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Interim report

Role of soils in climate change mitigation

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Abstract: The role of soils in climate change mitigation

Soils play a central role in climate mitigation. They are both as a carbon sink and a source of greenhouse gas emissions (GHG). This report outlines the mitigation potential for GHG emissions of climate friendly soil management options at global, EU and German level. It also discusses different types of climate-friendly soil management measures and key considerations for their implementation.

Kurzbeschreibung: Die Rolle von Böden für den Klimaschutz

Böden fungieren sowohl als Emissionsquellen bedingt durch Bodenbearbeitungsprozesse als auch als Kohlenstoffspeicher. Mit diesem Bericht wird das Minderungspotential für Treibhausgasemissionen durch Maßnahmen zur klimafreundlichen Bodennutzung auf globaler, EU- und deutscher Ebene analysiert und verschiedene Maßnahmen zur klimafreundlichen Bodennutzung sowie Bedingungen und Herausforderungen für ihre Umsetzung diskutiert.

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List of abbreviations

C	Carbon
CH_4	Methane
CO_2	Carbon dioxide
EU	European Union
FAO	Food and Agriculture Organisation
FCC	Farm Carbon Calculator
GHG	Greenhouse gas
Gt	Gigatonne
ha	Hectar
Kha	Kilo hectar
LC	Land change
LULUCF	Land use, land use change and forestry
MC	Management change
Mha	Million hectar
MRV	Monitoring, Reporting and Verification
Mt	Megatonne
N	Nitrogen
N_2O	Nitrous oxide (laughing gas)
NbS	Nature-based Solutions
NI	Nitrification inhibitor
SNI	Synthetic nitrification inhibitors
SOC	Soil organic carbon
t	Tonne

Summary

This report provides an overview of the mitigation potential of climate friendly solutions for soil management, including nature-based mitigation options. For specific demands of this report we developed a working definition of Nature-based solutions (NbS) with an orientation towards mitigation, comprising such options. According to the working definition used in this paper NbS are defined as "*locally appropriate, adaptive actions to protect, sustainably manage or restore natural or modified ecosystems in order to address targeted societal challenge(s) - such as climate change mitigation -, while simultaneously enhancing human well-being and providing biodiversity benefits*" (Reise et al. 2022). The working definition was developed in the context of this research project and is based on the IUCN definition and the definition by the UNEA 5.2 Resolution 5 on NbS.[1] The mitigation potential associated with nature-based soil management is examined at global, EU and German level (chapter 2).

The report also examines the most relevant climate friendly soil management options, their mitigation potential, their co-benefits and trade-offs, as well as implementation challenges. This includes both nature-based soil management measures as well as a number of management options which may have the potential for improving the climate impact associated with soil management but are not aligned with the definition of nature-based solutions (chapter 3). In 10 separate factsheets a subset of these measures are discussed in more detail (see Annex 1).

Soils have a double role as sources and carbon storages of GHG emissions. Globally, soils store two to three times more carbon than the atmosphere, but these carbon stocks have decreased significantly due to conversion of land to agricultural use, peatland drainage, simplified crop rotations, removals of crop residues, separation of arable and livestock farming as well as losses from soil erosion.

The climate mitigation potential associated with soil management includes three elements: 1) additional sequestration, which is primarily focused on mineral soils although peatlands can also sequester additional carbon once rewetted; 2) preservation of existing stocks (in particular peatlands because of the high losses on peatlands), and 3) reducing emissions associated with reduced application of fertilizers due to improved nutrient management and inclusion of, for example, legumes, compost/manure and improved crop rotation. Table 1 below summarises the mitigation potentials for peatlands as well as croplands and grasslands on mineral soils.

Table 1: GHG emissions mitigation potential of agricultural soils at global level, in the EU and in Germany

	Absolute mitigation potential ($Mt\ CO_2e$/year)	Per hectare mitigation potential ($t\ CO_2e$/ha/year)
Peatlands		
Global	800 - 900 (1)	16 - 18 (4)
EU	48 - 57 (2)	3.5 - 29 (5)
Germany	10 (3)	10 - 35 (12)
Croplands and grasslands on mineral soils - sequestration potential		
Global	200 - 1,000 (6)	0.2 (9)

[1] See https://www.unep.org/environmentassembly/unea-5.2/proceedings-report-ministerial-declaration-resolutions-and-decisions-unea-5.2 and https://www.iucn.org/theme/nature-based-solutions

	Absolute mitigation potential ($Mt\ CO_2e$/year)	Per hectare mitigation potential ($t\ CO_2e$/ha/year)
EU	23 - 58 (7)	0.1 - 0.4 (10)
Germany	1.4 [2] (8)	0.4 (11)

Sources: (1) (Leifeld and Menichetti 2018). (2) (UBA 2019), (European Union 2020). (3) (Roe et al. 2021). (4) (Leifeld and Menichetti 2018). (5) (Günther et al. 2020) (Joosten et al. 2015). (6) (Reise et al. 2022). (7) (Lugato et al. 2015). (8) (Wiesmeier et al. 2020). (9) Own calculation based on Bossio et al. (2020) and FAOSTAT (n.d.). (10) Own calculation based on Lugato et al. (2015) and (OECD n.d.). (11) Own calculation based on Wiesmeier et al. (2020). (12) Emission reductions/avoided emissions through rewetting (BMUV 2021).

Three main types of climate-friendly soil management measures are available: 1) land use change measures (e.g., silvoarable or silvopastoral agroforestry), 2) rewetting of peatlands and organic soils, and 3) agronomic measures on croplands and grasslands (e.g., the use of cover crops, the inclusion of legumes in crop rotations, permanent grassland management, residue management, mulching, applying manure / compost, reduction of compaction, nitrification inhibitors, precision farming3, low input grasslands, organic farming, and external inputs). While the majority of measures that are examined are aligned with the definition of NbS as provided in Reise et al. (2022), nitrification inhibitors and other external inputs are not aligned with the definition of nature-based solutions. There is high commercial interest to upscale them and promote them as part of climate mitigation strategies. Yet these measures are problematic both in terms of their climate and their environmental effects.

When assessing and promoting climate friendly soil management measures, several aspects should be considered:

- Measures with significant mitigation potential and co-benefits should be prioritized. These include rewetting of organic soils, the conversion from arable to grassland, as well as management and conversion to silvopastoral and silvoarable agroforestry systems.
- Systemic approaches, such as mixed-crop livestock systems and organic farming can play an important role but face legal and funding barriers.
- Prevention measures, such as reducing soil compaction and preventing land take support preservation of existing stocks.
- The mitigation potential of SOC sequestration in croplands and grasslands is limited, uncertain and the risk of intentional or unintentional reversal of sequestered SOC is high.
- There are also some management measures that have mixed impacts on both climate and soil health and need to be approached critically, including the use of nitrification inhibitors (NIs), the application of external inputs and precision farming.
- The issues of permanence, leakage, and saturation need to be recognized and addressed when considering climate impacts of soil management measures.
- Moreover, it is important that the total climate impact of soil management measures is considered since measures can remove CO2 from the atmosphere but can also lead to an increase in emissions. Improved understanding of the net climate impacts is needed so that

[2] The mitigation potential refers to Bavaria only. Estimates for Germany as a whole are not available.

[3] Precision farming is an approach applying georeferencing and technologies that enable a reduction of environmental impacts through a more precise application of inputs (plant nutrients, soil improving material (e.g., lime), pesticides, seeds, irrigation) and field trafficking (see section A.9).

measures with a net-positive mitigation effect can be prioritized and the full climate impacts of measures are captured in greenhouse gas inventories.

- Uncertainties remain in the estimates of the mitigation potentials both at the level of individual soil management measures, as well as at the level of aggregate assessments.
- More broadly, research should close information gaps and provide guidance to policy through improved assessments on where the most significant potentials are at national and regional level, where risks for losses of existing stocks are highest, and which combinations of practices would deliver most significant benefits for SOC levels and total climate impacts.
- When implementing measures, safeguards are important to ensure that measures form win-win solutions for both climate and biodiversity and other environmental objectives.

Zusammenfassung

Dieser Bericht gibt einen Überblick über das Minderungspotenzial für Treibhausgasemissionen durch Maßnahmen zur klimafreundlichen Bodennutzung. Naturbasierte Lösungen (NbS) mit einem Fokus auf Emissionsminderung, die solche Maßnahmen umfassen, werden definiert als "*lokal angemessene, anpassungsfähige Maßnahmen zum Schutz, zur nachhaltigen Bewirtschaftung oder zur Wiederherstellung natürlicher oder veränderter Ökosysteme, um gezielte gesellschaftliche Herausforderungen - wie die Abschwächung des Klimawandels - anzugehen und gleichzeitig das menschliche Wohlergehen zu verbessern und die biologische Vielfalt zu fördern*" (Reise et al. 2022). Diese Arbeitsdefinition wurde im Kontext des vorliegenden Forschungsprojekts entwickelt und basiert auf der Definition der IUCN sowie der Definition in der UNEA 5.2 Resolution 5 zu NbS.[4] Das mit naturbasierter Bodennutzung verbundene Minderungspotenzial wird auf globaler, EU- und deutscher Ebene untersucht (Kapitel 2). Außerdem werden die wichtigsten klimafreundlichen Bodenbewirtschaftungsoptionen, ihr Minderungspotenzial, ihre Zusatznutzen und Zielkonflikte sowie die Herausforderungen bei der Umsetzung untersucht. Dies umfasst sowohl naturbasierte Bodenbewirtschaftungsmaßnahmen als auch eine Reihe von Bewirtschaftungsoptionen, die das Potenzial haben, die mit der Bodenbewirtschaftung verbundenen Klimaauswirkungen zu verringern, aber nicht der Definition von naturbasierten Bewirtschaftungsmaßnahmen entsprechen (Kapitel 3). In 10 separaten Factsheets werden ausgewählte Maßnahmen ausführlicher behandelt (siehe Annex).

Böden fungieren sowohl als Emissionsquellen bedingt durch Bodenbearbeitungsprozesse als auch als Kohlenstoffspeicher. Weltweit speichern die Böden zwei- bis dreimal mehr Kohlenstoff als die Atmosphäre. Diese Kohlenstoffvorräte sind jedoch durch die Umwandlung von Flächen in landwirtschaftliche Nutzflächen, die Entwässerung von Mooren, vereinfachte Fruchtfolgen, die Beseitigung von Ernterückständen, die Trennung von Ackerbau und Viehzucht sowie durch Verluste durch Bodenerosion erheblich zurückgegangen.

Das mit der Bodenbewirtschaftung verbundene Klimaschutzpotenzial umfasst drei Elemente: 1) zusätzliche Sequestrierung, die sich in erster Linie auf mineralische Böden konzentriert, obwohl auch Torfböden nach ihrer Wiederbefeuchtung zusätzlichen Kohlenstoff binden können; 2) Erhaltung bestehender Bestände (insbesondere von Torfböden wegen der hohen Verluste auf Torfböden) und 3) Verringerung der Emissionen im Zusammenhang mit dem verringerten Einsatz von Düngemitteln aufgrund eines verbesserten Nährstoffmanagements und der Einbeziehung von z. B. Leguminosen, Kompost/Dünger und verbesserten Fruchtfolgen. In der Tabelle 2 sind die Minderungspotenziale für Moorgebiete sowie Acker- und Grünlandflächen auf Mineralböden zusammengefasst.

Tabelle 2: THG-Minderungspotenzial von landwirtschaftlich genutzten Böden auf globaler, EU-Ebene und in Deutschland

	Absolutes Minderungspotenzial ($Mt\ CO_2e$/Jahr)	Minderungspotenzial pro Hektar ($t\ CO_2e$/ha/Jahr)
Moorgebiete		
Global	800 - 900 (1)	16 - 18 (4)
EU	48 - 57 (2)	3.5 - 29 (5)
Deutschland	10 (3)	10 - 35 (12)

[4] Siehe https://www.unep.org/environmentassembly/unea-5.2/proceedings-report-ministerial-declaration-resolutions-and-decisions-unea-5.2 and https://www.iucn.org/theme/nature-based-solutions .

	Absolutes Minderungspotenzial ($Mt CO_2e$/Jahr)	Minderungspotenzial pro Hektar ($t CO_2e$/ha/Jahr)
Ackerflächen und Grünland auf mineralischen Böden - Sequestrierungspotenzial		
Global	200 - 1,000 (6)	0.2 (9)
EU	23 - 58 (7)	0.1 - 0.4 (10)
Deutschland	1.4 [5] (8)	0.4 (11)

Quellen: (1) (Leifeld und Menichetti 2018). (2) (UBA 2019), (European Union 2020). (3) (Roe et al. 2021). (4) (Leifeld und Menichetti 2018). (5) (Günther et al. 2020) (Joosten et al. 2015). (6) (Reise et al. 2022). (7) (Lugato et al. 2015). (8) (Wiesmeier et al. 2020). (9) Eigene Berechnung auf der Basis von Bossio et al. (2020) und FAOSTAT (n.d.). (10) Eigene Berechnung auf der Basis von Lugato et al. (2015) und (OECD n.d.). (11) Eigene Berechnung auf der Basis von Wiesmeier et al. (2020). (12) Emissionsreduktionen/vermiedene Emissionen durch Wiedervernässung (BMUV 2021).

Es gibt drei Haupttypen von klimafreundlichen Maßnahmen zur Bodennutzung: 1) Maßnahmen zur Landnutzungsänderung (z. B. silvoarable oder silvopastorale Agroforstsysteme, d.h. gleichzeitiger Anbau von Gehölzen und landwirtschaftlichen oder gartenbaulichen Kulturen oder Anbau von Gehölzen auf Weideflächen), 2) Wiedervernässung von Mooren und organischen Böden und 3) agronomische Maßnahmen auf Acker- und Grünlandflächen (z. B. der Einsatz von Deckfrüchten, die Einbindung von Leguminosen in Fruchtfolgen, Dauergrünlandbewirtschaftung, Rückstandsmanagement, Mulchen, Ausbringung von Wirtschaftsdünger/Kompost, Verringerung der Verdichtung, Nitrifikationshemmer, Precision Farming, Low-Input-Grünland, ökologischer Landbau und externe Einträge). Während die meisten der untersuchten Maßnahmen mit der Definition von NbS nach Reise et al. (2022) übereinstimmen, entsprechen Nitrifikationshemmer und andere externe Inputs nicht der Definition von naturbasierten Lösungen. Es besteht ein großes kommerzielles Interesse daran, sie zu vermarkten und als Teil von Klimaschutzstrategien zu fördern. Diese Maßnahmen sind jedoch sowohl im Hinblick auf das Klima als auch auf ihre Umweltauswirkungen problematisch.

Bei der Bewertung und Förderung von Maßnahmen zur klimafreundlichen Bodennutzung sollten folgende Aspekte berücksichtigt werden:

- Maßnahmen mit erheblichem Minderungspotenzial und Zusatznutzen sollten vorrangig gefördert werden. Dazu gehören die Wiedervernässung von organischen Böden, die Umstellung von Acker- auf Grünland, sowie die Bewirtschaftung und Umstellung auf silvopastorale und silvoarable Agroforstsysteme.
- Systemische Ansätze wie gemischte Bewirtschaftungssysteme, die Ackerbau und Viehzucht integrieren, und ökologischer Landbau können eine wichtige Rolle spielen, stoßen aber auf rechtliche und finanzielle Hindernisse.
- Präventionsmaßnahmen wie die Verringerung der Bodenverdichtung und die Verhinderung der Landnahme unterstützen den Erhalt der vorhandenen Kohlenstoffspeicher.
- Das Minderungspotenzial durch Erhöhung des Bodenkohlenstoffgehalts in Acker- und Grünlandflächen ist begrenzt und unsicher, und das Risiko, dass der gespeicherte Kohlenstoff absichtlich oder unabsichtlich wieder freigesetzt wird, ist hoch.
- Es gibt auch einige Bewirtschaftungsmaßnahmen, die sich sowohl auf das Klima als auch auf die Bodengesundheit auswirken und kritisch betrachtet werden müssen, darunter der

[5] The mitigation potential refers to Bavaria only. Estimates for Germany as a whole are not available.

Einsatz von Nitrifikationshemmern, die Anwendung externer Einträge und Präzisionslandwirtschaft (Precision Farming)6.

- Die Dauerhaftigkeit der Kohlenstoffspeicherung, mögliche Verlagerungseffekte und die Sättigung des Bodens müssen bei der Betrachtung der Klimaauswirkungen von Maßnahmen zur klimaschonenderen Bodennutzung erkannt und berücksichtigt werden.
- Darüber hinaus ist es wichtig, dass die gesamten Klimaauswirkungen von Maßnahmen zur klimafreundlichen Bodennutzung berücksichtigt werden, da Maßnahmen zwar CO2 aus der Atmosphäre entfernen können, aber auch zu einem Anstieg der Emissionen führen können. Ein besseres Verständnis der Netto-Klimaauswirkungen ist erforderlich, damit Maßnahmen mit einem positiven Netto-Minderungseffekt priorisiert werden können und die vollständigen Klimaauswirkungen von Maßnahmen in Treibhausgasinventaren erfasst werden.
- Es bestehen weiterhin Unsicherheiten bei der Abschätzung des Minderungspotenzials sowohl auf der Ebene der einzelnen Maßnahmen zur klimafreundlichen Bodennutzung als auch auf der Ebene der Gesamtbewertung.
- Insgesamt sollte die Forschung Informationslücken schließen und der Politik durch verbesserte Analysen von Maßnahmen Hinweise darauf geben, wo auf nationaler und regionaler Ebene die größten Minderungspotenziale liegen, wo die Risiken für den Verlust bestehender Kohlenstoffspeicher am größten sind und welche Kombinationen von Maßnahmen den größten Nutzen für den Kohlenstoffgehalt im Boden und die gesamten Klimaauswirkungen bringen würden.
- Bei der Umsetzung von Optionen zur klimafreundlichen Bodennutzung ist sicherzustellen, dass die Maßnahmen sowohl für das Klima als auch für die biologische Vielfalt und andere Umweltziele einen Nutzen mit sich bringen.

[6] Die Präzisionslandwirtschaft ist ein Ansatz, bei dem Georeferenzierung und Technologien eingesetzt werden, die eine Verringerung der Umweltauswirkungen durch eine präzisere Anwendung von Betriebsmitteln (Pflanzennährstoffe, bodenverbessernde Stoffe (z. B. Kalk), Pestizide, Saatgut, Bewässerung) und Feldbegehung ermöglichen (siehe Abschnitt A.9).

1 Introduction

Soils play a central role in climate mitigation. On the one hand, soils store significant amounts of carbon and have the potential to increase their sink capacity through soil organic carbon (SOC) sequestration. On the other hand, soils are also a source of GHG emissions. How significant these emissions are, depends on the specific land use and the management practices which are applied.

The report has three main components. First, chapter 2 provides an overview of the mitigation potential of climate friendly solutions for soil management. The mitigation potential associated with climate friendly soil management is examined at global, European Union (EU) and German level.

Secondly, in chapter 3 we examine the most relevant climate friendly soil management options, their mitigation potential, as well as their co-benefits and trade-offs. This includes both nature-based solutions as well as a number of management options which may have the potential for improving the climate impact associated with soil management but are not aligned with the working definition of nature-based solutions as per Reise et al. (2022).[7] According to this working definition NbS are defined as "*locally appropriate, adaptive actions to protect, sustainably manage or restore natural or modified ecosystems in order to address targeted societal challenge(s) - such as climate change mitigation -, while simultaneously enhancing human well-being and providing biodiversity benefits*" (Reise et al. 2022). The working definition is based on the IUCN definition and the definition by the UNEA 5.2 Resolution 5 on NbS[8].

The 'problematic' measures have been included because there is high commercial interest in their upscaling and also interest in allowing them to be eligible activities in soil carbon certification schemes or as part of broader climate mitigation policy strategies. As they have problematic impacts both in terms of their climate and environmental effects they are evaluated critically.

Chapter 3 first provides an overview of a longer list of possible management measures, and then presents key observations on their climate impacts, co-benefits, and implementation challenges. The Annex includes 10 detailed factsheets for measures which were selected from the longer list of options.

[7] For a definition of nature-based solutions see Reise et al. (2022).

[8] See https://www.unep.org/environmentassembly/unea-5.2/proceedings-report-ministerial-declaration-resolutions-and-decisions-unea-5.2 and https://www.iucn.org/theme/nature-based-solutions

2 Role of soils in climate change mitigation

2.1 Introduction

The climate mitigation potential associated with soil management includes three elements: 1) additional sequestration, which is primarily focused on mineral soils although peatlands can also sequester additional carbon once rewetted (Wilson et al. 2016); 2) preservation of existing stocks (in particular peatlands because of the high losses on peatlands), and 3) reducing emissions associated with reduced application of fertilizers due to improved nutrient management and inclusion of, for example, legumes, compost/manure and improved crop rotation. In this report, we focus on the first two elements, and we examine estimates available at global level, for the EU and for Germany.

Globally, soils store two to three times more carbon than the atmosphere (Le Quéré et al. 2016). Consequently, a relatively small increase or decrease in carbon stocks can play a significant role in climate mitigation. Historically, global SOC stocks have decreased significantly due to conversion of land to agricultural use, peatland drainage, simplified crop rotations, removals of crop residues, separation of arable and livestock farming as well as losses from soil erosion (Reise et al. 2022). SOC stocks will continue to decline if dominant agricultural land management practices are not improved. Moreover, climate impacts by themselves are also projected to lead to additional SOC losses (Wiesmeier et al. 2020). The scale of anticipated future losses is estimated for peatlands, but research provides very little insights into losses associated with the continuation of currently dominant agricultural management of mineral soils.

The mitigation potentials associated to soils vary across regions. The restoration of cultivated organic soils, for example, has the highest mitigation potential in East Asia and Southeast Asia (40%), Western Europe (26%) and the Russian Federation (11%) (Smith et al. 2014). Agricultural soils with the greatest carbon stocks are generally located in high latitudes and humid tropical areas, limiting the potential for additional soil carbon sequestration in those areas (Minasny et al. 2017). In addition to maintaining existing carbon stocks, significant additional sequestration potential has been estimated.

In EU Member States' national GHG inventories, the unreported GHG emissions in croplands are estimated around 70 Mt CO_2e/year, while the unreported gains in grasslands are estimated around 15 Mt CO_2e/year. Moreover, a wide adoption of carbon-farming practices such as peatland restoration, agroforestry, or substituting fodder crops with grass could additionally mitigate 150 - 350 Mt CO_2e/year by 2050 for mineral and organic soils combined (Bellassen et al. 2022).

Table 3 gives an overview of the mitigation potentials for:

- **Peatlands,** which are characterized by organic soils with an organic matter content of at least 30% which become a net carbon source when drained. No strict criterion has been adopted for minimum thickness of peatlands (Joosten et al. 2017). Peatland emissions can be avoided by preserving and restoring peatlands through rewetting. In Europe most peatlands are located in northern Europe.
- **Croplands and grasslands on mineral soils** constitute most of the cultivated land globally and are characterized by an organic matter content of up to 30%. They are subject to diverse management interventions such as tillage, fertilization, liming, harvest, irrigation, drainage, and grazing, all of which have an impact on SOC stocks to some extent.

Table 3: GHG emissions mitigation potential of agricultural soils at global level, in the EU and in Germany

	Absolute mitigation potential (Mt CO_2e/year)	Per hectare mitigation potential (t CO_2e/ha/year)
Peatlands		
Global	800 - 900 (1)	16 - 18 (4)
EU	48 - 57 (2)	3.5 - 29 (5)
Germany	10 (3)	10 - 35 (12)
Croplands and grasslands on mineral soils sequestration potential		
Global	200 - 1,000 (6)	0.2 (9)
EU	23 - 58 (7)	0.1 - 0.4 (10)
Germany	1.4[9] (8)	0.4 (11)

Sources: (1) (Leifeld and Menichetti 2018). (2) (UBA 2019), (European Union 2020). (3) (Roe et al. 2021). (4) (Leifeld and Menichetti 2018). (5) (Günther et al. 2020) (Joosten et al. 2015). (6) (Reise et al. 2022). (7) (Lugato et al. 2015). (8) (Wiesmeier et al. 2020). (9) Own calculation based on Bossio et al. (2020) and FAOSTAT (n.d.). (10) Own calculation based on Lugato et al. (2015) and (OECD n.d.). (11) Own calculation based on Wiesmeier et al. (2020). (12) Reduced/avoided emissions through rewetting (BMUV, 2021).

2.2 Emission reduction potential of peatlands

2.2.1 Peatlands at global scale

Peatlands globally represent about one fifth of the total global stock of soil carbon (~644 Gt C or 2,363.48 Gt CO_2e[10]) with high uncertainties (Leifeld and Menichetti 2018). An estimated 11-15% of global peatlands have been disturbed or drained for cropland or pasture purposes, forestry or peat extraction (Frolking et al. 2011; Leifeld and Menichetti 2018).

Preserving and restoring peatlands (50.1 Mha) through rewetting has a global mitigation potential estimated at around 0.8 Gt CO2e/year (Griscom et al. 2017) to 0.9 Gt CO_2e/year (Leifeld and Menichetti 2018). This equals to a mitigation potential of 16-18 t CO_2e/ha/year. In addition, avoiding further loss of peatlands could reduce emissions by 0.75 Gt CO_2e/year (Griscom et al. 2017). The mitigation potential can be limited by methane emissions that occur after rewetting (Parish et al. 2008; Hendriks et al. 2007). Topsoil removal (30 cm) can minimize the surge of methane emissions up to 99% (Harpenslager et al. 2015).

Uncertainties around the range of mitigation potentials of peatlands are linked to varying estimates for degraded peatland areas and for the full implementation of the global restoration potential, and to the emission factors reflecting the different phases of peat degradation. Uncertainties are also linked to future GHG emissions related to climate change which could increase emissions from intact peatlands (Henderson et al. 2022).[11]

[9] The mitigation potential refers to Bavaria only. Estimates for Germany as a whole are not available.

[10] One kilogram (kg) of carbon produces 3.67 kg of CO_2. 0.2 - 2Mt C is equal to 0.73 - 7.34 Mt CO_2e.

[11] For a discussion of uncertainties related to the estimation of mitigation potentials of nature-based solutions in different studies see also Reise et al. (2022).

2.2.2 Peatlands in the EU

Peatlands in Europe store approximately five times as much carbon as trees (Swindles et al. 2019). Drained peatlands account for 74% of total EU LULUCF emissions (European Union, 2020), which makes the EU the second largest global emitter of GHG from drained peatlands (van Akker et al. 2016). For 2017, the estimate of emissions was at 220 Mt CO_2e/year (Greifswald Mire Centre et al. 2019). Decreasing GHG emissions from organic soils is one of the most effective measures in reaching EU's climate targets (Pérez Domínguez et al. 2020).

In terms of total potentials, fallowing of all organic soils in the EU27+UK would have the potential to mitigate about 42 Mt CO_2e by 2030 (Pérez Domínguez et al. 2020). Furthermore, avoiding peat extraction can limit emissions of about 9 Mt CO_2e annually, corresponding to only 292,000 ha of peatland area, mainly in Poland, Germany, Estonia, Ireland and Finland (European Union 2020). Roe et al. (2021) estimated an economically feasible mitigation potential of 54 Mt CO_2e/year up to 2050 (average over 2020-2050).

Peatland rewetting is also a highly effective mitigation action on per area basis, with estimates ranging from up to 29.7 t CO_2e/ha/year (Abel et al. 2019) to 3.5-24 t CO_2e/ha/year, depending on previous land use and final state (Joosten et al. 2015). Peatland rewetting can also lead to additional sequestration, however, there is less certainty on this potential and in any case, it is of much lower magnitude than emission reductions. For example, one available estimate indicates this potential to be less than 1 t CO_2e/ha/year (Wilson et al. 2016).

The extent of degradation and corresponding mitigation potential of rewetting differs significantly between European countries. For example, 85% of Norway' peatlands are healthy compared to only 2% in Germany (Tanneberger et al. 2017).

2.2.3 Peatlands in Germany

In Germany, the total area of organic soil under agricultural land is almost 1,3 million ha or 7,7% of the total agricultural land in 2019 (UBA 2021). More than 98 % is drained (Trepel et al. 2017), contributing 53 Mt CO_2e or 7.5 % of total German annual GHG emissions in 2020 (UBA 2022). This makes Germany the largest emitter of CO_2 from drained peatlands within the EU. Roe et al (2021) estimate that the economically feasible mitigation from protecting and rewetting peatlands in Germany would be 10 Mt CO_2e/year (2020-2050). Tannenberger et al. (2021) develop two alternative pathways for reducing emissions from peatlands by 2050 in line with a 1.5 degree scenario, whereby a minor area of peatlands is left drained (26,200ha).[12] According to these pathways, emissions should be reduced from 43 Mt CO_2e/year for the time period 2020 - 2030 down to 11.62 Mt CO_2e/year for 2040 - 2050.

2.3 Sequestration potential of croplands and grasslands on mineral soils

2.3.1 Croplands and grasslands on mineral soils at global scale

The global SOC sequestration potential related to cropland and grassland is estimated at 930 Mt CO_2e/year (Bossio et al. 2020). This includes cover cropping, avoided grassland conversion, and improved grazing (optimal intensity, legumes in pastures) and corresponds to a sequestration rate of 0.19 t CO_2e/ha/year.[13]In croplands, global sequestration potentials range from 0.2 Gt

[12] This does not include net soil carbon sequestration potential.

[13] Reise et al. (2022) point out that reduced or no tillage allow to reduce soil disturbance and consequently the mineralisation of SOC, although the measure only impacts the concentration of SOC levels in the top soil layer. Because a single tillage event can reverse these effects, global climate mitigation potential is questioned. Because of a lack of robust data on the mitigation potential of no-till,

CO_2e/year to 11.0 Gt CO_2e/year. These estimates imply high uncertainties, due to the lack of systematic and reliable measurement of soil carbon in mineral soils in different countries (Reise et al. 2022). Protection of grassland is also important since grasslands hold about 20% of the world's SOC stocks (340 Gt C, Conant 2012). Avoiding grassland conversion to cropland (1.7 Mha/year) can avoid emissions up to 0.12-0.23 Gt CO_2e/year for temperate, tropical and subtropical grasslands depending on soil depth (Griscom et al. 2017; Bossio et al. 2020).

SOC sequestration potential is especially high in agroforestry systems. Only considering SOC contribution (excluding above ground sequestration), globally agroforestry systems under mineral soils are estimated to sequester on average 0.3 Gt CO_2e/year (Bossio et al. 2020).[14] Here, it is important to note that these assessments on SOC under agroforestry systems do not differentiate between short rotation coppicing (which is a short-term system) and other agroforestry systems, which are maintained over longer periods of time and thus have greater permanence.

2.3.2 Croplands and grasslands on mineral soils in the EU

The potential SOC sequestration of EU arable land is estimated at 23.1 - 57.9 Mt CO_2e/year by 2050 or 0.14 - 0.36 t CO_2e/ha/year[15] (Lugato et al. 2015). This estimate is based on the implementation of six alternative management practices: conversion of arable land to grassland, straw incorporation, reduced tillage, straw incorporation combined with reduced tillage, ley cropping system and cover crops.

2.3.3 Croplands and grasslands on mineral soils in Germany

On average, German mineral soils store 96 t C/ha in croplands (or 252.32 CO_2e/ha) and 135 t C/ha in grasslands (or 495.45 CO_2e/ha) including topsoils (0-30cm) and subsoils (30-100cm), with on average 56% of the SOC in the topsoil. This shows that grasslands in Germany have a 44% higher SOC stock than croplands in topsoil (Poeplau et al. 2020).

Looking at the five most promising management practices (cover cropping, agroforestry, improved crop rotation, organic farming and conversion of arable land to grassland), Wiesmeier et al. (2020) estimated the mean sequestration potential for a total area of applied measures of 3.316 Mha in Bavaria, Southeast Germany at 1.4 Mt CO_2e/year (or 0.4 Mt C/year). This corresponds to a mean sequestration potential of 0.42 t CO_2e/ha/year.

In particular, increasing agroforestry systems on mineral soils in Germany as a whole could feasibly sequester 0.7-7.3 Mt CO_2e/year (or 0.2 to 2 Mt C/year)[16] in the soil compartment, with hedgerows on croplands resulting in highest gains, followed by conversion of cropland to silvoarable systems, and then planting hedgerows on grasslands and conversion to silvopastoral systems on grasslands (Golicz et al. 2021).

Griscom et al. (2017) excluded the measure from their global assessment of carbon sequestration potentials of croplands and grasslands on mineral soils. Conant (2012) highlights that mechanisms of soil carbon sequestration in no-tillage systems are still poorly understood due to inconsistent results.

[14] For a discussion of uncertainties related to the estimation of mitigation potentials of nature-based solutions in different studies see also Reise et al. (2022).

[15] The per hectare value has been calculated assuming a total area of agricultural land (cropland and permanent pastures) in the EU-27 of 161,795 thousand hectares in 2015 (OECD n.d.).

[16] One kilogram (kg) of carbon produces 3.67 kg of CO_2. 0.2 - 2Mt C is equal to 0.73 - 7.34 Mt CO_2e.

3 Climate friendly soil management measures

3.1 Introduction

In this chapter, we examine the most relevant climate friendly soil management options, their mitigation potential, as well as their co-benefits and trade-offs. A total of 22 soil management measures (Table 4) were reviewed according to a range of criteria: SOC mitigation potential, GHG balance, co-benefits, limitations and trade-offs. The coherence of each measure with the working definition of nature-based solutions (NbS) of this research project as laid down in Reise et al (2022) was assessed according to alignment with natural ecosystems, benefits to biodiversity, adaptability, local suitability, multifunctionality and potential to address societal challenges. Finally, impacts on productivity and on the total system were also evaluated in terms of carbon sequestration, reduced/avoided emissions and movement of carbon within and outside the system.

From the longer list of 22 measures, a shortlist of 10 measures was selected (these measures are marked in bold in the overview Table 3-1). Factsheets with a more detailed analysis of these measures are provided in the Annex.

The majority of measures that were examined are aligned with the working definition of NbS as provided in Reise et al. (2022). However, some measures were also included that have the potential for improving the climate impact associated with soil management but are not aligned with the definition of nature-based solutions or where the measure relies on inputs for which the full climate impact may not be positive when the impacts along the whole life cycle are assessed. These include nitrification inhibitors and other external inputs, including manure, compost and biochar. There is high commercial interest in the upscaling for these measures and also their recognition and eligibility in soil carbon certification schemes and climate mitigation policy strategies. Yet these measures are problematic in terms of their climate and environmental effects and are thus evaluated critically.

Three types of climate-friendly nature-based soil management measures can be distinguished: 1) land use change measures, 2) rewetting of peatlands and organic soils, and 3) agricultural management measures on croplands and grasslands.

Land use change measures include the conversion from arable to grassland, and the prevention of land take. Silvoarable agroforestry (including hedgerows), silvopastoral agroforestry, and mixed crop-livestock systems require both management and land use changes. These measures are more significant in scale and cost.

Rewetting of peatlands and organic soils refers to the deliberate action of raising the water table on drained soils to re-establish water saturated conditions. Wetlands can be restored by elevating soil water tables and restoring the landscape water regime (Tiemeyer et al. 2020; Schumann and Joosten 2008). This measure requires land use changes.

Agricultural management measures require a change of management on the farm or field level. They comprise the use of cover crops, the inclusion of forage and grain legumes in crop rotations, permanent grassland management (optimised grazing), residue management (main crop or green manuring), mulching, applying manure / compost, improved crop rotation, tillage management, choice of cultivars, improving nitrogen efficiency,buffer strips, contour farming / terracing, reduction of compaction (controlled traffic farming), nitrification inhibitors: biological and synthetic, precision farming (site specific management), low input grasslands / set-aside areas, organic farming, and external inputs (off-farm compost, off-farm manure and biochar).

The measures included in Table 4 below all have high relevance within the EU / German context. The mitigation potential for the measures is given in terms of values per ha per year, since values for the total mitigation potential at EU or German level are not generally available for individual measures. For each figure provided, the source is given with a brief explanation of what the figure refers to. The current data availability does not allow to differentiate between regional variability in climate conditions and soil moisture for each measure. Yet, there are differences between northern and southern Germany with regard to soil organic content. There are even greater differences between northern and southern Europe. For silvoarable agroforestry for instance, the Mediterranean mountains zone, where lined poplar trees are interspersed with rotation of wheat, oilseed rape and chickpeas, have a particularly high per ha potential (Kay et al. 2019). The figures included in Table 4 present average values that combine different climatic conditions in the north and south.

Table 4: Overview of climate friendly soil management measures

Measure	Type of measure[1]	NbS fit[2]	SOC sequestration potential (t CO_2e/ha/year)	Co-benefits vs. Trade-offs
Conversion arable to grassland	LC	0	0.6 - 3.3[3]	+++
Rewetting of organic soils	LC	++	1.5-1.6[4]	++
Silvoarable agroforestry	LC, MC	++	0.8 - 7.3 [5]	+++
Silvopastoral agroforestry	LC, MC	+++	0.3 - 27 [6]	+++
Mixed crop-livestock systems	MC, LC	+++	0.1[7]	++
Use of cover crops	MC	+++	0.3-1.1 [8]	+++
Crop rotations with forage legumes	MC	+++	2 - 2.4[9]	++
Crop rotation with grain legumes	MC	+++	No data	+++
Permanent grassland management	MC	+++	0.2-1[10]	++
Residue management	MC	+++	2.5[11]	+
Mulching	MC	++	No data.[12]	+
Applying manure / compost	MC	++	1.39[13]	++
Prevention of land take	LC	++	10 - 66%[14]	++

Measure	Type of measure[1]	NbS fit[2]	SOC sequestration potential (t CO_2e/ha/year)	Co-benefits vs. Trade-offs
Improved crop rotation	MC	+++	0.2[15]	++
Buffer strips	MC	+++	7.2- 9.3[16]	++
Contour farming / terracing	MC	++	No data[17]	++
Reduction of compaction	MC	+++	No data	+
Nitrification inhibitors (biological / synthetic)	MC	Biological: +++ Synthetic: -	No data:[18]	-
Precision farming	MC	+	No data	++
Low input grasslands	MC	+++	0.14[19]	+
Organic farming	MC	+++	1.65	+++
Critical external inputs	MC	++	1.38[20]	++ / -

Source: Own compilation. Note: Absolute values or per hectare values are provided when available. When not available, percentages of reduction are provided. Measures highlighted in bold are assessed in more detail in separate factsheets accompanying this report. The scale of potential and degree of co-benefits is also expressed in the colour scheme, with dark green expressing higher positive value compared to light green. Orange reflects that the measure includes trade-offs. Symbol scale: (+, ++, +++) express the strength of impact, (-) expresses potentially strongly negative trade-offs.

[1] Types of measure include Land use change (LC) and/ or Management change (MC).

[2] The fit with the NbS definition varies according to the following scale from 0, +, ++ and +++ , and dark green being most positive, light green positive, and orange mixed. The fit was assessed according to alignment with the following criteria: natural ecosystems, benefits to biodiversity, adaptability, local suitability, multifunctionality and potential to address societal challenges.

[3] Per ha value at global scale (Contant et al. 2017). The avoidance of 1.7 M ha grassland conversion to cropland per year can prevent CO_2 emissions from SOC with 0.23 Gt CO_2e/year down to 1 m depth of grasslands in temperate, tropical and subtropical biomes.

[4] Carbon sequestration rates were estimated at about 1.5 to 1.6 t CO2e/ha/year for restored mangroves. A study showed the accumulation of 2.12 kg C m−2 in a peatland soil in Germany after 20 years of rewetting, amounting to an average annual uptake of ca. 0.4 kg CO2 m−2/year (Mrotzek et al. 2020).

[5] The higher range of per ha potential for silvoarable system is in the Mediterranean mountains zone where lined poplar trees are interspersed with rotation of wheat, oilseed rape and chickpeas (Kay et al. 2019). The lower range refers to the French national potential (Pellerin et al. 2020).

[6] Absolute sequestration potential of 7.7 to 234.8 Mt CO_2/year implemented on approximately 8.9% of EU farmland (EU-27 plus Switzerland) (Kay et al. 2019).

[7] Lugato et al. 2014.

[8] Lower range: Cover crops lead to an average C sequestration rate of 0.32 t CO_2e ha/year in a mean soil depth of 22cm, found in a meta study by Poeplau & Don (2015). Upper range: In the EU, introducing cover crops is estimated at 1.1 t CO_2e/ha/year (Pellerin et al. 2020).

[9] Estimated net mitigation potential due to the sowing of legumes on planted pasture globally (72 Mha) (reference).

[10] SOC sequestration of about 0.22 tCO_2/ha/year (Henderson et al. 2015)to 1 tCO_2/ha/year Conant et al. (2017).

[11] Use of crop residue has the potential to sequester 2.54 t CO_2eq ha^{-1} $year^{-1}$ in European soils (EC 2004).

[12] No estimates available. In an organic field site in Lithuania, peat and sawdust mulching led to twice as much SOC content after one year of treatment and this also increased slightly with the thickness of the mulch (Bajoriene et al. 2013).

[13] Van-Camp et al. (2004) describes a carbon sequestration potential as high as 1.38 t CO_2e ha^{-1} year^{-1} resulting from either animal manure and composting has been reported for European soils.

[14] Land take can result in a loss of soil organic carbon from 10% to 66% of total stock present in the soils that are affected (Lorenz and Lal 2017; Verzandvoort et al. 2010).

[15] A meta-analysis on long-term experiments found a sequestration rate of 0.2 t C ha^{-1} year^{-1} when enhancing the complexity of crop rotations (West and Post 2001).

[16] Estimates with 7.2- 9.3 t C ha^{-1} year^{-1} accumulated in the soil and 80 t C ha^{-1} year^{-1} high in wood and soil combined due to riparian buffer strip system in arable soils in Italy (Borin et al. 2010).

[17] There is currently no information on the changes in SOC stocks and GHG emissions associated with these farming techniques, both in temperate climatic zones and in other regions.

[18] There are currently no known reports on effects of NIs on soil carbon sequestration rates and SOC stocks even within the EU.

[19] The time for restoration and build-up of SOC depends on the soil biophysical characteristics and climate. Under semi-arid Mediterranean conditions, an increase in SOC was not observed after 6 years of set-aside practice, but an increase of 0.14 t C ha^{-1} year^{-1} were found over a timeframe of 50 years.

[20] Carbon sequestration potential resulting from animal manure composting reported for European soils (Van-Camp et al. 2004).

3.2 Key observations on climate friendly soil management measures

This section summarises key observations across different climate friendly soil management measures that are dealt with in greater detail with regard to specific measures in the factsheets on ten selected measures that accompany this report.

Three key land use change measures have significant mitigation potential and co-benefits, but also involve some trade-offs that would need to be managed. The rewetting of organic soils, the conversion from arable to grassland, as well as management and conversion to silvopastoral and silvoarable agroforestry systems have the highest absolute mitigation potential in the EU and in Germany, according to available data. Although there are some uncertainties about the mitigation potential, there is a clear consensus that these measures make a significant contribution to climate protection and should be prioritized. Also, these measures have a range of co-benefits for other environmental objectives, for example improving biodiversity, flood protection to water filtration. However, the implementation has to manage some important trade-offs. For example, rewetted peatlands can lead to the temporary, substantial emission of CH_4 that need to be managed through appropriate measures, such as mowing and biomass removal before raising water table (Günter et al. 2020).

System approaches i.a. mixed-crop livestock systems and organic farming can play an important role for realising mitigation potentials. The mitigation potential is estimated to 1.65 t CO_2e/ha/year, however involving high uncertainties. System approaches promise to be long-term approaches, with rollbacks being costly and time consuming. They also offer several co-benefits for other environmental objectives especially with regard to biodiversity and nutrient management. The barriers for implementation are generally high due to significant changes within the operational procedure. This usually involves labour, planning, investment costs and legal requirements.

Reducing soil compaction and preventing land take are crucial for preserving soil health and ecosystem services, with significant benefits for climate mitigation and adaptation. The effects on the climate involve the GHG emissions due to the destruction of soil profile that enhances the loss of existing SOC stocks and the loss of future carbon sequestration potential. Both are highly dependent on the soil type, previous land use, and the type of destruction. Therefore, the total climate impact has high uncertainties and more research in this area is necessary. The reduction of soil compaction involves three main approaches: improving soil management, increasing awareness about soil compaction and technical measures to reduce wheel loads. However, lack of standards regarding the latter two aspects lead to implementation challenges, with the need to unlock these challenges. The prevention of land take is directly linked with population growth and density involving the need for social and economic activities such as housing, infrastructure, and industrial and commercial sites, which is the major trade-off and implementation challenge.

A range of measures are available for cropland and grassland management that improve the climate impact and deliver co-benefits. For example, these measures are cover crops, crop rotation, permanent grassland management, residue management, mulching and applying manure and compost. This involves improving soil biophysical capacity and adding organic matter for additional SOC sequestration and preventing further SOC losses from mineral soils. The estimates for additional SOC sequestration in EU croplands are up to 70 Mt CO_2e/year (Roe et al. 2021). The mitigation potential of SOC sequestration in croplands and grasslands is limited and uncertain, due to the heterogeneity of soils, climatic conditions, existing SOC levels and management practices. The latter also involves the combination of practices which cannot be added up with regards to their SOC sequestration potential. This increases the costs of measuring and monitoring, reporting and verification (MRV) standards and makes the feasible potential difficult to assess. The risk of intentional or unintentional reversal of sequestered SOC is relatively high as most countries do not have legal protections on soil management of the kind that are available for water and biodiversity protection. Co-benefits with regards to the on-farm measures are improved soil structure and soil fertility, increased water holding capacity and overall resilience to climate impacts.

There are also some management measures that have mixed impacts on both climate and soil health and need to be approached critically. One such measure is the use of **nitrification inhibitors (NIs)** with the goal to reduce nitrous oxide emissions (and nitrate leaching) by preventing bacteria from converting nitrogen from mineral and organic fertilizer into nitrate and nitrous oxide. Biological NIs are naturally present, but synthetic NIs are chemical compounds which can potentially have negative side effects, in particular on soil biodiversity and aquatic organisms. Moreover, their efficacy in delivering positive climate impacts is debated. Given the unclear long-term impacts of synthetic NIs, precautionary principles should be applied and their use should be restricted. Secondly, the application of **critical inputs** also carries risks. Critical inputs are off-farm organic nutrients derived from plant biomass and organic waste materials (plant and animal wastes) for the purpose of soil amendment as well as other environmental applications where carbon is limiting. They are considered critical because of a) bearing the risk of organic and heavy metal contaminants and b) the risk of high leakage effects regarding climate change mitigation due to excessive import of organic materials from elsewhere.

Precision farming is an approach applying georeferencing and technologies that enable a reduction of environmental impacts through a more precise application of inputs (plant nutrients, soil improving material (e.g., lime), pesticides, seeds, irrigation) and controlled traffic farming. While it can lead to improved environmental impacts, it is often associated with agro-industrial structures with large field sizes and simplified crop rotations. There are concerns that by itself precision agriculture simply supports business-as-usual, with no/little benefit for specific aspects in agricultural sustainability (biodiversity, resilience, governance) and it therefore needs to be evaluated in the context of overall farm performance and agricultural sustainability.

Furthermore, the issues of permanence, leakage, and saturation need to be recognized and addressed when considering climate impacts of soil management measures.[17] Permanence refers to the need to ensure that carbon which is removed from the atmosphere also stays permanently stored and is not released again at a later point. In the case of additional sequestration, the risk can be high either due to intentional change (e.g., because the farmer converts grassland back to arable land or simplifies cropping patterns) or unintentional change due to, for example, fires or diseases. In the case of soil carbon, the risk of intentional reversibility needs to be managed carefully.

Leakage occurs when increase in sequestration or reduced emissions in one area is offset by an increase in production and increase in emissions in another area. This can result, for example, if productivity and yields decrease. How to monitor, evaluate, and manage leakage is a very complex task, and the timeframe is also important. For example, a change in practices may result in short term reduction of output but increase stability of output over a longer period of time because the resilience of the farming system increases. This impact of management practices on

[17] These issues are dealt with in separate factsheets as part of the research project, see www.umweltbundesamt.de/publikationen/Funding-climate-friendly-soil-management.

stability of yields, especially given the anticipated climate impacts, is an under-researched area that needs greater attention.

Saturation of soil refers to the level where soils are no longer able to store additional carbon and reach a maximum level. In soils which are saturated, the priority has to be on maintaining existing carbon. Understanding the state of soils and how close they are to saturation levels can help in understanding what the additional mitigation potential of those soils is and what kind of policy support is most appropriate.

Moreover, it is important that the total climate impact of soil management measures is considered since measures can remove CO_2 from the atmosphere but also lead to an increase in emissions of other GHG. As already mentioned above, for example, peatland rewetting can lead to temporary increase in CH_4 emissions which need to be managed. Studies and assessments of mitigation potentials do not often make the total net mitigation impacts explicit when the aggregate potential of multiple measures is assessed. Improved understanding of the net climate impacts is needed so that measures with the 'net' mitigation effect can be prioritized.

Uncertainties remain in the estimates of the mitigation potentials both at the level of individual soil management measures, as well as at the level of aggregate assessments. These uncertainties can result from the lack of understanding of certain impacts that have not been studied enough. For example, there is general understanding that due to increased water retention/infiltration and reduction in topsoil loss, contour farming and terracing help to preserve organic matter and enhance SOC sequestration. However, there is currently no available information on the changes in SOC stocks and GHG emissions associated with these measures in temperate zones. For nitrification inhibitors, it is expected that these would also increase nitrogen availability to plants and thus potentially increase the below ground biomass (roots) and thus increase SOC. However, there are currently no known reports on effects of nitrogen inhibitors on soil carbon sequestration rates and SOC stocks within the EU. Moreover, the mitigation potential of soil carbon management more broadly is likely overestimated by neglecting N_2O emissions (Lugato et. al 2018).

More broadly, research should provide guidance to policy **through improved assessments** on where the most significant potentials are at national and regional level, where risks for losses of existing stocks are highest (not just on peatlands but also on mineral soils), and which combinations of practices would deliver most significant benefits for SOC levels and total climate impacts (COWI, Ecologic Institute and IEEP 2021). Moreover, the understanding of mitigation potentials also needs to be part of a broader integrated modelling that can account for the interactions between consumption and production changes (e.g., how reduced demand for animal products or shift from highly intensified/dependent on import systems would potentially impact land use and to what extent changes in consumption can counter any leakage effects).

Our analysis also shows that **when implementing measures, safeguards are important.** For example, in the case of agroforestry, these should not be targeted at peat soils because of risks of GHG emissions during the phase of tree planting (COWI, Ecologic Institute and IEEP 2021). Moreover, with agroforestry, intensive coppicing systems should not be introduced on farmland or land with existing high biodiversity value. Such safeguards can ensure that measures form win-win solutions for both climate and biodiversity and other environmental objectives.

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A Annex 1: Factsheets on climate-friendly soil measures[18]

A.1 Silvopastoral agroforestry

A.1.1 Measure definition

Agroforestry in grasslands, also known as silvopastoral agroforestry system, is a mild-successional system of grasslands for the purpose of grazing or fodder production, interspersed with trees and shrubs (Jose and Dollinger 2019). To establish this kind of agroforestry, trees or shrubs for diverse purposes such as fruit and berry production, timber, energy biomass or fodder are planted either solitary or in lines on existing or newly converted grassland. The perennial structures may also function as barriers and provide shade for the grazing animals.

By establishing agroforestry on existing grasslands, the previous land use, the grassland, is maintained and the trees or shrubs add an additional value by their produce or ecosystem services, e.g. carbon sequestration.

Agroforestry covers approximately 8.8% of the EU's utilised agricultural area and is concentrated in the Mediterranean and southeast Europe (Burgess et al. 2018). Most existing systems are silvopastoral agroforestry systems, which are long-established and locally adapted. Examples for such extensive systems include the *dehesa* in Spain, the *montado* in Portugal, or the meadow orchards in the Alpine regions. The protection of these long-established systems needs to be a priority and they need to be distinguished from the more recently established and often more intensively managed systems.

Geographical and biophysical applicability

- **Suitability to different biophysical conditions:** Due to the diversity of potential silvopastoral systems, these systems are suitable for several terrains and climatic regions by adapting species and landscape design. In general, any grassland can be converted to a silvopastoral agroforestry system. Limitations in establishing trees might be given on steep slopes with very shallow soils, or north-facing exposed hillsides where trees may reduce light levels.
- **Suitability in EU/German conditions:** Agroforestry systems are less common in the EU and Germany compared to other management or land use measures. In principle, silvopastoral agroforestry can be established anywhere where there are grasslands. However, the baseline ecological and social/cultural situation must be considered when evaluating the suitability of silvopastoral agroforestry systems for specific locations and types of grasslands. This needs to ensure that natural and semi-natural grasslands are protected so that no biodiversity loss occurs. Agroforestry systems should not be established on peatlands or rich organic soils, both due to emissions that occur during the phase of planting trees and because planted trees might hinder rewetting of the soil, which is a much more effective GHG mitigation option on these soils. Due to emissions that occur during the phase of planting trees, agroforestry systems should not be established on peatlands or rich organic soils. Kay et al. 2019 give an overview of the range of agroforestry systems in the different European regions, such as the *dehesa* in Spain, *montado* in Portugal, meadow orchards in Alpine regions, or different types of other orchards, hedgerows, wooded grasslands, and alley cropping.

[18] All factsheets included in this Annex are also published separately, see www.umweltbundesamt.de/publikationen/Role-of-soils-in-climate-change-mitigation.

Fit with NbS definition

Integrated systems of permanent grassland and trees (silvopastoral agroforestry systems) are in alignment with all aspects of nature-based solutions as defined in the working definition for NbS for this research project by Reise et al. (2022), provided that natural and biodiversity rich semi-natural grasslands are respected and protected from conversion.

A.1.2 Mitigation Potential

Carbon sequestration

The sequestration potential of agroforestry depends on the type of system implemented, the climate and the previous land use. Carbon is sequestered by establishing trees or shrubs and stored both in soils as well as in the above- and belowground biomass of the trees.

Kay et al. 2019 estimate the carbon storage potential of all agroforestry in the EU27 (plus Switzerland) to be between **0.3 - 27 t CO_2e/ha/year** or a total of **7.7 - 234.8 Mt CO_2/year** (Kay et al. 2019). The sequestration potential in particular depends on the type of trees, density of trees, lifespan and final use for the timber. This estimate assumes that agroforestry would be implemented on approximately 8.9% of EU farmland, or so-called "priority areas" in Europe, which face the highest environmental pressure. However, this estimate does not include below-ground SOC potential which is shown to be higher under agroforestry than under croplands or grasslands by themselves (Upson and Burgess, 2013).

In Germany, the introduction of trees or hedgerows on 1 to 10% of existing grassland can increase SOC and carbon stored in biomass by **0.2 to 2 Tg C/year** (Golizc et al. 2021).

Total climate impact

In general, silvopastoral agroforestry systems have a strong positive climate impact due to the large amount of carbon in soils and biomass. Moreover, the planting of trees can also reduce nitrogen-related emissions (Garcia de Jalón et al. 2017).

Agroforestry systems should not be established on peatlands or rich organic soils, both due to emissions that occur during the phase of planting trees and because planted trees might hinder rewetting of the soil, which is a much more effective GHG mitigation option on these soils.

To assess the total climate impact of silvopastoral agroforestry systems over longer period, emissions from the livestock component of the system should also be considered. Depending on the type of livestock that is integrated, the impact will vary.

Existing studies examine either the carbon sequestration potential and/or add some consideration of nitrogen-related emissions, but integrated assessments that look at the total climate impact on both sequestration and emissions, and additionally consider the impact of different types of livestock emissions are currently not available. There is the need to assess silvopastoral practices across different locations within the EU to enable a better assessment of how different practices in different biophysical conditions affect the climate, yield, and biodiversity impacts.

Limitations on the mitigation potential

The extent of the carbon sequestration potential on a given land depends on climatic and soil conditions, land-use history, and the design (species and planting patterns) of the agroforestry system. The soil carbon sequestration potential is furthermore naturally limited by the carbon saturation of the soil (Lugato et al. 2014).

Silvopastoral systems with high density of fast-growing trees increase the mitigation potential (Feliciano et al. 2018); whereas increasing hedgerow or field boundary tree cover offers lower mitigation potential.

The permanence of the carbon removal depends on the type of trees and their end use (e.g., timber for fuel versus construction). Poor management, the change in management system and natural events can lead to losses of sequestered carbon, although the fire risk is likely to be lower than in forest areas because agroforestry systems contain firebreaks to avoid the spread of fire.

A.1.3 Adaptation and co-benefits

Most agroforestry systems deliver multiple ecosystem services with few to no trade-offs for other ecosystem services, provided that safeguards outlined above are taken into account (protection of existing extensive systems, no planting on peatlands or natural / semi-natural grasslands).

- **Micro climate**: Introducing agroforestry on grazing lands contributes to climate adaptation and mitigation similar to agroforestry in croplands (Torralba et al. 2016). On grazing lands, it provides a cooler environment for livestock, serving as wind and rain shelter and buffering weather extremes. Through its cooling effect on micro-climate, agroforestry can reduce damage from droughts.
- **Yields:** Forage plants grown under improved microclimatic conditions can be more nutritious for livestock (Brantly 2014). The availability of animal manure leads to reduced use of fertilizers which can cross-benefit tree growth.
- **Animal welfare:** Sun protection by trees and lower body temperature lead to increased welfare performers of animals, such as heifer cows (Brantly 2014; Lemes et al. 2021). Also, agroforestry systems can encourage natural behaviour among animals such as foraging and scratching. Research shows for example, that laying hens bred in a woodland environment are less prone to feather-pecking and the share of eggs with poor-quality shells can be reduced (EPRS 2020).
- **Soil health and biodiversity:** agroforestry systems protect against erosion, nitrate leaching and flooding and provide improved habitat for wildlife and insects (Kay et al. 2019; Drexler et al. 2021).

A.1.4 Trade offs

- **Animal impact:** The animals can enter the system only when trees are strong enough to withstand their presence, or young trees have to be protected from animals. This protection causes labour and is cost intensive. The trampling of animals can damage the sward which is often wetted under the shading trees. Hence, grazing intensity has to be adjusted and possibly extensified to protect SOC.
- **Management:** Planting fast-growing trees in high density increases the mitigation potential of the system but requires more management costs and increases the total shade on the grassland. Also, risk of short-term and long-term environmental failure can be high if not properly managed (Brantly 2014). Systems with lower tree density will therefore be easier to integrate in the landscapes as they would affect a smaller portion of the grassland (Drexler et al. 2021).

A.1.5 Implementation challenges

Increasing the uptake of agroforestry systems in general, not just silvopastoral systems, is constrained by the permanent nature of the change and significant shift in the farming systems which carries economic and legal implications and uncertainty. Where farmers lease the land, they may not be able to convert to agroforestry because this leads to a permanent land use change. Very intensive production systems and fragmented agricultural land can also hinder conversion to agroforestry systems (Rodríguez-Rigueiro et al. 2021).

Successful implementation of silvopastoral agroforestry systems is also knowledge- intensive as it is a complex farming approach and requires specific and often new knowledge. For example, strong understanding of the regeneration process for desired tree species, the herbivore/plant interactions that may arise and how to avoid sapling damages done by animals (Brantly 2014).

These barriers to implementation are also reflected in the low uptake of agroforestry measures funded under the current EU's Common Agricultural Policy: It remains to be seen whether the stronger promotion of agroforestry in the coming CAP funding period (2023-27) will lead to at least a partial reduction of these implementation barriers.

A.1.6 References

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A.2 Silvoarable agroforestry (including hedgerows)

A.2.1 Measure definition

Agroforestry with cropland or silvoarable agroforestry is a system where woody perennials such as trees or hedges and agricultural, usually annual crops are grown on the same cropland in a specific spatial and/or temporal fashion (Cardinael et al. 2017; FAO and ICRAF 2019). This involves tree lines but may also involve the use of hedgerows, woodlots (small parcels of woodland), and scattered trees (Golicz et al. 2021).

In Europe, five main categories of trees occur in agroforestry systems: fruit trees, olive trees, timber trees, oaks and fodder trees (Eichhorn et al 2006). Depending on the systems, cereals, vegetables, sunflowers or fodder crops (e.g., legumes, alfalfa) can be intercropped with trees. Systems can vary in terms of the intensity of management, with some managed extensively and others relying on fertilisation and irrigation. Olive trees (dispersed or in rows), linear systems of hybrid poplars, and oak systems intercropped with cereals are some of the most widely adopted systems. Systems with timber trees may be more promising commercially because they face fewer constraints than fruit trees (fruit trees compete more with crops on the same area of land; market standards for fruit trees) (Eichhorn et al. 2006).

Some systems combine trees with both arable and grassland use (grazing, fodder cultivation) so that the term *agrosilvopastoral* is used. For example, in Spanish *dehesas*, the grazing component is dominant, but a small proportion of land may also be cultivated with crops such as cereals, sunflower or fodder crops (Eichhorn et al. 2006).

Agroforestry covers approximately 8.8% of the EU's utilised agricultural area and is concentrated in the Mediterranean and southeast Europe (Burgess et al. 2018). There is insufficient quality of data to be able to determine the share of silvoarable as opposed to silvopastoral or silvoarable-pastoral systems. However, pure silvoarable systems represent a minor share of agroforestry in the EU.

Geographical and biophysical applicability

- **Suitability to different biophysical conditions:** In Northern Europe silvoarable systems are limited by light availability due to higher latitudes (lower photon flux densities) which reduces the economic viability of crops under tree canopies (Eichhorn et al. 2006). In the Mediterranean, there is a greater diversity of silvoarable systems with the limiting factor here being water availability. Sloping land should not be kept exposed due to risk of soil erosion, so that silvoarable systems should also not be established here unless they use permanent soil cover (reduced or no-till organic systems that do not use herbicides).
- **Suitability in EU/German conditions:** Given the large diversity of potential combinations of trees and crops, silvoarable agroforestry systems can in principle be designed for and applied across Europe. They should not be established on rich organic soils due to emissions occurring during the planting phase of the trees and because this would limit rewetting of peatlands, which is a much more effective mitigation option.

Fit with NbS definition

Silvoarable agroforestry serves carbon sequestration objectives and fulfil all aspects of nature-based solutions as in the working definition for this research project as defined by Reise et al. (2022) provided that: the arable components of the system are locally appropriate and protect soils and that agroforestry is not situated on rich organic soils, does not involve conversion from grassland to arable land, and does not rely on intensive fertilisation/agro-chemical inputs or unsustainable irrigation.

A.2.2 Mitigation Potential

Carbon sequestration

Incorporating trees into croplands has the potential to promote soil carbon sinks compared to crop only (and especially monoculture) systems by sequestering more carbon in soils, and additionally through carbon stored by the trees in above ground biomass (Jose 2009). The sequestration potential will depend on biophysical conditions, land use history, type of management (rates of harvesting/pruning), tree density, and types of tree species (Golicz et al 2021).

Kay et al. (2019) estimate the carbon storage potential of all agroforestry in the EU27 (plus Switzerland) to be between **0.3 - 27 t CO_2e/ha/year** or a total of **7.7 - 234.8 Mt CO_2e/year**. The sequestration potential in particular depends on the type of trees, density of trees, lifespan and final use for the timber. This estimate assumes that agroforestry would be implemented on approximately 8.9% of EU farmland, or so-called "priority areas" in Europe, which face the highest environmental pressure.

However, this estimate does not include below-ground SOC potential which is shown to be higher under agroforestry than under croplands or grasslands by themselves and can deliver significant additional sequestration (Upson and Burgess 2013). For example, agroforestry using poplar trees increased soil carbon stocks to 60 cm depth by 13% compared to conventional arable croplands in England (Upson and Burgess 2013). In temperate climatic zones, the establishment of hedgerows could increase SOC stocks by 21 - 32% with a SOC sequestration potential of 0.9 - 0.3 Mg C/ha over a 20 to 50-year period. The reported increase in SOC stock is in close range to estimates of land use conversion from cropland to forests (Cardinael et al. 2018; Drexler et al. 2021).

Separate estimates for silvoarable systems provided in Kay et al. (2019) vary quite significantly across different biogeographic zones and types of system. They found the highest per ha potential for silvoarable systems in terms of above ground biomass in the Mediterranean mountains zone where lined poplar trees (200 trees per ha density) are interspersed with rotation of wheat, oilseed rape and chickpeas (5.76 - 7.29 C/ha/year). For Atlantic and continental regions the per ha potentials of silvoarable systems were in general lower (e.g. hedgerows as productive boundary for use as woodchips was estimated to have 0.1 - 0.45 t of C/ha/year or alley cropping with coppice in continental lowlands at 0.15 - 0.44 t C/ha/year).

In an assessment for Germany, Golicz et al. (2021) distinguished between three types of small woody landscape features (linear, patchy and additional) and provided an assessment of their additional mitigation potential. They found that cropland has the lowest share of features at 2.8% of total arable area, with south and north-east regions being dominated by cropland and low share of features, and northwest dominated by grasslands and higher share of woody features, and that cropland also has the highest potential through inclusion of additional features. Hedgerows as field boundaries have a higher potential than adding tree lines in cropland due to the structure of the hedges, high stem densities and regrowth capacity after trimming which leads to higher increase in soil organic carbon. In total, Golicz et al. (2021) estimate that increasing agroforestry on 1 - 10% of total agricultural land could potentially sequester 0.2 - 2 Tg C/year in soil and biomass and more than double the amount with the incorporation of hedgerows over the same area.

Total climate impact

Methods for estimating C stocks and GHG balances e.g., N_2O, CH_4 to monitor the net benefits of agroforestry on atmospheric GHG levels have not been optimized and are difficult and costly (Albrecht and Kandji 2003). Studies that examine the full GHG impact of agroforestry are hardly available. Underlying is the issue that there are no reliable statistical sources on trees located on agricultural land. Based on satellite data, Zomer et al. (2017) estimated that in 2000 more than 40% of the agricultural land area had more than 10% tree coverage with a CO_2 storage of 166 Gt CO_2. Average estimates range from 0.3 Gt CO_2e /year in Bossio et al. (2020) (only considering SOC contribution), 1.1 Gt CO_2e/year in Griscom et al. (2017) to 3.4 ± 1.7 Gt CO_2e/year in Kim et al. (2016). Jia et al. (2019) estimate the potential between 0.1 and 5.7 Gt CO_2e/year and Lal et al. (2018) between 1.6 and 3.5 Gt CO_2e/year (technical potential). Potentials for the enhancement of CO_2 storage by agroforestry vary widely with the type of system, soil types, climate, tree species and tree densities.

Agroforestry can be a source of N_2O emissions, depending also on the level of fertiliser use and intensity of management. Kim et al. (2016) estimated that 7.7 ± 3.3 kg N_2O emissions/ha/year can occur. Thus, a major trade-off might involve choosing between CO_2 sequestration and N_2O emissions.

The total impact also depends on the fate of the timber harvested, with the most significant benefits from long-term timber use, for example, in construction. Timber use for fuelwood reduces the total impact significantly.

Limitations on the mitigation potential

The amount of carbon sequestered will depend on the agroforestry system such as tree species, and management options (Albrecht and Kandji 2003). Research conducted in France showed that the potential for carbon sequestration by hedges was dependent on the hedgerow characteristics such as location in the landscape, the size and the height of the hedges (Aertsens et al. 2013). For short-rotation coppicing systems, the climate impact is limited since the system is not permanent and when the timber is harvested after a given cycle (at most 15-20 years), there is disruption and loss of carbon sequestered, the scale of which also depends on the final use of the timber harvested.

On plot level, the introduction of trees on agricultural fields can lead to competition for space, light or nutrients which may affect food/fodder production (EEA 2021). This can lead to leakage and thus reduced overall positive climate impact. However, this effect is suggested to diminish on a larger scale due to the more efficient use of nutrients in agroforestry systems (Aertsens et al. 2013) and thus a lower emission of total GHGs.

A.2.3 Adaptation and co-benefits

- **Air spread diseases:** The reduction of wind speed and temperature buffering in agroforestry systems reduces the dispersal of epidemic spores of airborne diseases (Boudrot et al. 2016) and the higher biodiversity supports pest regulation (Boinot et al. 2019).

- **Soil health:** Agroforestry reduces erosion by improving soil cover and reduces nutrient leaching. Plant root exudation can improve soil quality especially when compared to conventional cropland agriculture and forestry (Harvey et al. 2007, Jose, 2009; Smith et al. 2013; Torralba et al. 2016). Up to 65% reduction in erosion and 28% reduction in nitrogen leaching was observed for soils with the adoption of silvoarable agroforestry system using trees such as pine, oak, walnut, wild cherry and poplar in European regions (Palma et al. 2007).

- **Biodiversity:** Enhancing tree structures across croplands such as in agroforestry systems means to support biodiversity-friendly landscapes by achieving a large-scale mosaic of more natural habitats (Tscharntke et al. 2021). Agroforestry promotes soil biodiversity and ecosystem stability via suitable habitat for species (Harvey et al. 2007). The presence of tree row-associated bacteria in alley-cropping systems with poplar trees altered soil bacteria composition and increased overall microbial diversity of croplands in Germany (Beule and Karlovsky 2021).
- **Addressing societal challenges**: Agroforestry can improve food security, production of commercial products and energy production (e.g., timber) (Smith et al. 2012), thus diversifying income sources for farmers, improving wellbeing and offering economic benefits (Bene et al. 1977; Smith et al. 2014).
- **Yields**: Under drought conditions, agroforestry systems may maintain or enhance yields (Seddon 2020b). Research for Spanish conditions also predicts that crop production can be improved in agroforestry systems compared to open fields when there is an increase in warm springs (Arenas-Corraliza et al. 2018).

A.2.4 Trade offs

- **Land use:** Carbon sequestered by the trees can be reversed if the trees die, are harvested or removed due to land use change or fires. Carbon sequestration in above ground tree biomass is reversed if the biomass is used for energy production.
- **Management:** The combination of perennial trees with crops can make the management of agroforests difficult and time consuming (EEA 2021).
- Competition with crop only systems, limits on profitability and efficiency as well as limited market outlets (e.g., for high quality / specialty timber) currently limit their expansion in particular in northern Europe and in most intensified agricultural regions, where traditional agro-forestry systems have largely been abandoned (e.g. *Hauberg* system in North Rhine-Westphalia which combined trees for fuelwood with long rotations of crops and grazing) (Eichhorn et al 2006). Traditional systems in the Mediterranean, including France, have declined more slowly, but tend to remain more limited to marginal soils where cropland intensification was not as viable.

A.2.5 Implementation challenges

Until the current programming period, the CAP discouraged the maintenance of landscape features since areas with shrubs or trees were not eligible for payments. This has changed for the 2023-2027 period as the eligibility definition has been extended to include trees and landscape features. However, this only reduces the pressure to convert and remove landscape features, but does not provide an incentive to increase agroforestry coverage per se. Member States, however, can support agroforestry under eco-schemes and agri-environment-climate measures. In the past programming period of the CAP, the funding support for setting up new agroforestry was minimal.

Agroforestry systems are knowledge-intensive; the optimal combinations of trees and crops need to be determined for different biophysical conditions. The mainstream agricultural research activities and interests, however, have a strong bias towards single crop systems. One bottleneck is the development of systems where mechanization can reduce labour costs.

More limited profitability of single crops in agroforestry systems is also a significant barrier (e.g., due to cheaper imports of walnuts) and missing markets for different types of wood products limit commercial viability, so that research and piloting on how to improve efficiency and profitability while supporting climate and environmental objectives is needed. Increasing the economic value of trees through development of markets for high quality tree products is an implementation challenge (Eichhorn et al. 2006).

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A.3 Mixed crop-livestock systems

A.3.1 Measure definition

Mixed crop-livestock systems refer to farm-scale systems where livestock and cash crop production are combined to optimise resource efficiency (FAO 2001; Ryschawy et al. 2012; EIP-AGRI Focus Group 2017). Different types of integrated crop-livestock systems exist with varying degrees of integration of crops and livestock, and the volumes of external inputs, outputs and losses, including GHG emissions. Traditional mixed systems rely on low external inputs and often involve grazing on pasture, while modern systems seek to maintain high productivity with low inputs by increasing efficiency through synergies between crop and livestock systems (Garrett et al. 2020). Typical elements of mixed farming systems are organic matter recycling and forage legumes in the crop rotation. Livestock keeping is area-based, meaning that the organic fertilizer applied to one hectare corresponds to the manure of one livestock unit and livestock can be fed by on-farm products only (Gattinger et al. 2012).

Integration of animals and plant production was common throughout agricultural history but ongoing agricultural specialization and intensification leads to a separation of crop and livestock production (Schut et al. 2021). At present, mixed farming systems account for over 60% of animal production in Europe and worldwide (Herrero et al. 2013). However, taking into account all types of farming systems, i.e. cropping only, animal husbandry only and mixed farms, integrated systems make up only 10-20% of farms in Europe (Garrett et al. 2020). This indicates the dominance of farming systems with crop or animal production only nowadays compared to integrated crop-livestock systems. A shift in farming systems towards mixed farming could close nutrient cycles and reduce the number of animals in large industrial production, but must be combined with a paradigm shift in food and dietary systems.

A regional or landscape-scale integration of crop production and livestock husbandry can be an alternative to integration at farm level. According to this approach, income streams would be diversified while keeping costs down by economy of scale via specialized land use (Garrett et al. 2020). However, it requires strategic top-down planning and is currently not pursued as an explicit objective in EU agricultural or land use policies.

Geographical and biophysical applicability

- **Suitability to different biophysical conditions:** Integrated crop-livestock systems are generally applicable across landscapes and regions; mixed farming is typical for organic agriculture, but can be applied in any agricultural production system (Gattinger et al. 2012).
- **Suitability to EU/German conditions:** European landscapes offer great potential for mixed farming because of the climatic suitability to grow a variety of crops and forage. Farms with heterogeneous and small field sites as in many landscapes throughout Central and Southern Germany often have fields unsuitable for cropping and can use these as pasture for livestock.

Fit with NbS definition

Mixed farming systems are in alignment with all aspects of nature-based solutions as in the working definition for this research project defined by Reise et al. (2022). The integration of livestock husbandry in cropping systems enhances natural cycling of organic matter and nutrients within the farm, diversifies natural habitats across the farm landscape for wildlife conservation and improves microbial activities due to improved crop rotation and fertilization with farmyard manure. Several ecosystem services are provided benefiting natural environment, farmers and society.

A.3.2 Mitigation Potential

Carbon sequestration

In mixed farms, livestock manure is applied as fertilizer on organic matter basis. A cumulative C-input to the soil by farmyard manure increase the SOC stock by factor 1.26 (Maillard and Angers, 2013). Additionally, forage legumes and perennial grasses are key elements in the crop rotation of mixed-farms. They can lead to C accumulation in the soil with annual SOC sequestration rates of 0.11 t C/ha/year (Lugato et al. 2014). Organic matter recycling by manure application and an increase in SOC stocks was especially confirmed for organic farms (Gattinger et al. 2012).

Total climate impact

Agriculture accounts for approximately 11% of the total GHG emissions of the EU-KP[19], with almost half of the agricultural emissions come from enteric fermentation and manure management. The agricultural sector is responsible for around 49% of the total EU-CH4 emissions (deriving mainly from livestock) (EEA 2022). The share of total EU emissions from enteric fermentation in 2020 ranges between ca. 18% in France, 13% in Germany, 4% in Netherlands and 0% in Malta (EEA 2022).

Dairy farms and mixed farms have a similar amount of annual GHG emissions (5.5 t CO_2-eq ha^{-1} year^{-1}), mainly from enteric fermentation of the cows (Schader et al. 2014). Conventional farming with the use of farmyard manure also results in higher N_2O production compared to conventional farming with mineral fertilization, both per unit of yield and unit of area (Skinner et al. 2019). Nevertheless, re-integration of livestock with crop production closes farm-gate nutrient cycles. This closed-loop idea of crop-livestock production can reduce GHG emissions from livestock manure at farm-scale when integrating cropping fields beside livestock husbandry, where the manure can be recycled rather than wasted (Li et al. 2012).

Beyond farm-scale, additional GHG emissions from off-farm fertilizer production as well as transportation will be reduced by direct application of manure produced at the same farm. Finally, mixed farms with an equilibrated land to livestock ratio are producing also the fodder for their livestock on-farm, thus reducing GHG emissions from off-farm fodder production and transportation (Schader et al. 2014). Of course, the choice of fodder crop and the way of production, e.g., perennial grass in a crop rotation with a high mitigation potential versus intensive maize production (Christenson et al. 2021), offer further impact on GHG emissions that are closely linked to farm management practices, e.g. improved crop rotations.

Limitations on the mitigation potential

The climate mitigation potential at farm system level remains unclear. There is a lack of knowledge on the actual amount of GHG emissions that can reduced by (re-)integrating livestock and crop production, or the amount of SOC that can be sequestered using mixed farming systems (EIP- AGRI Focus Group 2017).

Achieving positive environmental performance on a mixed farm is closely related to the level of physical integration and complementarity between crop and livestock (home-grown feed, recycling of waste as fertilizer), thus relying on synergies, not just the coexistence of both on a farm (Leterme et al. 2019). Manure management and fodder production are key elements here to close the nutrient cycles. This is closely linked to improved crop rotations by higher diversity and length, and the grazing intensity (Garrett et al. 2017). Furthermore, management factors such as the degree to which farms rely on external inputs to intensify their operations such as N

[19] EU-KP = EU-27+ISL+UK.

and P fertilization, the tillage/ploughing intensity or the addition of nitrification inhibitors impact the mitigation potential at farm scale.

A.3.3 Adaptation and co-benefits

- **Yields**: Integrated crop-livestock farming show no declines in profitability or yields (Garrett et al. 2020). The integration of grasses and forages into cropland can even increase yields in subsequent crops as well as livestock profitability (Garrett et al. 2017).
- **Environment**: Mixed farms in commercial agricultural landscapes are associated with lower environmental externalities than specialized crop production and enhanced ecosystem services (Garrett et al. 2020).
- **Climate impacts**: The diversification of mixed farms, including a share of permanent grassland and forage legume production for the cattle, improves sustainability and resilience to inter-annual weather variability due to risk distribution (Regan et al. 2017; Garrett et al. 2020).
- **Soil and biodiversity**: Integration of grasses in the crop rotation (Garrett et al. 2017) and application of farmyard manure (Lori et al. 2017) from livestock integration rather than the use of synthetic fertilizers increase soil microbial activity and soil carbon sequestration. Due to their positive impact on beneficial soil biota, mixed farming is a measure of sustainable soil fertility management (Barbieri et al. 2017; Gattinger et al. 2012).
- **Biodiversity**: Mixtures of crops and pastures diversify the farm landscape and increase habitats for local wildlife, heterogeneity of species within patches (β-diversity), and related ecosystem services such as pollination and biological pest control (Garrett et al. 2017).
- **Nutrient management**: Separation of crop and livestock production increases slurry from livestock, with high GHG potential. Due to the EU-Nitrate Directive (91/676/EEC), manure is often transported from specialised animal production areas to other regions (Schut et al. 2021). The emissions from large distance transportation outweigh the emissions saved by its reuse. In mixed farms, the manure can be recycled by directly returning it back to crop production (Gattinger et al. 2012). Nitrogen pollution due to nitrogen surplus can be reduced compared to crop and dairy farming systems (Ryschawy et al. 2021).
- **Resource efficiency**: Land resources in mixed farms with fodder crop production are more efficiently used and can support more animals per hectare than farms relying solely on extensive grazing (Regan et al. 2017).
- **Costs**: Fodder and manure production at mixed farms reduces purchase and transportation costs and improve feed and fertiliser autonomy (Ryschawy et al. 2012; Regan et al. 2017).
- **Economic resilience**: Mixed farming can provide a more stable and diversified source of income, which helps farmers to reduce their risk major changes in prices (Ryschawy et al. 2012; Garrett et al. 2017).

A.3.4 Trade offs

- **Costs:** Diversification of farm production means higher upfront costs, e.g. for machinery (Garrett et al. 2017).

- **Economic dependencies:** Crop and livestock production requires dependency on a greater diversity of agricultural supply chain infrastructure, e.g., processing facilities, marketing channels and transportation routes (Garrett et al. 2017).
- **Management:** Re-integrating livestock in agricultural systems may lead to a loss of cropland due to conversion to pasture. If conversion of grassland to arable occurs (within the limits, e.g. set by the cross-compliance/conditionality under the Common Agricultural Policy), this can lead to loss of soil carbon.
- **Labour:** Better utilisation of labour throughout the year (Schut et al. 2021) is counterbalanced by the need for more or skilled labour. The year-round attention the livestock requires more labour compared to seasonal crop production (Garrett et al. 2017).
- **Nutrient management**: Livestock integration enhances nutrient cycling but the impacts on carbon and nutrient accumulation remain strongly influenced by co-management factors such as N and P fertilization intensity, tillage intensity, crop rotation length and grazing intensity (Garrett et al. 2017).
- **Policies**: Supportive policy environments and policy incentives for crop-livestock integration are limited (Garrett et al. 2017).

A.3.5 Implementation challenges

For practitioners used to segregated farm types, the integration of either livestock or crop production can be very challenging, labour-, planning- and cost-intensive, e.g., by infrastructure and further land necessary for the implementation. An alternative could be the unification of two formerly separated farms. This, however, is still challenging. Policy restrictions or non-supportive environments can be another limitation for the (re-)establishment of mixed farms across regions.

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A.4 Reducing soil compaction

A.4.1 Measure definition

Soil compaction due to vehicular traffic constitutes a major threat to agricultural soils by adversely affecting key soil functions for agricultural productivity and gas exchange. Furthermore, it may lead to a cascade of physical feedbacks by increasing runoff and the risk of soil erosion by water and wind (Horn et al. 1995). In combination with N fertilisation soil compaction leads to enhanced N_2O release because of favoured denitrification processes in compacted soils in zones of pronounced anaerobic conditions (e.g., Oenema et al. 1997; Schmeer et al. 2014).

The increasing size and weight of agricultural machinery in Europe has led to an increase in wheel loads from machinery from 1.5 to 8.7 Mg or by almost 600% between 1960 - 2010 (Schjoning et al. 2018). Since contemporary arable farming requires some type of vehicular traffic on agricultural land, zero soil compaction seems to be impossible. Manure distribution and harvesting have the highest impact on soil compaction (Thorsoe et al. 2019). Here we focus on the so-called harmful soil compaction ("Schadverdichtung" in German). Two types of soil compaction can be distinguished: topsoil compaction and subsoil compaction, i.e., compaction occurring in the layers below the tillage depth. Research from the RECARE project indicates that approximately 29% of subsoils across all Europe already are affected by subsoil compaction. Topsoils are similarly affected (Keller et al. 2019), but due to regular loosening with ploughing and other tillage operations, topsoil compactions and their implications are prevalent for shorter periods only. The economic costs of soil compaction are significant, with research in England and Wales indicating that harmful soil compaction (topsoil and subsoil) leads to total costs of 56.4 € ha−1 yr−1 (Keller et al. 2019; Graves et al. 2015). Long-term yield penalties from high-wheel load traffic in wet conditions are estimated to be from 6 - 12% (Schjønning et al. 2018). Hence reducing soil compaction has not only agronomic but also societal impact.

Three overall approaches need to be combined to reduce the risk of soil compaction: 1) improve overall soil management by improved crop rotations and maintaining good soil health/soil structure to increase resilience of topsoils; 2) increase awareness and knowledge about soil compaction, and support capacity building for farmers; 3) reduce wheel loads and develop preventive technologies. For the latter, three important measures are available: i) reducing vehicle mass, ii) increasing bearing surface of tyres and iii) controlled traffic farming. For reducing vehicle mass, there are novel strategies in progress such as using small robots operating in swarms and performing those jobs for which no traction for soil working devices is needed and which weigh only a portion of the 4 tonnes of an average tractor (Keller et al. 2019). The bearing surface of tyres can be increased through reduced tyre pressure. Controlled traffic farming often draws on GIS-based controlling systems to confine field traffic to specific or permanent tracks leaving about 85% of the field area with no traffic (Blanco-Canqui and Wortmann 2020). With this measure, farmers can reduce soil compaction by confining traffic to inter-rows that has already been trafficked, thus, limiting the amount of soil driven over (Crozia and Heitman 2014).

This factsheet focuses on the third approach of reducing wheel loads and developing preventive technologies on agricultural soils. Although harvesting machinery also has adverse impact on forest soils, this will not be addressed here.

Geographical and biophysical applicability

- **Suitability to different biophysical conditions** Reducing soil compaction can be applied anywhere and should be of highest priority at sites/regions with high proportion of soils prone to compaction (e.g. hydromorphic soils with high clay content or organic soils), and in particular with specific activities which result in the highest weight bearing of machinery (e.g. harvest of maize, tube crops in the fall, and application of slurry).
- **Suitability in EU/German conditions:** Because of the high mechanization in EU/German agriculture, the topic is of high relevance. Reducing soil compactions by means of controlled traffic farming is locally appropriate to a wide range of commercial farms in temperate regions (Crozia and Heitman 2014; Antille et al. 2016) including different European regions (Lamers et al. 1986; Chamen et al. 1992; Vermeulen and Mosquera 2009).

Fit with NbS definition

Reducing compaction is an effective means to maintain and enhance soil health, soil biodiversity, as well as soil regulating and productivity functions (Hagedorn et al. 2018). The reduced use of machinery in itself is not an NbS, however reducing compaction is in line with the working definition of nature-based solutions for this research project set out in Reise et al. (2022), provided that the measures put in place are of sufficient ambition to actually result in significant reduced risk and deliver benefits to soil health and functions.

A.4.2 Mitigation Potential

Carbon sequestration

Up to now, there are no robust estimates on the carbon sequestration potential due to adoption of measures reducing soil compaction. It can be assumed, however, that reducing compaction by introducing measures such as controlled traffic farming more SOC will be built up (Antille et al. 2015). Soil compaction affects plant growth in various ways as it increases the mechanical impedance to root growth, which decreases root elongation rates. This limits root growth and exudation (Keller et al. 2019). Root derived carbon, however, contributes much more to soil carbon sequestration than carbon from above-ground plant biomass (Poeplau et al. 2021).

Total climate impact

The overall impact on total GHG balance due to reduced soil compaction has not been estimated yet. More detailed studies exist for controlled traffic systems. The adoption of seasonal controlled traffic farming system in organic arable vegetable farms in the Netherlands resulted in a 20 - 50% reduction in N_2O emissions. Controlled traffic resulted in either increased CH_4 uptake (by a factor 5 - 20) or decreased emission (by a factor 4) compared with the random traffic farming. (Vermeulen and Mosquera, 2009). These effects are due to more anaerobic zones due to soil compaction. Based on a review by Gaso et al. (2013), five years of controlled traffic farming has the potential to reduce N_2O emissions by 21 - 45% and methane emissions by 372 - 2100% in a wide range of soils compared to random traffic farming.

More efficient trafficking also results in fuel savings, and thus reduced CO_2 emissions from fuel (Tseganesh et al. 2022).

Limitations on the mitigation potential

Positive outcomes related to soil compaction are dependent on soil texture and also when combined with other management systems like reduced tillage (Soane et al. 1982). Moreover, the beneficial impact of the practice will not grow continuously but the practice needs to be continued indefinitely to maintain the positive results.

Reports on the actual effects on SOC sequestration rates are limited in currently available literature.

A.4.3 Adaptation and co-benefits

- **Soil structure:** Controlled traffic with farming practices e.g., permanent wheel track, can improve soil structure, fertilizer use efficiency and crop yields with crops like cereal, tubers and perennials e.g., apples. Non-trafficked rows commonly have better soil properties compared with trafficked rows (Soane et al. 1982; Antille et al. 2016). Water erosion, poor drainage and aeration problems associated machinery related (e.g., ploughing) soil compaction are reduced /avoided (Soane et al. 1982).
- **Soil biodiversity**: Since soil compaction has strong impact on soil physics and nutrient flows, it alters the size and composition of microbial communities in soils (Hartmann et al. 2012; Hartmann et al. 2014). Plant symbionts, like ectomycorrhizal fungi, and saprobic taxa, such as ascomycetes and actinomycetes, are among the most sensitive to harvesting disturbances. Given their significant ecological role in forest development, the fate of these taxa might be critical for sustainability of forest ecosystems (Hartmann et al. 2012). By reducing soil compaction, this benefits soil microbial diversity and symbiotic fungi in forest ecosystems (Hartmann et al. 2012). Research in compacted arable soils confirmed changes in archaeal, bacterial and fungal diversity with a tendency towards more anaerobic archaea and bacteria (Gattinger et al. 2002), but until now we are not aware of modern molecular analyses conducted in harmfully compacted arable and grassland soils as described for forest soils above.
- **Yields and profitability**: Avoiding soil compaction helps to maintain or even increase crop yields as has been shown by Keller et al. (2019). Across four countries in Europe including Germany, Chamen et al. (1992) recorded up to 21% yield increase for wheat and barley and up to 14% increase in sugar beets, onions, ryegrass and potatoes due to zero traffic farming compared to conventional systems. On arable land in the UK, yield benefit of 4.6% was reported for a reduced wheel passes of 30% (Godwin et al. 2019). Moreover, there is also an improvement in fertilizer use efficiency and energy savings in form of reduced diesel use (Antille et al, 2015), and in profit (Blanco-Canqui and Wortmann 2010).
- **Flooding**: Soil compaction has been estimated to be responsible for 3 - 10% (average 7%) of the increase in the depth of runoff, resulting in compaction-induced flooding damage costs for England and Wales of 193 M€ year^{-1} (Graves et al. 2015).

A.4.4 Trade offs

- **Costs**: The costs of certain low-compaction measures such as controlled traffic farming is high and often not rewarding especially when considering immediate benefits. Thus, it is still most likely to be more profitable for farmers to use heavy machinery that results in soil compaction than to adopt preventive measures (Schjønning et al. 2013). Farmers will continuously need to balance different considerations such as profitability, capacity, efficiency, weather, labour and timing when planning their field traffic events (Schjønning et al. 2013).
- There is the problem of standardization of working widths of tractor implements of different manufacture and this inhibits the adoption of controlled traffic in commercial agriculture.

Also, there may be the need to customize equipment to meet specific requirement of different farming systems (Antille et al. 2016), e.g. customised wheel spacing, which can be expensive and limited to use (Soane et al. 1982).

- Due to the large areas lost to wheelways, controlled traffic farming might not be economically viable in some cases (Chamen et al. 1992).
- As reduced or controlled field traffic might be accompanied by zero-tillage practice (Soane et al. 1982), this might favor pesticide run-off (Blanco-Canqui et al. 2020), thus increasing the need and use of pesticides.
- New tramlining or tracks may need to be created often as previous ones get destroyed especially if needed for use for the crops later. New tramlines are needed when switching from cereals to row crops such as potato or maize.

A.4.5 Implementation challenges

The knowledge and data on the extent and severity of soil compaction at society-relevant scales needs to be improved (Keller et al. 2019). This would increase the visibility of the problem and help to guide policy action towards areas most at risk. However, even in absence of this improved data basis, there is enough information to warrant systemic action on this problem.

Limited awareness and knowledge of the problems of soil compaction, in particular of subsoil compaction which is not easily noticed, costs of preventive measures, and outsourcing of field operations are all barriers to reducing risk of soil compaction (Thorsoe et al. 2019). Within the German context, the good agricultural practice standards in the current Soil Protection Law (BBodSchG Article 17) do not include practices that would address field traffic and soil compaction problems.

A significant hurdle in introducing low-compaction measures is also absence of any limitation for the maximum wheel load. While there is a limitation for public traffic roads, this is not the case for agricultural and forest soils (also not, for example, in the German Soil protection Regulation as the implementing act (Bundes-Bodenschutz- und Altlastenverordnung).

However, this limitation would need to be combined with other measures such as increasing awareness among farming community, introducing compulsory training and risk assessment under the conditionality requirements in the Common Agricultural Policy (in particular GAEC 6), funding R&D for technological innovations (Schjønning et al. 2019).

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A.5 Critical External Inputs: off-farm compost, off-farm manure and biochar

A.5.1 Measure definition

Critical external inputs involve the application of off-farm organic nutrients derived from plant biomass and organic waste materials (plant and animal wastes) for the purpose of soil amendment as well as other environmental applications where carbon is limiting. We consider such inputs as critical because of a) bearing the risk of organic and heavy metal contaminants and b) the risk of high leakage effects regarding climate change mitigation due to excessive import of organic materials from elsewhere. This import could mean a SOC increase at the site where the material is applied, but a depletion in SOC where the material originates from (Gattinger et al. 2012) and no SOC gain in the context of climate change mitigation (Wiesmeier et al. 2019).

Within this scope, only external inputs in the form of solid off-farm manure, compost and biochar (charcoal in simple terms) are discussed, which are traditionally used for soil organic matter management. While manure and compost can be derived via biological decomposition processes, biochar is produced via pyrolysis (heating under limited or no oxygen conditions) respectively (Doble and Kumar 2005; Bihn et al.2014; Beusch 2021).

To avoid over-complexity, we exclude any liquid or half-liquid waste such as animal slurry and sewage sludge from the assessment here. Further, these two groups of organic wastes often result from industrial structures and are applied because of their N and P provision and not for the purpose of soil organic matter reproduction (Schubert 2017).

Geographical and biophysical applicability

- **Suitability to different biophysical conditions:** Off-farm compost, off-farm manure and biochar can be applied anywhere in different pedo-climatic conditions, as organic fertilization serves the purpose of nutrient provision and soil organic matter management in farming systems.
- **Suitability in EU/German conditions:** In many European countries quality assurance schemes exist to state the legal compliance regarding residues of heavy metal and organic contaminants. With such quality assurance schemes the conformation with EU organic farming regulation can also be met (e.g. the European Biochar Certificate). There are also restrictions to maximum application amounts per ha and year according to national law and some organic grower association further limit the amount of imported compost and manure (40 kg N equivalents per ha according to some organic growers' regulations).

Fit with NbS definition

As a result of the specialization trend in agricultural and human history since the middle of the 20th century, the exchange of on-farm nutrients between farms with/without livestock and between municipalities and their citizens through off-farm manures/composts is one component to close nutrient gaps at farm and even municipality level.

This can be considered as an attempt to mimic traditional, somehow natural food and farming systems. The transportation of manures from livestock dense areas into areas with low livestock density over hundreds of kilometers or even across borders cannot be seen as NbS.

To produce biochar, external energy is required (although Smith et al. (2016) report net energy gains that exceed energy costs) and there are potentially negative effects on biodiversity. Hence, the use of biochar is not fully aligned with the criteria for nature-based solutions as defined in the working definition for this research project as laid out by Reise et al. (2022).

A.5.2 Mitigation Potential

Carbon sequestration

- Application of organic materials can be judged as beneficial for soil carbon sequestration, if no leakage and SOC depletion occurs at the place of origin of the organic materials due to withdrawal of biomass (Wiesmeier et al. 2019). Carbon sequestration in soils is considered to be explicitly linked to a defined area (Olson 2013). Setting thresholds to limit the application amount to be aligned with-site biomass productivity or livestock density to somehow mimic a closed farming system is a means to overcome the leakage problem of off-farm organic materials (Gattinger et al. 2012). Therefore, in this overview we consider only those studies/meta-studies of carbon sequestration rates for application of organic materials where no or only a minor carbon leakage effect can be assumed.
- Regular application of farmyard manure, compost and biochar leads to an increase in SOC compared to mineral fertilization (e.g. Kirchmann et al. 2004; Fliessbach et al. 2007; Diacono and Montemurro 2011; Aguilera et al. 2013; Blanco-Canqui et al. 2019).
- Regular compost applications lead to a sequestration rate of 1.34 t C /ha/year (Aguilera et al. 2013), but these were achieved with application amounts > 3 t C/ha/year. This equals an organic fertilisation intensity of more than two livestock units per ha, which is well above the limit for a closed farming system (Gattinger et al. 2012).
- For the temperate climate, the DOK long-term farming systems trial in Therwil/CH[20] seems to be the only field trial providing accurate data on SOC and non-CO2 fluxes as influenced by compost, rotted manure, stacked manure, mineral and no fertilisation (Mäder et al. 2002; Skinner et al. 2019). There, compost and manure are applied according to a fertilisation intensity of 0.7 and 1.4 livestock units per ha, which can be considered free of any carbon leakage effect (see above). It turned out, that only at 1.4 organic fertilisation intensity carbon sequestration can be achieved but at rates well below 0.2 t C/ha/year (Krause et al. in prep).
- Not much is known regarding actual SOC sequestration rates or changes in SOC stocks due to biochar application in Germany or within the EU. However, the addition of biochar to soils of an experimental field site in Germany was reported to slow down SOC decomposition rates resulting in SOC decomposition of less than 0.3% per year (Kuzyakov et al. 2014). A field study in the US revealed that soil carbon increased by twice the amount of biochar carbon applied after 6 years. The corresponding sequestration rate due to biochar application is 1.97 t C/ha/year (Blanco-Canqui et al. 2019). The total increase in C stocks in the biochar-amended plots was nearly twice (14.1 t SOC/ha) the amount of C added with biochar 6 years earlier (7.25 t C/ha biochar), suggesting a negative priming effect of biochar on formation and/or mineralization (Blanco-Canqui et al. 2019). Similar phenomenon was reported from Brazil with an increase of soil carbon stocks by 2.35 t C/ha/year with an application rate of 0.4 t biochar /ha/year in sugarcane field sites (Lefebvre et al. 2020).

Total climate impact

The total climate impact of off-farm inputs will depend on the impact that these inputs have at farm level, as well as the additional emissions associated with the transport of off-farm inputs, leakage to other land, and substitution of previous use. Such assessments are not available, likely also due to lack of available synthesized information on patterns of transport and the amounts of off-farm inputs applied.

[20] Established in 1978; www.fibl.org/en/themes/projectdatabase/projectitem/project/404.

- The use of manure or compost can potentially reduce GHG emissions by avoiding uncontrolled storage of manure (Petersen et al. 2013). Composting systems such as `turned composting´ can potentially reduce GHGs emissions with reduction in N_2O by 50%, and CH_4 by 71% as documented from a global meta-analysis (Pardo et al. 2015). However, research on the impact of compost and manure storage and processing on total GHG emissions is very limited, with the Pardo et al (2015) meta-analysis based only on 11 original research papers.
- At the same time, the application of compost and manure in closed farming systems often leads to N2O emissions from soils which are higher in CO2 equivalents than the carbon sequestration effect (Gattinger et al. 2012; Skinner et al. 2014; Skinner et al. 2019; Wiesmeier et al. 2020). We are not aware of life cycle assessment (LCA) analyses which are based on measured GHG emission data from field experiments on compost and/or manure use. Nemecek et al. (2011) conducted a LCA on the various farming systems on the DOK trial using default values as emission factors. It turned out that the two systems with solely organic fertilization (compost and rotted manure) showed significantly lower carbon footprint per ha and per dry matter product than the system with synthetic fertilizer and stacked farmyard manure.
- Compost particularly green waste compost (wood clippings and other plant debris from public and private gardens) can offer a substantial contribution to replace peat as a growing substrate in horticulture. In the German federal government's climate protection plan for 2050 and in the coalition agreement from 2018, peat use in the horticultural sector is mentioned as a cause of greenhouse gas emissions and it is stated that the use of peat as a growing medium should be significantly reduced. In Germany, around 8 million cbm of peat are processed annually as a substrate for domestic horticulture and export (Thuenen Institut 2022). The extraction and use of peat as a plant substrate causes greenhouse gas emissions due to the decomposition of the peat. According to climate reporting data, emissions of more than 2 million t CO2 equivalents are generated in Germany from this activity (Thuenen Institut 2022). Several projects under the auspices of FNR and BLE are on-going to investigate and develop peat replacement products. Bundesgütegemeinschaft Kompost (BGK 2021) estimates, that the compost demand for potting mixes will rise from 1 million cbm in 2017 to 5 million cbm in 2050. Covering GHGs like CO2, CH4, and N2O, Teichmann et al. (2014) found that biochar soil incorporation has a GHG mitigation potential of 2.8 - 10.2 Mt CO2-eq. by 2030 and 2.9 - 10.6 Mt CO2-eq. by 2050 in Germany, if costs are not considered. This represents 0.4 – 1.5% and 0.3 - 1.1% respectively of Germany´s GHG reduction targets by 2030 and 2050.
- In a synthesis on 20 years of biochar reduced non-CO2 greenhouse gas emissions (N2O and CH4) from soil by 12% - 50% (Joseph et al. 2021). Although these potentials were often achieved with high biochar application amounts, comparable GHG mitigation potentials were not reported for compost and manure. The data on N_2O and CH_4 effects of compost and manure are not (yet) available.

Limitation on the mitigation potential

Apart from the restrictions when considering off-farm resources for soil carbon there are further limitations to list:

- Despite positive effects of GHG emissions, turned and forced aerated composting systems may cause an increase in NH_3 emissions by 54% - 121% (Pardo et al. 2015). Mismanagement of the application rate, method and timing can also lead to N_2O emissions, and should be optimized to avoid these effects (Petersen et al. 2013).

- The availability of excess feedstock biomass is limited to produce soil inputs such as biochar, and this was reported to lead to a lower "sustainable" global potential of 0.5-2.0 $GtCO_2$ per year with negative emissions (Fuss et al. 2018). Also, the experience with large-scale production and the use of biochar is missing and feasibility, long-term mitigation potentials, side-effects and trade-offs remain largely unknown (Fuss et al. 2018; Jian et al. 2019).
- Effects of manure and compost on SOC sequestration may vary depending on the manure application rate, initial SOC content, land use, management system, etc (Maillard and Angers, 2014). The precise impacts of biochar on field soils is also uncertain (Smith 2016; Tammeorg et al. 2016) as its use has not been considerably demonstrated beyond laboratory research settings (Griscom et al. 2017). Long term field trials are thus lacking, and few documented ones contradict with lab studies (Vijay et al. 2021). A broader lifecycle assessment is thus necessary to determine the mitigation effect of biochar as an exogenous carbon input to soils.
- When considering benefits to soil, manure quality is more important than manure quantity (Köninger et al. 2021), thus only application of manure that is free of contaminants / pollutants will be beneficial to soil biodiversity.
- The quality of animal manure applied and hereby, benefits to plant depends on the diet of the animals (Petersen et al. 2013). Similarly, the carbon conversion efficiency of biomass to biochar is highly dependent on the nature of the feedstock material (Lehmann et al. 2006).
- Surface application of biochar carries the risk of reducing the albedo effect of agricultural croplands / landscapes. The addition of high temperature-produced biochar to soils may enhance the decomposition of SOC (Budai et al. 2016). The addition of dark colour biochar may reduce the magnitude of solar radiation reflected to space (albedo) and this can increase soil temperature (Smith 2015), which in turn might lead to SOC decomposition and losses and increase CO_2 emissions. For example, 30 - 60 t ha^{-1} biochar application to experimental field soils in Italy decreased surface albedo by up to 80% (Genesio et al. 2012). Similar albedo reduction with 30 - 32 Mg ha^{-1} of biochar has been reported for arable field sites in Germany, leading to reduction of climate change mitigation potential by 13 - 22% (Meyer et al. 2012). The extent to which this would negate the positive climate impact of biochar is unclear as we do not have studies that address these trade-offs. This risk is reduced when biochar is incorporated in soils.

A.5.3 Adaptation and co-benefits

- **Waste management:** Adopting off-farm manure, compost and biochar as soil amendment enable improved waste management (Paul et al. 2001; Doble and Kumar 2005; Roberts et al. 2010) and thus can contribute to circularity in food and farming systems (Van Zanten et al. 2019).

- **Improved soil structure and soil health:** There is vast body of literature indicating the beneficial effect on improved soil structure and soil health as influenced by compost and manure (e.g. Diacono and Montemurro 2011) as well as biochar (e.g. Joseph et al. 2021).
- **Soil biodiversity:** There is vast body of literature indicating the beneficial effect on soil biodiversity as influenced by compost and manure (e.g., Diacono and Montemurro 2011; Hartmann et al. 2015) as well as biochar (e.g., Krause et al. 2018; Joseph et al. 2021).
- **Yield:** A vast body of literature exists to underline the fertilization and soil improving effects of manure and compost resulting in higher crop yields as compared to unfertilized or mineral fertilized treatments (e.g. Diacono and Montemurro 2011). For biochar, increase in agricultural productivity can be particularly beneficial in degraded or low fertility soils (Lehmann et al. 2006; Woolf et al. 2010) causing increase in plant growth and leaf cell expansion, most likely due to fertilisation effect and to the up-regulation of relevant plant hormones (Viger et al. 2015).
- **Reduced use of nitrogen fertilizers:** The use of external inputs such as manure, compost and biochar reduce the need for synthetic fertilizers (Borchard et al. 2019; EEA 2021).
- The application of biochar to soil can stabilize soil organic matter due to accelerated formation of microaggregates by organo-mineral interactions as described for a field site in Australia (Weng et al. 2017). It also improves soil porosity and decrease bulk soil density (Blanco-Canqui et al. 2017). In addition to effects on soil physical properties, adding of biochar to soils offer benefits to soil chemistry, e.g., can lead to a balance in soil pH, salinity/sodicity, and cation exchange capacity of soils (Vijay et al. 2021).
- **Improved water holding capacity, reduced erosion:** Increasing soil organic matter inputs to soils may increase water-stable large aggregates and this can improve water holding capacity and protect against soil erosion (Wortmann and Shapiro 2007).

A.5.4 Trade offs

- **Contaminants and foreign matter**: With the systematic accreditation of commercial composting plants with the RAL Gütesiegel[21], heavy metal and other pollutants could be reduced to an environmentally acceptable minimum level over decades. The same applies for the European Biochar Certificate in the case of biochar application. However, there is the issue of foreign matter, predominantly plastic in municipal compost particularly biowaste compost, which is produced by separate collection of household and kitchen waste. Despite the existence of various legal frameworks, the plastic content of representative composts varies between 0.05 to 1.36 g per kg compost (Braun et al. 2021). Upscaling these loads to common recommendations in composting practice, which range from 7 to 35 t compost ha^{-1}, suggest that compost application to agricultural fields goes along with plastic loads between 0.34 to 47.53 kg plastic ha^{-1} $year^{-1}$ (Braun et al. 2021).
- **Soil biodiversity:** In principle one could assume that the use of compost or manure increases soil biodiversity in comparison to solely mineral fertilisation. However, the impact on soils will depend on the quantity and the quality of these inputs, as shown in the previous bullet point. In terms of biochar, its effects on soil biodiversity is also dependent the feedstock and the pyrolysis temperature (Budai et al. 2016, Vijay et al. 2021) as microbial biomass varies with different types and amount of biochar used (Jiang et al. 2016). This

[21] www.ral-guetezeichen.de.

missing knowledge gaps stress the need for further investigation on its potential benefits and trade-offs.

- **Soil compaction:** As composts and farmyard manure are usually low in plant nutrients, their application on croplands goes along with high wheel loads on soil. Among harmful soil compaction by vehicular traffic, manure and compost application have the highest impact (Thorsoe et al. 2019). Thus, strategies reducing the frequency of broadcast application techniques are needed. One approach might be the row application of compost along with potato planting as invented by University of Kassel.[22] The same holds true for broadcast biochar applications. For instance, combining deep soil loosening with biochar application beneath the main rooting zones of crops is supposed to i) reduce application amounts and wheel loads, ii) promote plant growth and carbon storage and iii) enhance albedo effects as opposed to broadcast application.[23]
- **Particular matter:** The application of biochar to soils can lead to an increased emission of particulate matter as firstly biochar tends to absorb fine particles and secondly, soil properties can induce abrasion of larger biochar particles. These activities can also potentially lower its mitigation potential and increase air pollution (Ravi et al. 2015).
- **Nutrient availability:** Manure or compost application may increase the risk of phosphorus runoff especially within the first few days after application, limiting phosphorus availability to plants although increased macro-aggregation may afterwards protect against subsequent phosphorus losses (Wortmann and Shapiro 2007). With biochar, reports on its effect on plant defense system are uncertain, with studies reporting both positive and negative outcomes (Meller et al. 2012; Viger et al. 2016).

A.5.5 Implementation challenges

Sustainable utilisation of off-farm manure, compost and biochar requires schemes on quality control and environmental compliance. Several regulations are in place already, but orientation along the EU organic regulation for these off-farm inputs would bring highest environmental standards and help to consider these practices as means towards natural based solutions. Moreover, to ensure that the positive climate impact is not reduced or negated by long distance transport and to address the challenges of having limited availability of biomass and competing demands on it, strategic planning and a landscape level framework is needed for how to handle organic waste and biomass flows and prioritize their use at a landscape level. Uncertainties associated with biochar's impact on climate and biodiversity require that precautionary principles are applied, and this option is promoted only once and if its positive impact within the EU context is backed with clear evidence.

In terms of replacement of peat in growing media, this option has a high potential. A ban on its use or a strong reduction would reduce pressure on peatlands and have a positive climate impact. The phasing out of its use could be achieved by gradually decreasing the share of peat that is allowed in potting mixes, for example some organic grower associations already limit peat use by setting a maximum value of 70% peat in potting mixes for organic agriculture and horticulture.

[22] https://univideo.uni-kassel.de/category/video/-KOMPOST-in-Kartoffeln-Technik-zur-Reihenapplikation/8aba5a42cd03654da02095b9e159d0e9/1.

[23] A. Gattinger, personnel communication, see also www.humuvation.de.

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A.6 Improved crop rotation

A.6.1 Measure definition

Crop rotation means cultivating different crops in a temporal sequence on the same land, compared to monocultures continuously growing the same crop (Summer 2001).

Rotating crops is one of the oldest agricultural strategies to control environmental stresses, nutrient and water balances, crop performances and systems' resilience. Nevertheless, in the past fifty years, specialisation of farm production, e.g. the decoupling of mixed crop-livestock farming, combined with an increased availability and usage of plant protection agents were drivers to more simplified cropping systems reducing the length of rotations and diversity of crops (Barbieri et al. 2017). As a result, short cereal-based rotations today dominate many European agricultural landscapes (Peltonen-Sainio and Jauhiainen 2019).

Improved crop rotations benefit from synergies between crops in the temporal sequence and/or in the same space, such as with undersown cover crops. The crops in the rotation should derive from different categories, i.e. primary (wheat, maize) and secondary cereals (e.g. spelt, barley, triticale, oat), grain legumes, and temporary fodders, including forage legumes. Globally, oilseeds, vegetables and root crops have the lowest share of cropland in rotations (Barbieri et al. 2012). Depleting crops such as maize that cause higher loss of mineral nutrients or destruction of organic matter due to intensive management, are combined with or followed by replenishing crops, e.g. cover crops or legumes. Especially the integration of grain and fodder legumes, as well as temporary grassland shows benefits for the subsequent crops (Garrett et al. 2017; Peltonen-Sainio and Jauhiainen 2019).

In organic farming, extended and complex crop rotations with a high diversification of crops, e.g. including more fodder crops and legumes, catch crops and undersown cover crops, are key strategies to support agroecosystem functioning that keeps soils fertile and plants healthy since synthetic pesticides are prohibited (Barbieri et al. 2017). Relying on synergies between crops and resulting ecosystem services in improved crop rotations is not limited to organic agriculture, but any form of agriculture can make use of these benefits.

Geographical and biophysical applicability

- **Suitability to different biophysical conditions:** Crop rotations are used worldwide to manage crop production. Diversified and improved crop rotations relying on the integration of crops from different categories, e.g. grass, higher share of forage or grain legumes, can be applied to any area suitable for cropland.
- **Suitability in EU/German conditions:** The temperate climate and the landscape structure of central Europe allow for improved crop rotations with higher diversity of crops coming from different crop categories, including higher share of legumes and temporary grassland. Further support for diversification of crops in space and time has to be supplied from policy regulations.

Fit with NbS definition

Provided that crop rotations are locally adapted and follow the principles of good agronomic practice as outlined above, they contribute to carbon sequestration objectives and fulfil all aspects of nature-based solutions as defined in the working definition for this research project by Reise et al. (2022). Crop rotations have to be locally appropriate and protect soils, and not rely on intensive fertilisation/agro-chemical inputs or unsustainable irrigation.

A.6.2 Mitigation Potential

Carbon sequestration

Cropping sequences play a considerable role in either soil carbon stock loss, maintenance or increase. Integrating legumes, e.g. alfalfa, and fallow periods can increase carbon stocks in the long-term compared to monocultures (Blair and Crocker 2000; Yang and Kay 2001). Crop rotations with legumes show a maintenance of the initial SOC compared to a reduction in rotations without legumes (Pikula and Rutkowska 2014) and the integration of grass ley in a cereal rotation leads net SOC increase (Prade et al. 2017).

A meta-analysis on long-term experiments found a sequestration rate of 0.2 t C/ha/year when enhancing the complexity of crop rotations (West and Post 2001). A simulation across European arable land showed that integrating ley (two consecutive years of alfalfa) in the crop rotation lead to constant C accumulation with median annual SOC sequestration rates of 0.11 t C/ha/year by 2050. A scenario with cover crops (grass mix or rye grass) in the crop rotation resulted in similar sequestration potential magnitude as the integration of ley but with much higher variability related to climate change (Lugato et al. 2014).

Total climate impact

Agricultural systems are in general net sources of GHG emissions, but improving crop rotations can decrease total GHG emissions. A reduction of 28% CO_2e was shown by the integration of catch crops and spring cereals in typical northern European cereal rotations due to a better use of fertilizer-N, while N-leaching was reduced at the same time (Olesen et al. 2004). Further studies have shown that the integration of legumes in simple crop rotations can reduce N_2O emissions compared to monocropping systems (Behnke et al. 2018; Li et al. 2017), even though the responses are climate related and may change under future climate conditions (Li et al. 2017). The impact on the total GHG emissions can vary across crop rotations, depending on the crops, the sequence of crops and other management factors, e.g., fertilization and tillage, making the evaluation of GHG emissions on crop rotation or yield difficult.

Limitations on the mitigation potential

The carbon sequestration potential of improved crop rotation depends strongly on implementing co-management factors such as reduced tillage (Shreshta et al. 2015) and how single crops in the rotation are managed, e.g., with high- or low-input of organic matter and crop residue management (Vinther et al. 2004). The positive impact of improved crop rotation (e.g. inclusion of green manure crops) and reduced tillage on soil carbon stocks was shown in a study of nine longterm field trials in Europe (Krauss et al. 2022). However, long-term sequestration gains due to a beneficial cropping sequence can be reversed quickly by tilling/ploughing the soils due to fast mineralization processes of organic compounds. Sequestration continues to occur only until soils reach saturation state.

A.6.3 Adaptation and co-benefits

- **Yields:** Crop rotation diversification improves yield of single crops compared with monocultural production, e.g., spring wheat (Jalli et al. 2021) and increases temporal yield stability (Gaudin et al. 2015; Macholdt et al. 2020).
- **Soil and biodiversity:** Rotations with enhanced complexity provide higher microbial abundance and diversity (Tiemann et al. 2015) supporting soil health and fertility.

- **Biodiversity:** A diversification in the crop rotation also improves agrobiodiversity on farm and landscape-level in space and time, increasing habitat niches for wildlife biodiversity.
- **Landscape water management:** Improving crop rotations can help to manage the eco-hydrological regime of landscapes by higher daily discharge, groundwater seepage and lower evapotranspiration compared to simplified cropping patterns (Sietz et al. 2021).
- **Nutrient management:** The usage of N-fertilizers can be reduced when integrating legume crops in the rotation. The nitrogen fixing potential of the previous legume crop increases the N supply to the soil by 36 to 49% (Cox et al. 2010).
- **Climate impacts:** The diversification of crop rotations improves sustainability and resilience to inter-annual weather variability by lowering the risk of crop failure and supporting temporal yield stability (Macholdt et al. 2020). Specifically, the integration of permanent grassland, forage or grain legumes improved the resilience of cropping systems to hot and dry conditions by conserving soil moisture and/or improving plant access to water resources (Gaudin et al. 2015).
- **Weed** and **pest control**: Crop rotations avoiding the sequence of similar crops reduce weed and pest breakthrough due to changes in crops (host to non-host) and crop management. On a landscape scale, the diversification and length of crop rotations and their occurrence at different stages in one year prevent seed dispersal between fields and control short- and long-term weed population densities (González-Díaz et al. 2012). They also enhance natural pest control in agricultural landscapes (Rusch et al. 2013).

A.6.4 Trade offs

- **Costs**: Enrichment of farms' agrobiodiversity may increase costs of management and production because of the need for machinery and labour (Firbank et al. 2013).
- **Nutrient management**: Reducing N fertiliser can be achieved with integration of legumes in the crop rotation and reducing the doses of N fertilisation in the subsequent crop. This comes along with reduced gross margins, thus a trade-off between environmental and economic goals (Nemecek et al. 2015).
- **Economic return**: Diversifying crop rotations by integrating perennial polycultures, e.g., legume-grass mixtures or wildflower mixtures, increases regulating ecosystem services such as soil fertility, climate regulation or pollination, but scores lower for biomass production compared with maize (Weißhuhn et al. 2017).

A.6.5 Implementation challenges

A diversification of crops can be challenging for farmers used to the production in monocropping systems or very simple crop rotations due to lack of knowledge and local experiences or suitable machinery. Moreover, there are several more systemic barriers that hinder crop diversification, i.e., 1) crop diversification requires market outlets for minor crops which may not be available due to a lack of consumer demand for these crops; 2) uptake of new crops can also lead to higher costs since standards in processing and distribution are often specified for products of dominant species; 3) there is a lack of incentives and conditionality through the Common Agricultural Policy, accompanied with little public R&D on minor crops.; 4) there are few active substances (pesticides) approved on minor crops (Meynard et al. 2018).

A.6.6 References

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A.7 Prevention of land take

A.7.1 Measure definition

Land take can be defined as the destruction or covering of soils by housing, services, recreation, industrial and commercial sites, constructions sites, transport networks and infrastructure as well as mines, quarries and waste dumpsites (Stolte et al. 2016). It involves the removal of top soil (scalping) and adding anthropogenic material such as tarmac or concrete and other substances, thus sealing the soil. The prevention of land take combines all measure to prevent the transformation of natural, semi-natural and agricultural areas into sealed soil (Colsaet et al 2018). This can be achieved through e.g., legally binding land take targets, strengthening of inner urban development, reuse of brownfields, protection of agricultural soils and valuable landscapes.

According to the European Environment Agency (EEA) (2019), the main drivers of land take in Europe during 2000-2018 were the increasing demand for land due to population and income growth, as well as the development of transport infrastructure and automobile use. In total in this period 14,049 km^2 land was lost to land take, with 78% of the land take affecting agricultural areas, i. e. arable lands and pastures, and mosaic farmlands (European Environment Agency 2019). Between 2012 and 2018 one-fifth of the functional urban area[24] that became sealed was of high productivity potential (around 2/3 of medium productivity potential) in EU-27 + UK (Tóth et al. 2022).

With land take, soil as a finite natural resource is lost and the process is often irreversible. The unsealing, redevelopment or renaturation of soils is associated with high costs and the same soil quality cannot be achieved. Moreover, recultivation is very limited as eleven times more land is taken than recultivated, with new land take often affecting the most fertile soil (Burghardt 2015).

Geographical and biophysical applicability

- **Suitability to different biophysical conditions:** Due to historical development, the most productive soils can be found in sub-urban areas or close to urban areas. Prevention of land take, maintaining and conserving the soil in these areas has the highest potential to mitigate negative effects.
- **Suitability in EU/German conditions:** In 2018, 2.3% of the European and 5.1% of German territory was sealed. Germany has the highest share of area sealed (EEA 2018). Given the current high rates of soil sealing, there is a high potential for the prevention of land take within the EU and its Member States.

Fit with NbS definition

Since preventing soil sealing enables soils to maintain their ability to perform soil functions and deliver ecosystem services, prevention of soil sealing is aligned with the definition of nature-based solutions as defined in the working definition for this research project in Reise et al. (2022) provided that the original land use and management which is maintained are aligned with this definition as well.

[24] A functional urban area (FUA) consists of a city and its commuting zone.

A.7.2 Mitigation Potential

Carbon sequestration

Land take and soil sealing can lead to a significant reduction of soil carbon stocks. At the same time, soils have a significant potential for additional sequestration if they are not sealed. Land take can result in a loss of soil organic carbon from 10% to 66% of total stock present in the soils that are affected (Lorenz & Lal 2017; Verzandvoort et al. 2010). Between 2012 and 2018 the increase of sealed surface caused a loss of carbon sequestration potential estimated at around 4 million tons (approximate distribution among ecosystem types: urban ecosystems: 50%, cropland: 34%, grassland: 12%, others: 4%) in EU-27 + UK (Tóth et al. 2022).

Total climate effect

Land take, on the one hand, can lead to GHG emissions due to the destruction of soil profile and the loss of existing SOC stocks and on the other hand, reduces the area available for future carbon sequestration.

Sealing of organic and mineral soil leads to an increase of GHG emissions, because soil sealing is usually preceded by a destruction of the soil profile and scalping. The disturbance of soil causes mineralization especially of peat soils and thus a release of GHGs to the atmosphere (Stolte et al. 2016). The projections on SOC losses due to soil sealing have been reduced for the period 2000-2030 compared to the 1990-2000 period by a factor three due to regulations, restrictions and more compact urban growth (Verzandvoort et al. 2010). The most recent emissions resulting from conversion to settlement as reported under the UNFCC were 43 Mt CO_2e for the EU in 2018, and 2.5 Mt CO_2e for Germany in 2019.

Limitations on the mitigation potential

The loss of carbon sequestration potential and the loss of soil organic carbon stocks is highly dependent on the soil type, previous land use (e.g., grassland, peatland, agricultural land) and the type of sealing (total surface sealing, partial sealing, subsurface sealing covered by a soil layer). There is little knowledge on the effects of soil sealing in urban environments.

A.7.3 Adaptation and co-benefits

- **Yields:** Unsealed soils can be productive land used as agricultural area, grassland or forest positively impacting food sovereignty and food security.
- **Food and biomass production**: Due to historical development, the most productive soils can be found in sub-urban areas or close to urban areas to ease the access to crop markets and agricultural production. Maintaining and conserving productive soil delivers access to agricultural products to urban and sub-urban areas (Stolte et al. 2016). Studies show that between 1990 and 2006, 19 EU countries lost 1% of their potential agricultural production capability due to land take (Gardi et al. 2014). For the period 2000 to 2030 a similar loss was projected.
- Micro climate: Unsealed and green surfaces have a lower temperature compared to sealed surfaces and have the potential to better regulate the micro climate without artificially alteration (prevention of “urban heat island effects”). Surface temperature surveys from the cities of Budapest (Hungary) and Zaragoza (Spain) showed that temperatures in highly sealed areas can be up to 20°C higher compared to green shaded surfaces (Prokop et al. 2011).

- **Storing, filtering, buffering**: Soil and its organisms have the potential to filter, degrade, immobilize and detoxify organic and inorganic pollutants. Some of these pollutants are degraded by microorganisms and transformed into less harmful forms or held in the soil preventing them from contamination of air and water (Stolte et al. 2016). Sealed soil is withdrawn from these filter functions.
- **Ecosystem soil:** Soil and soil systems permanently interact with other ecologic compartments such as the biosphere, atmosphere, hydrosphere, and pedosphere. Sealing the soil interrupts these exchange processes.
- **Biodiversity:** Unsealed land and less fragmented landscapes usually provide a higher soil biodiversity and functioning as habitat for animal and plant species. Soil sealing leads to local extinction processes, elimination of native species or their displacement while soil biodiversity is practically lost due to limited soil function and interaction. From 2000 to 2030 a decrease of biodiversity of up to 35% due to sealing is expected in all EU27 Member States (Verzandvoort et al. 2010).
- **Water services:** Compared to urban land, unsealed land has a better water retention and storage, decreases water run-off and mitigates flood risks. Between 2012 and 2018 the estimated loss of potential water storage due to soil sealing in EU-27 + UK is estimated at 670 million m^3 (Tóth et al. 2022). From 2000 to 2030 a reduced water retention of 0.8% is projected in the EU due to sealing (Verzandvoort et al. 2010).

A.7.4 Trade offs

Prevention of land take is a no-regret option.

A.7.5 Implementation challenges

The EU27 population is expected to increase to a peak of 449.3 million in 2026 (+0.6%) and then gradually decrease to 416.1 million in 2100 (EUROSTAT 2020). With this expected population increase in the upcoming years the prevention of land take faces fundamental challenges. At the same time, the increased demand for living space per person, increased mobility and growth of transport infrastructure will potentially lead to a continuous demand for land and will be a fundamental driving force for soil sealing even if the population in Europe is decreasing in the future.

There are some relevant policies at EU level, however, none of them offer binding targets, incentives and measures to prevent land take aggravating the ambitions on the prevention of land take. The European Commission's Roadmap to a Resource Efficient Europe (COM(2011)571)[25] introduces a 'no net land take by 2050' initiative that would imply that all new urbanisation will either occur on brownfields or that any new land take will need to be compensated by reclamation of artificial land. However, this initiative is not legally binding.

Some EU Member States introduced national policies, which partly address this issue. The German national sustainability strategy set the target of limiting the increase in settlement and transport area to 30 ha per day by 2020, which, however, was not achieved. The recent Coalition Agreement of the new German government stresses the need to achieve the 30 ha target by 2030.

[25] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52011DC0571

Therefore, one of the main challenges with regard to the prevention of land take is the absence or insufficient political willingness and the lack of legally binding targets. At the same time, there are EU funding schemes that support soil consumption, for example, the Trans European Transport Network (TEN-T), the EU Structural and Investment Funds and the European Investment Bank (Prokop 2011).

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A.8 Nitrification inhibitors: biological and synthetic

A.8.1 Measure definition

Nitrification inhibitors (NIs) are compounds that delay bacterial oxidation of NH_4^+ to NO_3^- (Nitrification) by depressing the enzymatic activities of nitrifiers (e.g. Nitrosomonas) in the soil (Subbarao et al. 2006). NIs were developed to prevent nitrate leaching by stopping bacteria in the soil from converting nitrogen from fertilisers or animal urine into nitrate. Inhibition of nitrification can improve the sustainable use of nitrogen by reducing nitrate leaching to groundwater (Qiao et al. 2015). Lower nitrate concentrations in soils also contribute to reduced nitrous oxide emissions.

Geographical and biophysical applicability

- **Suitability to different biophysical conditions:** They can be used in different cropping systems across various climatic regions (Subbarao et al. 2006). Because a wide geographical range of plant species possess nitrification inhibitory effect (Wang et al. 2021), BNIs can be locally applied in different geographical regions. SNIs are less effective in soils with heavy texture, high soil organic matter as this might cause sorption of the inhibiting compounds and affect its mobility (Subbarao et al. 2006). For example, in a plane loamy soil in Wisconsin, US, nitrap yearin completely inhibited nitrification in soils with 1% SOM and at higher pH whereas this was not effective in soils with 5% SOM (Hendrinkson and Keeney 1979). Also, in an arable soil in Germany, SNIs like DCD was found to perform better at reducing nitrate formation in sandy than in loam and clay soils (Barth et al. 2019). This is not surprising since their original application was to prevent nitrate leaching from sandy soils.
- **Suitability in EU/German conditions:** SNIs are widely used on conventional farms with livestock and/or biogas production, where ammonia-rich slurries prone to gases and dissolved nitrogen losses are regularly applied. They are also widely used by arable farms with light soils and urea-based fertilisation regimes. The further expansion of SNIs is limited because of the European and German goal to increase the share of organic agriculture to 30% and SNIs are per definition not compliant with the EU organic regulation.

Nitrification inhibitors can be either biological (BNI) or synthetic (SNI)[26] (Coskun et al. 2017).

Subbarao et al. (2006) listed 64 synthetic compounds which have been proposed as SNI. Most of these SNIs inhibit the first enzymatic step of nitrification (inhibition of the ammonia oxidase enzyme AMO) (Ruser and Schulz 2015). Commercially and widely utilized SNIs are nitrap yearin, dicyandiamide (DCD) and 3,4-dimethylp yearazole phosphate (DMPP) (Ruser and Schulz 2015; Subbarao et al. 2006). Nitrap yearin and dicyandiamide (DCD) belong to a large extent to the inhibition group of Cu chelators and the same mechanism of inhibition is also assumed for DMPP (Ruser and Schulz, 2015.), whereby a strict classification of SNIs in only one group of inhibitors is not possible. However, some SNIs also carry risks for soil health and biodiversity as they can be ecotoxic for terrestrial and aquatic organisms: in a study of two commercial NIs (Piadin and Vizura) and an active ingredient of another NI (dicyandiamide (DCD)), Piadin and Vizura showed ecotoxic effects in all experiments conducted (Kössler et al. 2019). Concerns have also been raised about risk to human health since the active ingredient, dicyandiamide (DCD), was found as a residue in milk (Ray et al. 2020). This underlines the importance of applying the precautionary principle and a comprehensive risk assessment.

[26] There are also urea inhibitors (UI). SNI and UI are often grouped together as "inhibitors", however they are chemically different and have different modes of action. This factsheet focuses on SNI and BNI.

Biological nitrification inhibitors (BNIs) are an alternative to SNIs. Some plant species have the natural ability to release compounds (from either their root, rhizosphere, tissue, litter or tissue extract) that suppresses the activity of nitrifiers (Subbarao et al. 2013a; Wang et al. 2021; Zhang et al. 2021). Examples of BNIs extracted from root tissues are linoleic acid and linolenic acid (Ma et al. 2021). Common temperate crops with BNI function are the pasture grass and some landraces of wheat (O'Sullivan et al. 2016). E.g., BNI levels in the rhizosphere of wheat landraces ranged from 25-45% reduction in nitrification (O'Sullivan et al. 2016). Some BNIs secreting crops such as sorghum and Brachiaria grasses can be used as cover crops (Subbarao et al. 2013b).

The research on BNI is still in its infancy and more crop species or varieties may exudate compounds with BNI function that can be integrated in crop rotations. The extraction and technical production of BNI might then become feasible (Wang et al. 2021). Research and breeding for BNI expression of the relevant plant gens in the rhizosphere of important crops may also provide new management options for improving nitrogen efficiency in cropping systems (Zhang et al. 2021).

Information on prevalence of use of SNIs and BNIs is not available.

Fit with NbS definition

Various plant species release molecules with different chemical properties as root exudates that regulate soil nitrification by blocking the enzymatic pathways of nitrifying bacteria, e.g., Nitrosomonas (Subbaroa et al. 2013). This suggests the alignment of BNIs with nature.

Exudates released from plant roots, i.e. BNIs, can be seen as an adaptive mechanism for the efficient conservation and use of nitrogen in natural ecosystems including agricultural systems where nitrogen is limiting (Subbarao et al. 2006; Qiao et al. 2015; Ma et al. 2021).

However, SNIs are synthetic chemicals applied as external inputs and potentially with negative side-effects, therefore their alignment with natural ecosystems is not given.

A.8.2 Mitigation Potential

Carbon sequestration

There is currently no available research on the effects of NIs on soil carbon sequestration rates and SOC stocks even within the EU.

Total climate impact

Total GHG balance: Multiple studies have reported reduction in N_2O emissions rates by 18 to up to 92% using different BNIs (Wang et al. 2021, Ruser and Schulz 2015). 67 - 76% reduction in N_2O emissions with the use of SNI has been reported for arable soils in LA, US (Meng et al. 2021).

In a European grassland site in Wales, UK with very high nitrification rates, Ma et al. (2021) reported up to 93.5% reduction in NO3- concentration with 1g linoleic acid per kg of soil which is a BNI found in Brachiaria spp (Subbarao et al. 2008). Studies on BNI on GHG emissions within European regions are currently still limiting.

In a global meta-analysis using 62 studies, SNIs were found to decrease direct N2O emissions by 39 - 48% and NO3- leaching by 38 - 56%, leading to a net reduction of 16.5% of total nitrogen loss to the environment (Qiao et al. 2015).

However, some nitrification inhibitors carry the risk of higher ammonia (NH3) emissions in some pedo-climatic conditions (Wang et al.2020; Qiao et al. 2015).

Limitations on the mitigation potential

The efficacy, synthesis and release of BNIs from plants as well as SNIs are highly variable and vary depending on the type of NIs released, the presence of NH4+, the abundance of the soil nitrifier population in the rhizosphere and the soil chemical and physical properties such as soil texture, organic matter content, pH, moisture and temperature, oxygen concentration (Coskun et al. 2017; Gopalakrishnan et al. 2009; Subbarao et al. 2013a; Subbarao et al. 2006).

For effectiveness, NI compounds must retain their persistence and bioactivity in the soil, thus the effectiveness of NIs in soils often dependent on the length of time it can be persistent in soils (Subbarao et al. 2006). Loss of NIs by volatilisation, leaching and microbial turnover decreases its effectiveness in soils (Hendrinkson and Keeney 1979; Ruser and Schulz 2015).

Common SNIs like Nitrap yearin can be specific and effective on some bacterial groups (e.g., *Nitrosomonas*) over others (e.g., *Nitrobacter*) (Subbarao et al. 2006). Thus, the composition of the nitrifier community should be considered before adoption.

Despite laboratory-based evidence for inhibitory activity on some microbial nitrifiers, not all BNIs released from plant roots will be effective in suppressing soil nitrification activity in the field (Lu et al. 2019). Some BNIs have been found to lose their activity in soils after 80 days (Subbarao et al. 2008). Due to these uncertainty, further field testing is required (Wang et al. 2021). Such information reported for soils within European region is also missing in current literature.

A.8.3 Adaptation and co-benefits

- Yields and efficiency: There is some evidence that the use of SNIs in combination with split fertilizer application or No-till cultivation can lead to an increase of crop yields up to 7% (Del Grosso 2009), while increasing the nitrogen use efficiency (NUE) indicated by higher N uptake (Abolos et al. 2014).
- **Soil quality**: Soil acidification is one of the most common consequences of soil degradation caused by N overuse (Qiao et al. 2015). Reducing N overuse could therefore contribute to alleviating soil acidification. The long-term impact of SNIs on the soil microbiome is uncertain. Agrochemicals such as NIs may bear the risk of developing tolerant populations or negative effects on non-target organisms. Hence further research is needed ideally by focussing on soils with long-term history of NI application (Ruser and Schulz 2015).
- **Air pollution:** SNIs application significantly decrease NO emissions up to 38% (Qiao 2015).
- **Water quality:** The use of SNIs and BNIs reduce the nitrification process and the risk of leaching of NO3- and therefore have the potential to improve the quality of waterbodies close to agriculture areas. The use of N fertilizer can lead to nitrification and leaching of NO3- NO3- moves through the soil and potentially ending up in water bodies leading to euthrophication and health risk for aquatic organisms (Subbaro et al. 2006).
- **Human health**: The use of SNIs and BNIs reduce the nitrification process, thus leading to reduced nitrate leaching and reducing the risk of high nitrate concentrations in groundwater and therefore also the risk of nitrate consumption. Nitrate consumption can lead to human health risk through drinking contaminated water or consumption of high nitrate containing vegetables ultimately leading to various kinds of human cancer, neural tube defects, diabetes and blue baby syndrome (Ahmed et al. 2017).

- **Economic benefits**: There is evidence, that the economic benefit of reducing N's environmental impacts offsets the cost of SNI application with a potential increase of revenues for the farmers of up to 9%, using a US maize farm as a case study (Qiao et al. 2015).
- **Energy saving**: The use of SNIs can ultimately result into saving energy inputs into agricultural systems due to decreased amount of N fertilizer use. The process of producing synthetic N fertilizer requires a considerable amount of energy plus the energy spent for transport, application and incorporation (Subbaro et al. 2006).

A.8.4 Trade offs

- **Soil*:*** SNI reduce activity and abundance of target nitrifying bacteria (Nitrosomonas genera), but also shift abundance of non-target bacteria. The negative effects of fertilization on soil functionality are partially alleviated but the complexity of bacterial interaction networks can be reduced (Corrochano-Monsalve et al. 2021).
- **Disease** resistance **in crops*:*** SNIs can influence disease development and host resistance e.g., corn, soybean and potato (Subbaro et al. 2006).
- **Water bodies**: There is research that indicate ecotoxic effects of SNIs on terrestrial and aquatic organism (Kösler et al. 2019).
- **Air pollution:** There is a risk of higher ammonia (NH_3) emissions with the use of some SNIs in some pedo-climatic conditions (Wang et al. 2020; Qiao et al. 2015)

A.8.5 Implementation challenges

There are several implementation challenges acting as a barrier for the uptake of SNIs and BNIs as practices by farmers, including uncertain effects of SNI and BNI usage under field condition since these effects also depend strongly on weather conditions after application, application knowledge by farmers, additional cost and regulation/restrictions. SNIs are not allowed in organic agriculture. Beyond this, once the produce is approved, no further regulation of their use is set. Often, SNIs are already included in synthetic urea fertilisers.

Given the unclear long-term impacts of synthetic NIs on soil biodiversity, precautionary principles should be applied. Until further clarity is available on long-term effects, the use of SNIs should be restricted.

The use of BNIs is still in its infancy, with limited knowledge on their NI specificity, pathways, locations, mechanisms of release and interactions with other BNIs and with other biotic and abiotic components of the soil matrix and the environment (Coskun et al. 2017).

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A.9 Precision farming (site-specific management)

A.9.1 Measure definition

Precision farming or precision agriculture is an approach that applies appropriate management practice at the place and time where and when it is needed, adjusted to spatial and temporal variability of crop and environmental traits over farm areas and small-scale heterogeneity of soil conditions (Finger et al. 2019). It is a technology intensive practice assisted by GIS technologies, considering site-specific sensor information of nutrient status, soil moisture, and other soil properties (Roy and George 2020). Management practices include controlled traffic farming during tillage and harvest, adjusted site-specific application of inputs such as nitrogen and pesticides (Balafoutis et al. 2017), and precise seeding and irrigation. Precision farming is often combined with zero tillage systems on large farms (Finger et al. 2019).

Geographical and biophysical applicability

- **Suitability to different biophysical conditions:** Precision farming is independent from biophysical constraints; it can be applied on any field where machinery is typically used. Steep slopes or very small patches may not be suitable.
- **Suitability in EU/German conditions:** Site-specific management relies on processing sensor data by GIS technology on heterogeneity over fields and farms. Beside the willingness of farmers to deal with new information technology, these processes require power supply and access to internet or satellite connection (GPS). In Germany and other European countries, companies offer services for field data collection by scanning the field and data interpretation, thus making precision farming more accessible for farmers. Main adopters until now are mainly large-scale conventional farms, but site-specific fertilizer management and irrigation or precise seeding and harvesting can be suitable for organic agriculture or application on smaller field sizes.

Fit with NbS definition

Precision farming does not rely on natural processes or mechanisms, and is therefore not a nature-based solution as defined in the working definition for this research project in Reise et al. (2022), but rather technological-based to reduce external input and impact on field-scale.

However, precision farming can lead to improved environmental impact of agriculture by enabling small-scale adjustment in application of fertilizer or pesticides and thus reducing the impact on the environment, including nitrate leaching, gaseous emissions (N2O), and fluxes of pesticide residues to water bodies (Balafoutis et al. 2017). The reduction of nutrient and pesticide excess along the sites of the croplands and buffer strips may promote wild plants that are adapted to lower nutrient availability and targeted pesticide application can reduce negative impact on beneficial insects.

Despite its potential to be applied in a more environmental suitable way (Roy and George 2020) precision farming is up to now typically part of large farms with highly intensive management systems that rely on high levels of inputs of fertilisers and pesticides, e.g., zero tillage systems.

A.9.2 Mitigation Potential

Carbon sequestration

A site-specific N-fertilizer application across a field, i.e., the reduction of overfertilization and supplying enough fertiliser where needed, taking into account soil heterogeneity and N availability, could be a way to increase the carbon stock in the soil by reducing soil respiration (Khan et al. 2007) while maintaining crop root production and C input to the soil.

Total climate impact

Controlled machine guidance and traffic farming can lead to an optimization of fossil fuel consumption due to limited overlap in farm operations, resulting in a reduction of up to 6% of fuel use (Shockley et al. 2011).

The site-specific adjusted management is more efficient in the use of fertilizers, seeds, and pesticides; e.g. the use of herbicides can be reduced by site specific spraying ranging from 11% reduction in herbicides for broadleaf weeds in maize to 90% savings of herbicides for grass weeds in winter cereals (Balafoutis et al. 2017). This also reduces the indirect energy consumption footprint from such inputs (Finger et al. 2019).

The precise nitrogen fertilization reduces nitrogen losses such as ammonia and N2O-emission by up to 34% (Sehy et al. 2003).

Limitation on the mitigation potential

Like in all technologies, when responsibility is transferred from persons to algorithms, precision farming depends greatly on the way of usage and the modelling / programming behind the application. Small changes in the modelling can increase the use of fertilizers above the needs, thus drastically limiting its potential of mitigation and reducing GHG.

A.9.3 Adaptation and co-benefits

- **Weed control:** Camera based automatic mechanical weed control can reduce herbicide use (Zimmermann et al. 2021).
- **Costs**: Reduced traffic by precise machine guidance can result in a 25% reduction of expenditures for fossil fuels (Jensen et al. 2012).
- **Environment and biodiversity**: Site-specific pest control reduces pesticide residues in the environment, e.g., contamination of water bodies or fallows and natural habitats of insects (Balafoutis et al. 2017).
- **Yield:** Site-specific fertilization rate and precision harvesting increases the potential to meet quality standards in wheat (Morari et al. 2018). The yield shows greater uniformity over the field area (Diacono et al. 2014).
- **N** management**:** Site-specific N fertilization according to field heterogeneity can reduce nitrate leaching (Delling and Stenberg 2014).

A.9.4 Trade offs

- **Herbicide use**: Precision farming is as of now often used in combination with no tillage practices (Jensen et al.2012), that require a higher usage of herbicides to control weeds.

Thereby it is perceived as a technique designed to enable intensive land use and promote herbicide use.

- **Costs and availability of technology**: This technique requires information of environmental sensors or field data collection. Diagnostic tools or access to remote sensing data might be not available for everyone or cost intensive.
- **Data management and security**: Data management can be complicated and a security issue for farmers. Big data sets can increase the vulnerability of users and their dependencies from companies.

A.9.5 Implementation challenges

Precision farming requires tools, technical understanding and big data sets on the field sites that might be difficult and costly to obtain and maintain. The interpretation of the data and implementation of site-specific management can be challenging for farmers. It is mostly applicable to mechanized and large-scale agriculture (Finger et al. 2019). There is concern that precision agriculture simply supports further intensification of yields, without absolute reductions in the intensity of management and without reducing negative environmental impacts. The approach has been criticized for increasing the dependency of farmers on input suppliers and data industry, without necessarily delivering sufficiently on environmental and social objectives (Duncan et al. 2021).

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A.10 Low input grasslands / set-aside areas

A.10.1 Measure definition

There is no official definition of “low input grasslands” with several different definitions among the literature sometimes referred to as high-nature value grassland, natural grassland, semi-natural grassland, unimproved grassland or extensive grassland.

Low input grassland can be described as an optimized management and use of internal production inputs (e.g. manure management, late mowing, limited livestock density) with minimized or no use of external production inputs such as mineral fertilizer and pesticides and low yielding. A distinction can be made between pasture grazing and meadow use or the combination of both.

Set-aside areas are usually described as arable land taken out of production and out of the crop rotation for a certain time. This can be for one year or longer. In set-aside areas, pesticides and heavy machinery are prohibited and fertilizer application is limited (Rural payments agency 2021).

Grasslands in Europe have a long management history and are part of the cultural landscape. The majority of European grasslands are semi-natural and have a basic role in feeding herbivores and ruminants and provide important ecosystem services, including erosion control, water management and water purification. Grasslands provide important fire-breaks in Mediterranean forest landscapes. Grasslands also support biodiversity and cultural services. Grasslands are an important stock of carbon while the cultivation of grasslands, and other modifications of grasslands through desertification and intensive livestock grazing can be a significant source of carbon emissions. Low input grasslands and set-aside areas can increase the benefits described above especially regarding biodiversity. Both systems are characterized as biodiversity rich habitats in the agricultural area. They are habitats for numerous plant and animal species, rare species of flowers and grasses, for grasshoppers and butterflies, for birds (meadow breeders) and mammals.

Geographical and biophysical applicability

- **Suitability to different biophysical conditions:** Due to the diversity of potential, low input grasslands are suitable for several terrains and climatic regions by adapting species and landscape design. In general, any arable land or permanent grassland can be converted to a low input grassland system or set-aside area. Extensive grazing close to water bodies could lead to nutrient pollution of such and needs to be considered.
- **Suitability in EU/German conditions:** Permanent grassland accounts for almost one third (31.2%) of the utilised agricultural area in Europe and is mainly used to provide fodder and forage for animals (Eurostat 2021). The CAP 2023 will include permanent grassland as part of the conditionality (GAEC 1) as well as a minimum share of agricultural area devoted to non-productive areas or features (GAEC 8).

Fit with NbS definition

Provided that the management of low-input grasslands is adapted to local conditions they fulfil all aspects of nature-based solutions as defined in the working definition for this research project by Reise et al. (2022).

A.10.2 Mitigation Potential

Soil organic carbon (SOC) sequestration

In general, carbon sequestration increases when grassland management is intensified including an increase of nutrient inputs especially nitrogen (Kätterer et al. 2012). Therefore, low input grasslands and set-aside areas usually have a lower carbon sequestration potential. However, the climate mitigation effect of intensified grassland management may be offset by increased emissions of greenhouse gases other than CO_2. Bellarby et al. (2013) even argue that beef and dairy production on natural grasslands and rough grazing land, as opposed to intensive grain-fed production from croplands, may reduce GHG emissions. Roe et al. (2021) estimate that improved grassland management[27] in the EU could feasibly sequester 27 Mt CO_2e per year[28].

Total climate impact

Permanent grasslands store large quantities of carbon in the soil. However, it involves the potential risk of reversal because carbon is rapidly decomposed and released as CO_2 if grasslands are transformed into cropland or managed intensely by ploughing and re-sowing. Intensification of grassland management especially through N fertilization can lead to N_2O emissions that exceed the carbon sequestration potential (Henderson et al. 2015). Apart from direct management interventions, also human-induced climate change is likely to be a threat to soil organic carbon (SOC). Increasing temperatures are acknowledged to catalyse microbial activity and thus SOC mineralisation, inducing a climate-carbon cycle feedback loop (Davidson & Janssens 2006). Grasslands can also be sources of GHG especially due to nutrient application (N_2O).

Integrated assessments that look at the total climate impact on both sequestration and emissions of low input grassland and set aside areas are currently not available. There is need to assess low input grasslands across different locations within the EU to enable a better assessment of how different practices in different biophysical conditions affect the climate, yield, and biodiversity impacts.

Limitations on the mitigation potential

The mitigation potential of stored carbon and sequestered carbon in grasslands is limited and uncertain due to the heterogeneity of soils, climatic conditions, existing SOC levels, their potential saturation and management practices.

A.10.3 Adaptation and co-benefits

- **Biodiversity**: Low input grassland and set aside areas offer a unique biodiversity value, because of moderate human disturbance (Herzon et al. 2021). This includes plant species diversity providing habitats for breeding and migratory birds (Báldi et al. 2013), invertebrates, fungi and other organisms. Usually, the plant species diversity is rather small-scale with a high share of indigenous and endemic species including red-listed species (Wilsen et al. 2012; Eriksson 2014).
- **Soil**: Grasslands in Europe (including intensive farming grassland) are estimated to store 5.5 Gt of carbon in the top 30 cm of soils (Lugato et al. 2014). High livestock grazing intensity

[27] Enhanced soil organic carbon sequestration in managed pastures, by shifting from current practices to improved sustainable management with light to moderate grazing pressure and at least one improvement. For rangelands, a shift from current management defined by land degradation to nominally managed.

[28] The technical mitigation potential of improved grassland management in the EU is estimated to 45 Mt CO_2 per year.

significantly increases the SOC storage and soil quality (bulk density, pH), however climatic conditions and grassland types need to be considered (Lugato et al. 2014, Abdalla et al. 2018). Study results indicate that semi-natural grasslands can lead to an increased nutrient cycling and nutrient retention (Pecina et al. 2019). Soil microbial biomass increases in set-aside areas of formerly agricultural land. This comes along with a change in the microbiological community structure and a greater microbial C:N ratio that results in reduced C and N turnover rates (Landgraf et al 2001). Set-aside areas after intensive cultivation restore soil metabolic activity and soil fertility (Masciandaro et al. 1998).

- **Pollination**: One of the main benefits of grassland positively affecting agricultural protection are pollination and biological control. Especially insect-pollinating crops have potentially higher pollination close to grassland areas (Werling et al. 2014). However, there is only limited research on grassland and crop pollination interaction.

- **Prevention of** erosion: Permanent soil cover generally protects against soil erosion by reducing water run-off, and stabilizing the soil. Grasslands in general can contribute to soil erosion prevention (<10% compared to soil erosion on cropland) if managed appropriately and without overgrazing (Cerdan et al. 2010). In general, erosion reduces with vegetation cover, therefore forests have an even lower risk of erosion compared to grassland.

- **Water** services**:** Natural and semi-natural grasslands can improve the water quality and regulate the water flow (Bengtsson et al. 2019). However, compared to forest the water supply is rather small due to small-scale plot sizes.

- **Cultural** services: Natural and semi-natural grasslands are an important landscape feature throughout Europe offering several cultural ecosystem services. These include tourism, recreation, hunting, cultural heritage (e.g., burial mounds) and scientific studies (Bengtsson et al. 2019).

A.10.4 Trade offs

- **Management:** The effect of carbon sequestration is reversed, when the set-aside area is reused for intensive cultivation.

- **Yields**: Low-input grasslands and set-aside areas are generally low-yield systems due to reduced inputs. This includes fodder quantity and quality. Especially digestibility is an important factor for meat and dairy production and is lower compared to high input grasslands. However, a direct linkage between fodder and livestock quality needs to be assessed carefully, including definitions of meat and dairy quality criteria (e.g. taste, texture, aroma) (Bengtsson et al. 2019).

A.10.5 Implementation challenges

Grasslands in Europe have played an important role throughout history especially for fodder production for livestock (Emanuelsson 2009). During the last century natural and semi-natural grasslands have declined and have been fragmented due to conversion to arable land, intensive grassland, settlement area and infrastructure. In the United Kingdom around 90% of the semi-natural grasslands have been lost since 1945. Therefore, implementation challenges are mainly around halting the trend of declining grasslands rather than reversing this trend.

Especially the trade-offs on yield and production hinder farmers' continued low-input management. There are missing incentives for farmers to compensate yield loses on low input grasslands and set-aside areas.

Research on ecosystem services, biodiversity, fodder, meat and dairy production, as well as monitoring on low input grasslands as a basis to support policymaking is also missing.

A.10.6 References

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