t C/ha					Potter et al 1997
No Till	v plough tillage	increases soluble soil carbon in top 10 cm	Experiment	1	Mexico		+20 mg/kg					Roldan et al (2004)
No till	v minimum tillage	had minimal effect on soil carbon in surface layers	Meta-analysis		Western Canada		0					VandenBygaart et al (2003)
No till	v largely plough	increased soil organic carbon in surface layers	Meta-analysis		Eastern Canada		+2.9 Mg C/ha					VandenBygaart et al (2003)
No till	v conventional tillage	increased soil organic carbon	Review	1	Canada		+0.05-0.25 Mg C/ha/yr					Hutchinson et al (2007).
		results in similar levels of soil carbon in 15-35 cm of soil	Meta-analysis	93	Global		0					West and Post (2012)
		results in similar levels of soil carbon in 0-60 cm of soil	Field trials	11	United States		0					Blanco-Canqui and Lal (2008)
		results in similar levels of soil carbon in 0-150 cm of soil	Meta-analysis	351	Global		+0.83-1.65 Mg/ha					Haddaway et al (2017)
No till	v conventional tillage	reduced N_2O emissions for a oat/maize rotation	Experiment		Brazil			-0.47 kg N/ha				Bayer et al (2015)
No till	v conventional tillage	increased N_2O emissions in a vetch/maize rotation	Experiment		Brazil			+0.33 kg N/ha				Bayer et al (2015)
No till	v disc till	resulted in similar N2O and NO emissions	Experiment		Brazil			Similar				Passianoto et al (2003)
Min-till	v ploughed	tended to increase N2O emissions	Review	19	Mediterranean			+0.9 kh N_2O N/ha/yr				Fernandez (2016) page 97
No tillage	v ploughed	decreased growing season CO_2 emissions	Experiment		USA			-0.33 Mg C/ha				Alluvione et al. (2009)
No till	v disc till	Decreased CO2 emissions	Experiment		Brazil			-2.57 Mg /ha				Passianoto et al (2003)
No till	v conventional	assumed to decrease GHG emissions per ha in JRC model	European Model		Europe			-0.4 Mg CO_2e/ha/yr				Tuomisto et al (2013)
No tillage	v ploughed	increased growing season CH_4 emissions	Experiment		USA			+19 g CH_4/ha				Alluvione et al. (2009)
No till	v plough tillage	increased the count of microorganisms in top 7 cm of soil	Experiment	7	United States				increase			Doran (1980)
No till	v plough tillage	reduced microorganism counts below the top 7 cm of soil	Experiment	7	United States				decrease			Doran (1980)
No till	v disc and chisel tillage	had no effect on fungi, bacteria levels in top 15 cm	Experiment	1	United States				similar			Mathew et al (2012)
No till	v disc and chisel tillage	increased PLFA reading in top 15 cm	Experiment	1	United States				+65 nmol/g			Mathew et al (2012)
No till	v intensive tillage	reduced machinery energy inputs	Article		United States						0.20-0.50	Huggins and Reganold (2008)
No till	v intensive tillage	reduced labour inputs	Article		United States					0.50-0.70		Huggins and Reganold (2008)

Colour code: Positive: Similar Negative: Inconclusive or confounding factors:

Table C.2. Evidence worksheet for organic crop production

Intervention A	Baseline B	Impact		Type of study	Number of studies	Location	Inputs	Crop yield ratio: A/B	Additional carbon storage	Soil carbon (A/B)	GHG emission system A/System B	Pest or weed	Reference
Regenerative agriculture	Conventional			Desk study				*1.08*	*0.40-1.40*		*-0.23 t CO_2eq/ha/a*		*Drawdown Project (2017)*
Organic agriculture	Conventional	increased bean yield (organic had more irrigation)		LCA analysis	*2*	Greece		*1.12-1.32*					Abeliotis et al (2013)
Organic maize/legume	Conventional maize/soya	resulted in similar (but less frequent) maize yields		Farm results	*1*	USA		1.00					Drinkwater et al (1998)
Low input practices	Conventional	resulted in similar or lower yields		Article (no data)		USA		0.90-1.00					Kamenetsky and Maybury (1989)
Organic agriculture	Conventional	resulted in lower yields		LCA metaanalysis	37	Global		0.48-0.80					Clarke and Tilman (2017)
Organic agriculture	Conventional	resulted in lower yields		Meta-analysis	115	Global		0.81					Ponsio et al (2014)
Organic agriculture	Conventional	resulted in lower yields		Meta-analysis	20	USA & Europe		0.74					Skinner et al (2014)
Organic agriculture	Non-organic	resulted in lower yields		Meta-analysis	10	Developed		0.83					Mondelaers et al. (2009)
Organic farming	Conventional	reduced the yield of wheat and potatoes		Experimental	1	Germany		0.48-0.58					Lin and Hulsbergen (2017)
Organic horticulture	Non-organic	resulted in lower yields		Meta-analysis	300-560	Global		0.83					Lesur-Dumoulin et al. (2017)
Regen. Ag.	Conventional	resulted in lower maize yields		Field comparison	40 v 38	USA		0.71					LaCanne and Lundgren (2018)
Organic farming	Conventional	resulted in lower yields		Global	315	Global		0.75					Seufert et al. (2012)
Organic	Non-organic farming	reduced yields of wheat, barley, oats		Experiment plots	2	Norway		0.40-0.47					Korsaeth (2012)
Organic no-till	Organic-ploughing	resulted in lower yields		Meta-analysis	21	Europe		0.92					Cooper et al. (2016)
Organic no-till	Organic-ploughing	Increased weeds		Meta-analysis	21	Europe						1.56	
Adding organic inputs	Field with no nutrient def.	had statistically similar yields across most crops		Meta-analysis	107	Europe		1.01					Hijbeek et al. (2017)
Adding organic inputs	Field with no nutrient def.	resulted in higher yields with potatoes		Meta-analysis	11	Europe		1.07					Hijbeek et al. (2017)
Adding organic inputs	Field with no nutrient def.	resulted in higher yields with maize		Meta-analysis	15	Europe		1.04					Hijbeek et al. (2017)
Adding manure	Adding manure + P_2O_5	reduced crop yield		Experiment	1	Senegal		0.71					Diop AM (1999)
Adding manure	Not adding manure	increased sorghum yields		Meta-analysis	13	Africa		+480-880 kg/ha					Tonitto and Ricker-Gilbert (2016)
Not supplying N	Supplying synthetic N	reduced sorghum yields		Meta-analysis	13	Africa		-390-720 kg/ha					Tonitto and Ricker-Gilbert (2016)
Organic	Non-organic	increases organic matter inputs		Meta-analysis	71	Europe	1.35						Tuomisto et al (2012)
Regenerative agriculture	Conventional	increases soil organic carbon		Field comparison	40 v 38	USA				1.09			LaCanne and Lundgren (2018)
Organic	Non-organic	increases soil organic matter		Meta-analysis	9	Developed				1.12			Mondelaers et al. (2009)
Organic	Non-organic	increases soil organic matter		Meta-analysis	71	Europe				1.07			Tuomisto et al (2012)
Add organic amendments	no organic amendments	increases soil organic carbon		Meta-analysis	174	Mediterranean			+1.31 Mg/ha/yr				Aguilera et al (2013)
Addition of manure	no addition of manure	increases soil organic carbon		Meta-analysis	298	Global			+1.8 g C/kg				Han et al (2016)
Organic plough + legumes	Conventional	increased soil carbon		Field study	1	USA			+0.08 Mg/ha/yr				Robertson et al (2000)
Organic cattle production	a maize rotation	increased soil carbon		Field study	1	USA			+0.1 Mg/ha/yr				Drinkwater et al (1998)
Adding green manure	fallow in rotation	increased soil carbon storage		Meta-analysis	7	Canada			+150 kg C/ha/yr				VandenBygaart et al (2003)
No chemical fertilizer	chemical fertilizer	decreases soil organic carbon		Meta-analysis	298	Global			-1.7 g C/kg				Han et al (2016)
Organic apples	Conventional apples	had a higher level of soil carbon		Experiment	1					+1.17%			Kranmer et al (2006)
										1.08			
Regenerative agriculture	Conventional	reduced the numbers of an non-economic pest		Field comparison	40 v 38	USA						0.10	LaCanne and Lundgren (2018)
Organic agriculture	Conventional	increased GWP per unit food		LCA analysis	*2*	Greece					1.22-1.45		Abeliotis et al (2013)
Organic agriculture	Conventional	increased GWP per unit area		LCA analysis	*2*	Greece					1.39-1.91		Abeliotis et al (2013)
Addition of legumes	no legumes in rotation	reduced net GHG gas emissions		European model	1	Europe					-0.4 Mg CO_2e/ha/yr		Tuomisto et al (2013)
Soil cover for whole year	incomplete soil cover	reduced net GHG gas emissions		European model	1	Europe					-0.3 Mg CO_2e/ha/yr		Tuomisto et al (2013)
Organic agriculture	Conventional	reduced GWP per unit area		Meta-analysis	5	Developed					0.57		Mondelaers et al. (2009)
Organic juice production	Conventional	reduced GWP per unit food		LCA analysis	2	China & Brazil					0.60-0.85		Knudsen (2011)
Organic agriculture	Conventional	similar GWP per unit food		Meta-analysis	2	Developed					0.93		Mondelaers et al. (2009)
Organic agriculture	Conventional	similar global warming potential per unit food		LCA meta-analysis	37	Global					0.96		Clarke and Tilman (2017)
Organic agriculture	Conventional	reduced nitrous oxide emissions per unit area		Meta-analysis	20	Europe & USA					0.86		Skinner et al (2014)
Organic agriculture	Conventional	reduced N2O emissions per area (less N applied)		Meta-analysis	10	Europe					0.69		Tuomisto et al (2012)
Organic agriculture	Conventional	increased nitrous oxide emissions per unit food		Meta-analysis	20	Europe & USA					1.08		Skinner et al (2014)
Organic agriculture	Conventional	used similar GHG gas emissions per unit food		Meta-analysis	23	Europe					1.00		Tuomisto et al (2012)

Table C.3. Evidence worksheet for organic crop production (continued)

Intervention A	Baseline B	Impact		Type of study	Number of studies	Location	Eutrophication or acidification potential	Water quality or nitrogen export	Biodiversity	Labour	Energy	Costs	Profit	Reference
Organic agriculture	Conventional	greater eutrophication potential per unit food		LCA meta-analysis	37	Global	1.37							Clarke and Tilman (2017)
Organic agriculture	Conventional	similar acidification potential per unit food		LCA meta-analysis	37	Global	0.87							Clarke and Tilman (2017)
Organic agriculture	Conventional	reduced nitrate leaching per area (less N applied)		Meta-analysis	71	Europe		0.69						Tuomisto et al (2012)
Organic agriculture	Conventional	increased nitrate leaching per unit product		Meta-analysis	71	Europe		1.49						Tuomisto et al (2012)
Organic apples + manure	Apples + synthetic fertiliser	reduced nitrate leaching (for constant N appliied)		Experiment	1			-1.1 mg NO_3-N						Kranmer et al (2006)
Organic agriculture	Conventional	had mixed effects on freshwater toxicity potential		LCA per m2/a	2	Greece								Abeliotis et al (2013)
Organic agriculture	Conventional	reduced the less of nitrate leaching per unit area		Meta-analysis	14	Developed		0.68						Mondelaers et al. (2009)
Organic	Inorganic farming	resulted in depleted soil nitrogen and phosphorus		Experiment plots	2	Norway		-30 kg N - 8 kg P/ha/yr						Korsaeth (2012)
Organic agriculture	Conventional	has a higher energy output/energy input ratio		Review							consistent increase			Gomiero et al (2001)
Organic agriculture	Conventional	uses less energy per unit food		LCA meta-analysis	37	Global					0.85			Clarke and Tilman (2017)
Organic agriculture	Conventional	uses less energy per unit food across all systems		Meta-analysis	37	Europe					0.79			Tuomisto et al (2012)
Organic horticulture	Conventional	generally uses less energy per unit area		LCA study	1	UK					reduction			Metcalfe and McCormack (2000)
Organic horticulture	Conventional	generally uses less energy per unit food		LCA study	1	UK					reduction except carrots			Metcalfe and McCormack (2000)
Organic farming	Inorganic farming	reduces fossil-fuel based inputs		Review							0-50-0.70			Zeismer (2007)
Organic farming	Non-organic farming	increases floral and faunal diversity		Review	21	Global			Consistent increase					Gomiero et al (2001)
Organic farming	Conventional farming	increased arthropod abundance		Meta-analysis	81	Global			1.45					Lichtenberg et al (2017)
Organic farming	Conventional farming	increased abundance of pollinator species		Meta-analysis	20	Global			1.90					Lichtenberg et al (2017)
Organic farming	non-organic farming	increases biodiversity in most environments		Meta-analysis	396	Global			83% pos; 3% neg					Rahmann (2011)
Organic farming	Non-organic farming	increases species richness for most species groups		Meta-analysis	63	Global			1.30					Bengtsson et al (2005)
Organic farming	Non-organic farming	increases the mean abundance of species		Meta-analysis	63	Global			1.50					Bengtsson et al (2005)
Organic farming	Conventional farming	increased arthropod abundance		Meta-analysis	81	Global			1.10-1.21					Lichtenberg et al (2017)
Organic farming	Conventional farming	increased abundance of pollinator species		Meta-analysis	20	Global			1.32-1.55					Lichtenberg et al (2017)
Organic farming	Non-organic farming	increases the mean abundance of weed species		Meta-analysis	5	Global			1.50					Bengtsson et al (2005)
Organic farming	Non-organic farming	did not significant affect the species richness of soil organisms		Meta-analysis	63	Global			Positive but not significant					Bengtsson et al (2005)
Low input farming	Conventional farming	resulted in higher species richness		Modeling		Global			1.64					Elshout et al (2014)
Adding manure	Not adding manure	increased crop revenue from sorghum		Meta-analysis	13	Africa							+$133-176/ha	Tonitto and Ricker-Gilbert (2016)
Regenerative agriculture	Conventional	resulted in lower cost of production		Field comparison	40 v 38 field	USA						0.58		LaCanne, CE, Lundgren JG (2018)
No fertiliser input	conventional beef	reduced net returns		Article (no data)		USA							Reduced	Kamenetsky and Maybury (1989)
Organic maize/ legume rotation	Conventional Maize/soya rotation	requires more labour		Farm comparison	1	USA				Higher				Hanson et al. (1997)
Organic farming	Inorganic farming	increases labour requirements		Review						Higher				Gomiero et al (2001)
Organic farming	Inorganic farming	increases labour requirements		Review						1.30-1.35				Zeismer (2007)
Organic farming	Inorganic farming	increases labour costs		Meta-analysis	129	Global				1.07-1.13				Crowder and Reganold (2015)
Organic farming	Inorganic farming	reduces profitability (if no organic premium)		Meta-analysis	129	Global							0.73-0.77	Crowder and Reganold (2015)
Organic farming	Inorganic farming	increases profitability (with organic premium)		Meta-analysis	129	Global							1.22-1.35	Crowder and Reganold (2015)

Table C.4. Evidence worksheet for tree crops

Intervention A	Baseline B	Impact		Type of study	Number of studies	Location	Inputs	Crop yield ratio: system A/System B	Additional carbon storage	Soil carbon (System A/System B)	GHG emission system A/System B	Biodiversity	Profit	Reference
Tree crops														
Tropical staple trees	*Annual crops on degraded land*			*Desk study*	*9*	*Global*		*2.40*	*4.70* t C ha^{-1} a^{-1}					*The Drawdown project (2017) on degraded land*
Plantation	Cropland	increased soil carbon		Meta-analysis	74	Global				1.18				Guo and Gifford (2002)
Shaded perennial system	Agriculture	increased soil carbon		Review/meta-analysis	2	Global				1.01				Kim et al. (2016)
Bananas	Maize	increased calorie production		Model	1	Rwanda		1.60						Bidogeza et al. (2015)
Bananas	Maize	reduced protein production		Model	1	Rwanda		0.75						Bidogeza et al. (2015)
Agroforestry	Degraded arable and grassland	can increase above ground carbon sequestration		Review		Global			0.4-2.8 t C/ha/yr	0.2-0.6 t C/ha/yr				Mutoni et al (2005)
Fruit trees	Arable	increased the potential carbon sequestration by plants		Regional study	2	Bari				2-28 t CO_2/ha/yr				Dal Sasso et al (2012)
Tree plantation	Agricultural land	had no significant effect on nitrous oxide emissions		Review/meta-analysis	1						-1.4 kg NO_2/ha/yr			Kim et al. (2016)
Orchard	Arable cropping	Increases biodiversity of arthropods and insectivorous birds		Review	1	Global						increases		Simon et al (2010)

Table C.5. Evidence worksheet for tree intercropping

Intervention A	Baseline B	Impact		Type of study	Number of studies	Location	Crop yield ratio: A/B	Additional carbon storage	Soil carbon (A/B)	GHG emission system A/System B	Water quality or nitrogen export	Soil erosion: A/ B	Biodiversity	Labour	Energy	Profit	Reference
Tree-intercropping	*Annual crops*			*Desk study*		*Global*		*0.90-2.70*								*1.02*	*The Drawdown project (2017) on degraded land*
Tree intecropping with soybean	Soybean production	increased potential carbon sequestration		Field experiment	1	Canada		+0.84 to +2.12 relative to -1.15 tC/ha/yr									Thevathasan et al (2016) in Paulo et al(2016)
Silvoarable agroforestry	Arable	increased carbon sequestration		Modeling	1	UK		+4 t CO2/ha/yr									Garcia de Jalon et al (2018)
Silvoarable agroforestry	Arable	increased carbon sequestration		Review		Europe		+2.75 tC/ha/yr									Aertsens et al (2013)
Intercropping	Arable	increases soil organic content		Review/meta-analysis	4	Global			1.16								Kim et al. (2016)
Silvoarable	Arable	Increases biodiversity and wildlife habitat		Interviews	58	Europe							Increases				Garcia de Jalon et al (2018a)
Silvoarable agroforestry	Arable	increased biodiversity		Meta-analysis		Europe							1.37				Torralba et al (2016)
Silvoarable agroforestry	Arable	reduced food production		Experiment and model	1	UK	0.42										Garcia de Jalon et al (2018)
Silvoarable agroforestry	Arable	maintained food production		Experiment	1	Germany	0.95										Kanzler et al (2018)
Adding hedges and landscape features	arable landscape	reduced net GHG gas emissions in JRC model		European model	1	Europe				-0.1 Mg CO_2e/ha/yr							Tuomisto et al (2013)
Silvoarable agroforestry	Arable	reduced CO_2 emissions		Modeling	1	UK				0.46							Garcia de Jalon et al (2018)
Intercropping	Arable	increased NO_2 emissions		Meta-analysis	4	Global				+1.0 kg NO_2/ha/yr							Kim et al. (2016)
Silvoarable agroforestry	Arable	reduced soil erosion losses		Modeling	1	UK						0.50					Garcia de Jalon et al (2018)
Silvoarable agroforestry	Arable	reduced nitrogen surplus		Modeling	1	UK					-22 kg N/ha/yr						Garcia de Jalon et al (2018)
Silvoarable agroforestry	Arable	reduced erosion losses		Meta-analysis		Europe						0.40					Torralba et al (2016)
Increasing tree cover	no increase in tree cover	reduced sediment loss in an extreme rainfall year		Watershed review		Iowa						0.05					Asbjornsen et al (2013)
Increasing tree cover	no increase in tree cover	reduced nitrogen export in an extreme rainfall year		Watershed review		Iowa					0.15						Asbjornsen et al (2013)
Silvoarable agroforestry	Arable farm	increased the energy produced per unit energy input		Experimental farm	1	Germany									1.18		Lin et al (2017)
Silvoarable	Arable	increases management costs and labour		Interviews	58	Europe								increased			Garcia de Jalon et al (2018a)
Silvoarable agroforestry	Arable	increased and reduced net margins		Modeling	42	Europe										Some positive; some negative	Graves et al (2007)
Silvoarable agroforestry	Arable	reduced net margin		Modeling	1	UK										-€196/ha/yr	Garcia de Jalon et al (2018)
Silvoarable agroforestry	Arable	similar societal benefits		Modeling	1	UK										1.10	Garcia de Jalon et al (2018)

Table C.6. Evidence worksheet for multistrata agroforestry

Intervention A	Baseline B	Impact		Type of study	Number of studies	Location	Inputs	Crop yield ratio: system A/System B	Additional carbon storage	Soil carbon (System A/System B)	GHG emission system A/System B	Biodiversity	Profit	Reference
Multistrata agroforestry														
Multistrata agroforestry	*Degraded grassland*			*Desk study*		*Global*		*NA*	*7.00* t C ha^{-1} a^{-1}				*NA*	*The Drawdown project (2017) on degraded land*
Fruit trees	Arable	increased the potential carbon sequestration by plants		Regional study	2	Bari				2-28 t CO2/ha/yr				Dal Sasso et al (2012)
Banana/coffee	Banana	increased soil carbon		Survey	1	Uganda				1.57				Zake et al (2015)
Shaded perennial system	Agriculture	increased soil carbon		Review/meta-analysis	2	Global				1.01				Kim et al. (2016)
Plantation	Cropland	increased soil carbon		Meta-analysis	74	Global				1.18				Guo and Gifford (2002)
Cocoa and coffee agroforestry	Cocoa and coffee plantation	increased biodiversity		Meta-analysis	74	Global						Positive		De Beenhouwer et al (2013)
Complex agroforestry	Simple agroforestry	Increased biodiversity		Meta-analysis	44	Brazil						1.15		Santos et al. (2019)
Agroforestry Cocoa	Conventional cocoa	resulted in reduced cocoa yields		Experiment	1	Bolivia		Cocoa production decreased						Niether et al. (2019)
Agroforestry Cocoa	Conventional cocoa	resulted in similar total crop yields		Experiment	1	Bolivia		Total crop production maintained						Niether et al. (2019)
Agroforestry Cocoa	Conventional cocoa	resulted in increased cocoa yields		LCA	60 farms	Colombia		3.00						Ortiz-Rodriguez et al (2016)
Agroforestry Cocoa	Conventional cocoa	increased above ground carbon storage		Experiment	1	Bolivia			4.00 ratio					Niether et al. (2019)
Shaded perennial system	Agriculture	had no significant effect on nitrous oxide emissions		Review/meta-analysis	5	Global					+5.5 kg NO_2/ha/yr			Kim et al. (2016)

Table C.7. Evidence worksheet for silvopasture systems

Intervention A	Baseline B	Impact		Type of study	Number of studies	Location	Crop yield ratio: system A/System B	Additional carbon storage	Soil carbon (A/B)	GHG emission system A/System B	Soil erosion A/B	Biodiversity	Labour	Profit	Reference
Silvopasture	Business as usual grazing			*Desk study*	*"4-8 sources"*	*Global*	*1.10*	*4.80*						*3.79*	*Drawdown Project (2017)*
Silvopasture	Pasture	resulted in a similar level of food production		Meta-analysis	*82*	Europe	1.18								Torralba et al (2016)
Silvopasture	Pasture	reduced the herbage yield		Field measurements	1	Italy	0.77								Seddaiu et al (2018)
Silvopasture	Pasture	reduced herbage yield where grass was fertilised		Survey	1	Spain	reduced								Moreno et al. (2007)
Silvopasture	Pasture	increased herbage yield where grass was not fertilised		Survey	1	Spain	increased								Moreno et al. (2007)
Silvopasture	Pasture	enhances animal health and welfare		Interviews	187	Europe	Enhances animal health and welfare								Garcia de Jalon et al (2018a)
Silvopasture	Pasture	increases carbon storage		Review	1	Europe		2 t C/ha/yr							Aertsens et al (2013)
Silvopasture	Pasture	increases soil carbon storage		Field measurements	1	Italy			1.18						Seddaiu et al (2018)
Silvopasture	Pasture	similar soil carbon storage		Field measurements	1	UK			1.00						Upson et al. (2016)
Silvopasture	Pasture	increases soil carbon at 0-15 cm		Meta-analysis	2	Global			1.05						De Stefano and Jacobson (2018)
Silvopasture	Pasture	enhances soil fertility		Meta-analysis	*82*	Europe			1.07						Torralba et al (2016)
Integration of crops, trees and livestock	Conventional agriculture	reduced net GHG gas emissions		LCA		Brazil				0.45					Costa et al 2018
Silvopasture	Pasture	enhances erosion control		Meta-analysis	*82*	Europe					0.37				Torralba et al (2016)
Silvopasture	Pasture	enhances biodiversity		Interviews	187	Europe						Enhances			Garcia de Jalon et al (2018a)
Silvopasture	Pasture	enhances biodiversity		Meta-analysis	*82*	Europe						1.21			Torralba et al (2016)
Silvopasture	Pasture	enhances gamma biodiversity		Field measurements	1	Italy						1.31			Seddaiu et al (2018)
Silvopasture	Pasture	increases labour and management costs		Interviews	187	Europe							Increases		Garcia de Jalon et al (2018a)

Table C.8. Evidence worksheet for multi-paddock grazing

Intervention A	Baseline B	Impact		Type of study	Number of studies	Location	Crop yield ratio: system A/system B	Additional carbon storage (t C ha^{-1} a^{-1})	Soil carbon (A/B)	Water quality	Runoff	Soil erosion: A/B	Costs	Profit	Reference
Managed grazing	*conventional grazing*			*Desk study*		*Global*	*1.10*	*0.63*						*1.74*	*Drawdown (2017)*
Multi-paddock	Continuous grazing	resulted in increased stocking rates		Experiment	1	Australia	1.07-1.22								Badgery et al (2017)
Multi-paddock	Continuous grazing	used higher stocking rates		Experiment	1	Texas USA									Heitschmidt et al. (1982)
Multi-paddock	Continuous grazing	resulted in greater grass consumption		Modelled	1	USA	Generally positive but dependent on rotation length and stocking density								Chen and Shi (2018)
Multipaddock	Continuous grazing	increases consumption of palatable grasses		Modelled		USA	1.09								Wang et al (2016)
Multipaddock	Continuous grazing	resulted in similar pasture productivity		Experimental	12 v 11	South Australia	about 1								Sanderman et al (2015)
Multi-paddock	Continuous grazing	resulted in similar grass yields		Meta-analysis	75	Global	1.00								Hawkins (2017)
Multipaddock	Continuous grazing	results in similar yields		Experimental	9 years	Central Plains, USA	0.98						0.993		Derner and Hart (2007)
Multi-paddock	Continuous grazing	resulted in similar liveweight gains per hectare		Meta-analysis	75	Global	+7 kg/ha/d								Hawkins (2017)
Multi-paddock	Continuous grazing	resulted in reduced herbage quality		Experiment (3.5 ha plots)	1	Australia									Cox et al. (2017)
Multipaddock	Continuous grazing	plots had a higher soil organic matter concentration		Experimental	1	USA			1.15						Teague et al (2010)
Multipaddock	Continuous grazing	plots had a higher soil organic matter concentration		Experimental	1	USA			1.50						Teague et al (2011)
Multipaddock	Continuous grazing	resulted in similar soil organic matter levels		Experimental	12 v 11	South Australia	1		0.99						Sanderman et al (2015)
Multipaddock	Continuous grazing	increased perennial grass cover		pairwise comparison]	2	Botswana	+20%								Mudongo et al. (2016)
Multipaddock	Continuous grazing	decreased tree cover		pairwise comparison]	2	Botswana	-7 to -17%								Mudongo et al. (2016)
Multipaddock	Continuous grazing	decreased surface runoff		Modelled (with experimental data)	4x study ranches	Texas, USA					0.53				Park et al (2017)
Multipaddock	Continuous grazing	increased infiltration rates		Experimental	1	USA					1.34				Teague et al (2010)
Multipaddock	Continuous grazing	increased soil aggregate stability		Experimental	1	USA				1.15					Teague et al (2011)
Multipaddock	Continuous grazing	decreased sediment loss		Experimental	1	USA						0.22			Teague et al (2011)
Multi-paddock	Continuous grazing	resulted in increased management costs		Meta-analysis observation	75	Global							Increased costs		Hawkins (2017)

Table C.9. Evidence worksheet for organic livestock systems

Intervention A	Baseline B	Impact		Type of study	Number of studies	Location	Crop yield ratio A/B	Additional carbon storage (t C ha^{-1} a^{-1})	Soil carbon (A/B)	GHG emission system A/B	Water quality	Biodiversity	Energy	Reference
Organic grassland														
Grass receiving FYM	Grass receiving NPK	increased grass yield		Field comparison	1	England	1.50							Kidd et al (2015)
Organic grass (+ 125 kg N/ha from legumes)	Grass receiving 125 kg N/ha	increased grass yield		Field comparison	1	Scotland	1.22							Topp et al (2007)
Adding organic amendments	Not adding amendments	increased dry matter production on rangelands		Meta-analysis	92	Global	1.98							Table S2 (Gravuer et al. 2019).
Organic dairy	Conventional dairy	reduced milk yield per cow		Farm comparison	15	Sweden	0.93							Mueller et al. (2014)
Organic dairy	Conventional dairy	reduced milk yield per agricultural area		Farm comparison	15	Sweden	0.70							Mueller et al. (2014)
Grass-fed beef	Grain-fed beef	has lower output per unit land		LCA meta-analysis	4	Global	0.71							Clarke and Tilman (2017)
Grass-fed beef	Grain-fed beef	similar GHG emissions per unit food		LCA meta-analysis	7	Global				1.19				Clarke and Tilman (2017)
Organic diary	Non-organic dairy	increased GHG emissions per unit milk		Review	3	Global				1.13				Gomiero et al (2001)
Grass receiving FYM	Grass receiving NPK	increased soil carbon		Field comparison	1	England			1.20					Kidd et al (2015)
Adding organic amendments	Not adding amendments	increased soil carbon levels on rangelands		Meta-analysis	92	Global			1.30					Table S2 (Gravuer et al. 2019).
Addition of legumes	before legumes	increased soil carbon sequestration		Review	6	Global		+0.75 Mg C/ha/yr						Conant et al (2001)
Addition of earthworms	before earthworms	increased soil carbon sequestration		Review	2	Global		+2.35 Mg C/ha/yr						Conant et al (2001)
Adding organic amendments	Not adding amendments	reduced runoff from rangelands		Meta-analysis	92	Global					0.49			Table S2 (Gravuer et al. 2019).
Adding organic amendments	Not adding amendments	increased the concentration of nitrate in runoff		Meta-analysis	92	Global					5.59 for N 8.96 for P			Table S2 (Gravuer et al. 2019).
Adding organic amendments	Not adding amendments	had no statistical effect on native plant communities		Meta-analysis	92	Global						0.94		Table S2 (Gravuer et al. 2019).
Organic dairy production	Conventional dairy	reduced the biodiversity damage impact		Modelling study	1	Sweden						0.42		Mueller et al. (2014)
Organic grass (receiving 125 kg N/ha from legumes)	Grass receiving 125 kg N/ha	increased energy efficiency (energy out/energy in)		Field comparison	1	Scotland							3.02	Topp et al (2007)
Organic dairy	Conventional dairy	generally reduced energy use per litre of milk		Review	7	Global							0.78	Gomiero et al (2001)
Organic dairy	Conventional dairy	reduced energy use per hectare		Farm study	1	Denmark							0.67	Dalgaard (2013)
Organic dairy	Conventional dairy	reduced energy use per cow		Farm study	1	Denmark							0.77	Dalgaard (2013)

Table C.9. Evidence worksheet for rewilding and agricultural land abandonment

Intervention A	Baseline B	Impact		Type of study	Number of studies	Location	Crop yield ratio A/B	Additional carbon storage (t C ha^{-1} a^{-1})	Soil carbon (A/B)	GHG emission system A/B	Water quality	Biodiversity	Energy	Reference
Land abandonment and rewilding														
Land abandonment	Agricultural land	reduces food production		Case study	1	Italy	Decreased							Smiraglia et al. (2016)
Annual sale of 75 t high value beef, pork and venison from rewilding project across 1100 ha	Mean UK lowland lamb production/ha across 1100 ha	reduces quantity of meat production		Case study	1	UK	0.11 = 75 t /660 t							Spencer (2017); Redman (2019)
Rewilded land	Agricultural land	reduces grass and crop production		Case study	1	Spain	0.80							Cerqueira et al. (2015)
Tropical reforestation	Agricultural land	above ground regrowth during first 20 years		Meta-analysis	143	Tropics		+6.4 Mg/ha/yr						Silver et al. (2000)
Perennial vegetation	degraded agricultural land	increases soil carbon (over 100 cm)		Review	11	USA		+0-660 kg C/ha/yr						McLauchlan (2004)
Pasture	Cultivation	increased soil carbon sequestration		Review	23	Global		+1.01 Mg C/ha/yr						Conant et al (2001)
Pasture	Cropland	increased soil carbon		Meta-analysis	74	Global			1.19					Guo and Gifford (2002)
Native soil	Agricultural land	decreased soil carbon		Meta-analysis	50	Canada			1.32					VandenBygaart et al (2003)
Abandonment	Extensive grazing	Reduced biodiversity		Review		Global						Decreased		Rey Benayas et al. (2007)
Abandonment	Agricultural land	increased short-term biodiversity		Review		Global						Increased		Lasanta et al. (2015)
Abandonment	Agricultural land	increased mega fauna abundance		Review		Global						Increased		Ceaușu et al. (2015)
Rewilding	Agricultural land	Increase invasive species		Review		Global						Increased invasives		Corlett (2016)

Appendix D: Calculation of the area of tree crops

Table D.1 Definition of "tree-based" fruits and nuts and areas based on FAOSTAT (FAOSTAT 2019)

Category	Tree or non-tree based	Species	Area in 2010 (ha)	Area in 2017 (ha)
Fruits	Tree- and plantain based	Apples; Apricots; Avocados; Bananas; Fruit, stone nes; Blueberries; Carobs; Cashewapple; Cherries; Cherries sour; Cranberries; Currants; Dates; Figs; Fruit, citrus nes; Fruit, fresh nes; Fruit, pome nes; Fruit, stone nes Fruit, tropical fresh nes; Gooseberries; Grapefruit (inc. pomelos); Grapes, Kiwi fruit; Lemons and limes; Mangoes, mangosteens, guavas; Melons, other (inc. cantaloupes), Oranges, Papayas, Peaches and nectarines, Pears, Persimmons, Plantains and others; Plums and sloes; Quinces; Tangerines, mandarins, clementines, satsumas	56,882,884	60,130,281
Nuts	Tree-based	Almonds; Brazil nuts; Cashew nuts; Chestnut; Hazelnuts; Nuts, nes; Pistachios; Walnuts	10,111,224	11,784,160
Oil crops	Tree-based	Castor oil seed; Coconuts; Jojoba; Kapok; Karite nuts (sheanuts); Oil palm; Olives Tallowtree; Tung nuts	41,331,187	47,248,671
Other	Tree-based	Cloves, Cocoa, Coffee, Rubber, Tea	33,124,130	39,039,460
Subtotal			**141,449,425**	**158,202,572**
Fruits	Non-tree based	Pineapples, Raspberries; Strawberries; Watermelons	4,751,605	5,090,053
Oil crops	Non-tree based	Groundnuts; Hemp; Linseed; Melonseed; Mustard seed; Oilseeds nes; Poppy; Rapeseed; Safflower; Seed cotton; Sesame; Soybeans; Sunflower	230,407,182	263,851,664

Nes = not elsewhere specified