Large-scale deployment of in-rotation grass cultivation as a multifunctional soil climate mitigation strategy

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Abstract

The agricultural sector can contribute to climate change mitigation by reducing its own greenhouse gas (GHG) emissions and sequestering atmospheric carbon in vegetation and soils, and by providing biomass for substituting fossil fuels and other GHG intensive products in the energy, industry and transport sectors. New policies at EU level provide incentives for more sustainable land use practices, for example, cultivation systems using perennial plants that provide biomass for food, bioenergy and other biobased products along with land carbon sequestration and other environmental benefits. Based on spatial modelling across more than 81,000 landscapes in Europe, we find that introduction of grass-clover leys into rotations with annual crops could result in soil organic carbon sequestration corresponding to 5-10% of total current GHG emissions from agriculture in EU27+UK, annually until 2050. The combined annual GHG savings from soil carbon sequestration and use of biogas produced in connection to grass-based biorefineries equals 13-48% of current GHG emissions from agriculture. The assessed environmental co-benefits (reduced wind and water erosion, reduced nitrogen emissions to water, and mitigation of impacts associated with flooding) are considerable. Besides policy instruments, new markets for grass biomass, e.g., as feedstock for producing biofuels and protein concentrate, can incentivize widespread deployment of in-rotation grass cultivation.

Introduction

The recently published IPCC WG1 AR6 report[1] concluded that global warming of 1.5°C and 2°C will be exceeded during the 21st century unless substantial reductions in greenhouse gas (GHG) emissions occur in the coming decades. The majority of climate scenarios limiting warming below 1.5°C and 2°C (with no or limited overshoot) deploy carbon dioxide removal (CDR) from the atmosphere[2,3]. The agricultural sector can contribute to climate change mitigation through greenhouse gas (GHG) emissions reductions and CDR via carbon sequestration in vegetation and soils, and by providing biomass for mitigation in the energy, industry and transport sectors through substitution of fossil fuels and other GHG-intensive products[4]. At the same time, the agriculture sector needs to address water, soil, and biodiversity impacts caused by historic and current practices[5,6] and adapt to climate change, which is expected to cause new stresses on agricultural systems and exacerbate risks to livelihoods, human and ecosystem health, and food systems[4].

The European Union (EU) Common Agricultural Policy (CAP) for the period 2021-2027 includes regulations and incentives to promote climate change mitigation, environmental protection, and preservation of biodiversity[7]. Other EU policies that are likely to influence agricultural practices include the Renewable Energy Directive[8], the European Green Deal[9], the Biodiversity Strategy for 2030[10], and the Farm to Fork Strategy[11]. Changes in agricultural practices towards increased cultivation of perennial plants in intensively cultivated agricultural landscapes, can contribute to many of the objectives underlying these policies by providing biomass for food, bioenergy and other biobased products while reducing environmental impacts from agriculture[12–17]. The strategic design, localization and management of cultivation systems using grasses and leguminous plants (from here on referred to as "grass") is one example of such beneficial land use change. For example, biomass production in species-rich mixtures of perennial grasses on marginal land have shown potential for enhancing biodiversity and carbon sequestration into soils[18], and increased grass cultivation in cereal-dominated crop rotations can increase the soil organic carbon (SOC) content and enhance crop yields in the longer term[19].

Thus, as grass is introduced in crop rotations, the decrease in area under annual crops used for food and feed, can be counterbalanced by improved soil fertility and higher crop yields. The food/feed crop displacement effect is further reduced when grass biomass is used in biorefineries producing food and feed, along with bioenergy and other biobased products[20,21]. For example, lactic acid bacteria can facilitate the use of grass biomass to produce a protein concentrate suitable for feeding monogastric animals as well as ruminants, and also other products for material or energy use[22]. Such solutions, using alternatives to high-input and high-emission annual grain and seed crops as feedstock, can enable sustainable intensification of the agricultural systems with reduced environmental impacts[23]. To illustrate, grass production on one hectare of cropland in EU (assuming 10 tonne dry matter (DM) annual yield) can support protein concentrate production in a biorefinery equivalent to soy meal from 0.8 hectare of soybean cultivation in EU (2.8 t y^{-1}) or 0.6-0.8 ha of soybean cultivation in Brazil (2.8-3.5 t y^{-1}). This reduces the cropland displacement effect with 60-80%. Higher crop yields from improved soil fertility would reduce the cropland displacement effect even further. When factoring in also other biorefinery outputs, such as biogas and biobased products, the deployment of in-rotation grass cultivation may in some regions even result in net cropland savings.

Here, we estimate the effects of widespread deployment of in-rotation grass cultivation, aimed to remediate SOC losses from historic land-use while providing biomass and additional environmental benefits. We model the introduction of perennial grasses into annual crop rotations in more than 81 000 sub-watersheds across Europe (EU27+UK). We then quantify expected increases in SOC and grass biomass production, in terms of dry matter (DM), extractable protein, energy content, and biogas output, and the corresponding GHG emissions savings. Finally, we quantify and indicate multiple environmental co-benefits.

The results show that widespread deployment of in-rotation grass production would result in significant carbon sequestration in agricultural soils. The annual carbon sequestration until 2050 in two illustrative deployment scenarios corresponds to some 5-10% of current GHG emissions from agriculture in EU27+UK. The combined annual GHG savings from soil carbon sequestration and biogas use amounts to 20-50% of current GHG emissions from agriculture. In addition, environmental co-benefits can be substantial, including avoided soil loss by wind and water erosion, reduced nitrogen emissions to water, and mitigation of flooding events.

Some European farmers may consider soil quality improvements sufficient motivation for in-rotation grass cultivation. Grass cultivation may also be an attractive option where intensive annual crop cultivation becomes restricted to protect the environment. In other places, incentives such as payments for soil carbon sequestration and other environmental benefits may be needed[16]. Investors need to be confident in the long-term economic viability of grass-based biorefineries[24], which is likely to be influenced by the outcome of the current process following the European Commission's proposal[25] to revise the Renewable Energy Directive (RED). For example, treatment of biogas from biorefineries in the revised RED will depend on whether biogas is considered a main product or co-product of the biorefinery process.

Table 1: Summary of results when modelling large-scale introduction of grass production into crop rotations, aggregated to European (EU27+UK) scale. BAU = Business as usual - continued land-use. Numbers are rounded. See Supplementary Table 2-12 for country-level aggregates.

		2y system	**3y system**	**4y system**	**Low deployment scenario**	**High deployment scenario**
Area on which grass is included in annual crop rotations (Mha)		91				
Average area under grass production (Mha)		30	39	46	15	38
Biomass output (Mt DM y^{-1}| PJ y^{-1})		209 | 3908	298 | 5573	365 | 6826	102 | 1907	286 | 5348
Biogas production (PJ y^{-1})		1932	2760	3404	938	2631
Extractable crude protein (Mt) | true protein (Mt)		43 | 27	62 | 38	76 | 47	21 | 13	59 | 37
Average SOC increase on total cropland area (tC ha^{-1} relative BAU | 2020)	2050	3.2 | 3.5	4.1 | 4.4	4.8 | 5.1	1.5 | 1.9	4.1 | 4.3
	2080	4.4 | 4.9	5.7 | 6.2	6.6 | 7.2	2.1 | 2.6	5.5 | 6.0
Total SOC increase (Mt relative BAU | 2020)	2050	294 | 335	378 | 419	442 | 483	141 | 181	363 | 404
	2080	402 | 476	517 | 591	603 | 677	193 | 266	497 | 570
Annual GHG emission savings from SOC sequestration until 2050 (% relative total current GHG emissions from agriculture compared with BAU | 2020)		8.3 | 9.5	10.7 | 11.9	12.5 | 13.6	4.0 | 5.1	10.3 | 11.4
Annual GHG savings when biogas substitutes petrol and diesel in cars (Mt C yr^{-1} | % relative total current GHG emissions from agriculture)		32 | 27	46 | 39	56 | 47	16 |14	44 | 37
Annual GHG savings when biogas substitutes natural gas for electricity (Mt C yr^{-1} | % relative total current GHG emissions from agriculture)		20 | 17	29 | 25	35 | 30	10 | 8	27 | 23
Avoided soil loss by water erosion (Mt y^{-1})		76	97	114	37	95
Avoided soil loss by wind erosion (Mt y^{-1})		18	23	27	9	22
Avoided N emissions to water (kt y^{-1})		271	348	406	119	324

Results

Perennial grass was introduced into crop-rotations on 115 million hectares (Mha) of arable land, in 24 363 landscapes (see Methods), including about 80% of all arable land in Europe currently used for annual crop cultivation. Most of these landscapes (76%) are classified as subject to “high” accumulated SOC losses, while 17% and 7% are classified as subject to “medium” and “very high” accumulated SOC losses, respectively. Adding two years of grass cultivation to a four-year crop rotation (2y system) in all these landscapes results in 30 Mha of land being used for cultivation of grass instead of annual crops, on average over time. Adding one or two additional years of grass cultivation in the crop rotation (3y system and 4y system) increases the grass area to 39 Mha and 46 Mha, respectively. The corresponding grass production on these areas is about 210, 300, and 370 Mt DM y^{-1}, for the 2y, 3y, and 4y systems, respectively. The estimated energy content in this biomass is about 4-7 EJ and the corresponding biogas output is about 2-3.4 EJ. Extractable crude- and true protein amounts to about 40-80 Mt and 30-50 Mt, respectively. The SOC increase corresponds to 290, 380, and 440 Mt C by 2050, and about 300, 510, and 600 Mt C by 2080, respectively. The SOC simulations showed no further SOC increases at European scale between 2080 and 2100. (Table 1)

In a “low estimate” deployment scenario – in which the 2y system is implemented on all agricultural land where the accumulated SOC loss is classified as "very high", on 50% of the lands where it is classified as "high", and on 25% of the lands where it is classified as "medium" - the total area under grass production amounts to 15 Mha, corresponding to 16% of the area under annual crops in the affected landscapes and 13% of the total area under annual crops in Europe. The corresponding grass biomass production is 100 Mt DM y^{-1}, equivalent to about 1.9 EJ. Biogas output is about 1 EJ. Extractable crude- and true protein amounts to about 20 Mt and 10 Mt, respectively. The SOC increase amounts to about 140Mt C by 2050, and 190 Mt by 2080. (Table 1)

In a “high estimate” deployment scenario – in which the 2y system is implemented on all land currently under annual crop production where the accumulated SOC loss is classified as "medium", the 3y system is implemented where it is classified as "high", and the 4y system is implemented where it is classified as "very high"- the total area under grass production amounts to 38 Mha, corresponding to 41% of the area under annual crops in the affected landscapes and 35% of the total area under annual crops in Europe. The corresponding grass biomass production is 290 Mt DM y^{-1} corresponding to about 5.3 EJ. Biogas output is about 2.6 EJ. Extractable crude- and true protein amounts to about 60 Mt and 40 Mt, respectively. The SOC increase amounts to about 360Mt C by 2050, and 500 Mt by 2080. (Table 1)

In the two deployment scenarios, 70% of the new in-rotation grass production is established in Poland, Spain, France, Romania, Germany, and Italy. The greatest deployment in relation to area under annual crop production takes place in Denmark, Bulgaria, Hungary, Italy, Poland, Greece, Romania, and the Czech Republic. (Supplementary Table 2)

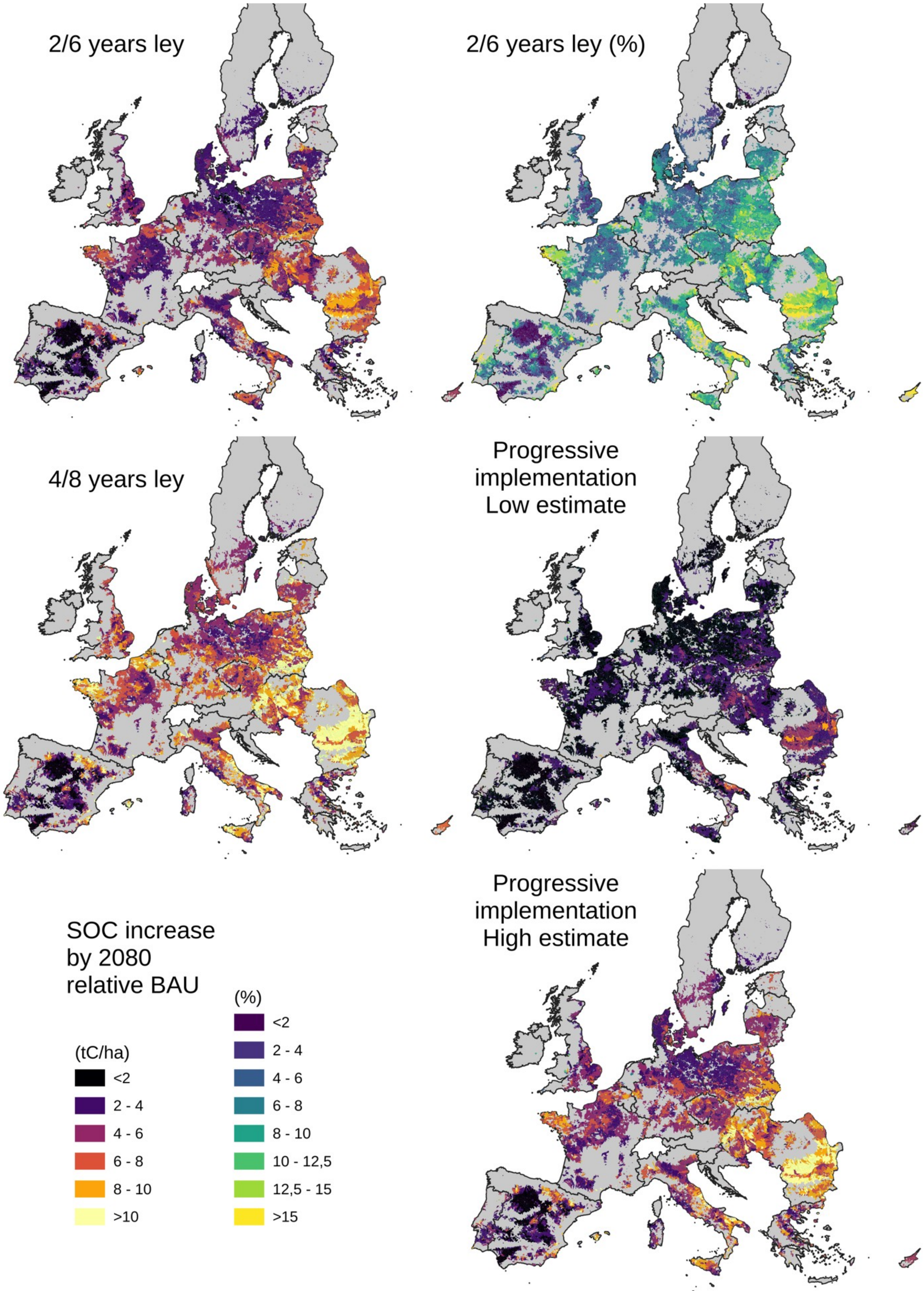

Figure 1: Soil organic carbon (SOC) increase by introducing grass production in crop rotations, relative a Business as usual (BAU) scenario.

Effects on SOC vary substantially between the different systems and deployment scenarios, as well as between different regions and individual landscapes. Naturally, areas subject to the largest accumulated SOC losses also show the greatest potential for SOC increase. Since the calculations were made on a landscape scale, the density of annual crop production in each landscape also affects SOC increases. Higher densities result in larger areas of grass production in rotations, causing larger SOC increases compared with landscapes with lower densities. In the deployment scenarios, higher implementation results in larger areas under grass production in rotations, and consequently larger SOC increases.

At the landscape scale, the average SOC increase in the 2y system at 100% implementation is 3 t ha^{-1} by 2050, and 4.1 t ha^{-1} by 2080. For the 4y system, the corresponding increases are 4.6 t ha^{-1} and 6.2 t ha^{-1}. In most landscapes (80%), SOC increases by 2080 are between 2.1-7.3 t/ha for the 2y system and 3.1-11 t ha^{-1} for the 4y system. In the low estimate deployment scenario, the average SOC increase is 1.4 t ha^{-1} by 2050 and 1.9 t ha^{-1} by 2080. In the high estimate deployment scenario, the corresponding increases are 3.7 t ha^{-1} and 5.1 t ha^{-1}. In most landscapes (80%), SOC increases by 2080 are between 0.8-2.6 t/ha (low estimate) and 2.2-6.3 t ha^{-1} (high estimate).

Bulgaria, Romania, Belgium, Slovakia, and Hungary have the greatest average SOC increase in the two deployment scenarios. Finland, Estonia, Slovenia, and Sweden have the lowest. In total, 80 % of the modelled SOC increases takes place in France, Romania, Poland, Denmark, Italy, Spain, Hungary, and Bulgaria (Figure 1; Supplementary Table 7-9).

Total average annual SOC sequestration in the high- and low estimate deployment scenarios amounts to 12.1 and 4.7 Mt C y^{-1}, respectively, by 2050, relative a business as usual scenario with continued land use. This is equivalent to 4.0-10.3 % of total current GHG emissions from agriculture in EU27+UK[26]. Comparing with 2020 levels instead of BAU results in slightly higher values. The combined GHG savings from SOC increase and biogas use is equivalent to 13-48% of current GHG emissions from agriculture. The range depends on the deployment scenario, whether biogas displaces natural gas in power plants or is upgraded to vehicle fuel displacing petrol and diesel in cars, and whether SOC increases is calculated relative BAU or 2020 levels. (Table 1)

Co-benefits

The degree of other environmental impacts differs spatially across Europe (Supplementary Figure 1; see also Englund et al. [15,17]). For example, N emissions to water are high in the northwest and central parts of Europe, whereas water erosion is primarily a problem in southern and central parts. Wind erosion is a problem primarily in coastal areas in northern and eastern Europe, whereas recurring floods are problematic all over Europe, primarily around major rivers. While all these impacts could be mitigated by increased grass production in the agricultural landscape, the mitigation potential is, naturally, determined by the location and degree of the impact. (Figure 2).

N emissions to water are decreased by a total of 119 kt N y^{-1} in the low estimate and 324 kt N y^{-1} in the high estimate deployment scenario (Table 1). In the low estimate scenario, grass rotations contribute with 34% of the reductions necessary to achieve a "low" impact level (median for all individual landscapes). In the high estimate scenario, the contribution surpasses 100% in the median landscape.

A substantial mitigation potential can be seen also for soil loss by water erosion, which is reduced by 37 and 95 Mt annually in the low and high impact scenarios, respectively (Table 1). At the landscape scale, an average of 33% of the reduction necessary to achieve a "low" impact is achieved, and in the high estimate scenario, the reduction amounts to 85%.

Soil loss by wind erosion is generally a lesser problem, but the mitigation potential is nevertheless substantial in areas where it is severe. The total reduction potential is 9 Mt and 22 Mt y^{-1} in the low and high impact scenarios, respectively (Table 1). At the landscape scale, an average of 48% of the reduction necessary to achieve a "low" impact is achieved, and in the high estimate scenario, the reduction surpasses 100%.

The co-benefits are thus considerable; in the high estimate deployment scenario, no further measures are needed to reduce either N emissions to water or soil loss by wind erosion in most landscapes where in-rotation grass production is established with the purpose of enhancing SOC. In addition to the co-benefits described above, there are multiple other co-benefits that are possible, and even likely, but that have not been quantified, such as reduced need for pesticides and mitigation of recurring floods. Concerning the latter, an indicative assessment suggests that most of the landscapes where in-rotation grass is established has a "very low" (46%) or low (26%) likelihood of mitigated flooding events, but in 12 % of the landscapes it is classified as "medium", in 13% as "high", and in 3% as "very high" (Figure 3). This illustrates that more efforts should be directed towards better understanding and quantifying other potential co-benefits than what has been done here, to get a more complete picture of the positive effects of large-scale deployment of in-rotation grass production.

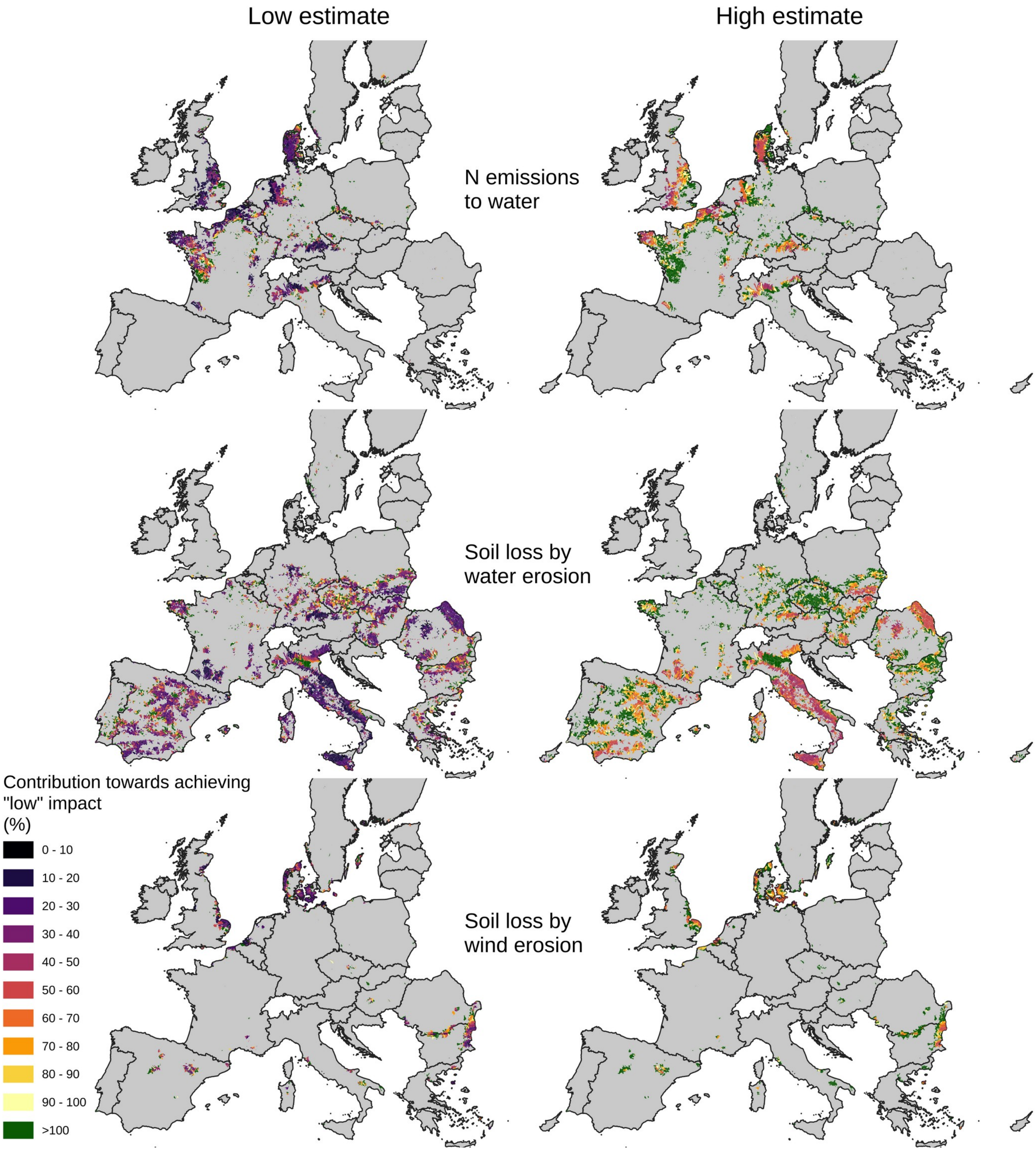

Figure 2: Co-benefits of introducing grass production in crop rotations with the primary objective to enhance soil organic carbon. The figure shows the relative contribution towards achieving a "low" impact at the landscape scale for N emissions to water, soil loss by water erosion, and soil loss by wind erosion, respectively, in the low estimate (left) and high estimate (right) deployment scenarios. Landscapes already having a "low" or lower impact are excluded.

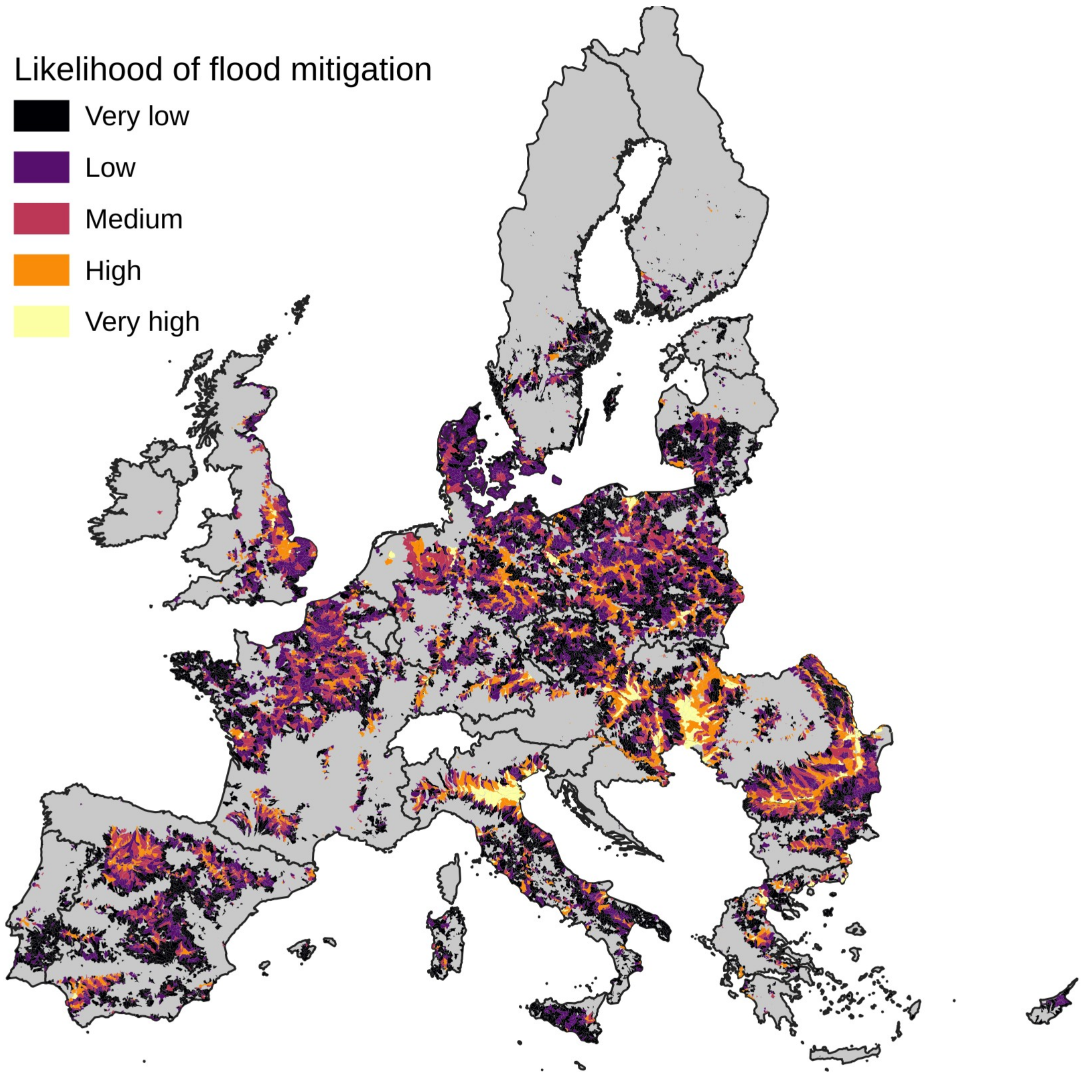

Figure 3: Likelihood of mitigated flooding events as a result of widespread deployment of in-rotation grass production.

Discussion

In line with previous research[27] the results show that there is a substantial SOC sequestration potential on European cropland, possibly exceeding 10% of total annual GHG emissions from agriculture in EU27+UK, when grass-clover leys are introduced into rotations with annual crops at a large scale. The results also show that this potential can be realized with multiple environmental co-benefits, including reduced wind and water erosion, reduced N emissions to water, and, possibly, mitigated flooding events.

Average annual SOC-sequestration rates for the base rotations (2y, 3y, and 4y) are in the range of 0.11 – 0.16 t C ha^{-1} yr^{-1} in a 30 year perspective, and 0.07 – 0.11 t C ha^{-1} yr^{-1} in a 60-year perspective (Supplementary Table 1). This illustrates that a larger share of leys (longer leys) in the total crop rotation is positive for SOC sequestration[28,29] It also confirms that SOC sequestration tends to be larger in the years following deployment of measures, and then decline towards a new equilibrium level; so-called carbon sink saturation[30].

Grass/legume leys are commonly included in crop rotations in mixed farming systems in cold or humid climate[28], thus primarily in northern Europe. To validate modelled SOC sequestration, measurements from long term agricultural field trials are valuable, albeit scarce. In England, SOC changes have been measured since 1938, when an arable 5-year rotation with cereals and root crops were changed into a ley-arable rotation with three years of ley and two years of cereal crops (i.e., a 0.6 share of ley in the overall rotation, cf. Supplementary Table 1). The measurements over 70 years reveal an average annual SOC sequestration in the topsoil (0-25 cm) of 0.34 tC ha^{-1} yr^{-1} during the first 30 years, and 0.15 tC ha^{-1} yr^{-1}, thereafter [31]. Another example of long-term field measurements is reported by Börjesson et. al [32], for two sites in southern Sweden with different climate and different soil characteristics. Here, a four-year rotation with cereals was changed into a ley-rotation with three years of ley and one year of cereals (4 yr rotation: 0.8 ley) around 1980. After 35 years, significant increases in SOC concentrations and stocks were found in the ley-dominated rotations compared with cereal monoculture rotations; 0.36-0.59 tC ha^{-1} yr^{-1} (topsoil, 0–20 cm). The modeling results reported in this study appears to be conservative when comparing with these field trails.

There is an on-going rapid decline in biodiversity[33] Insecticides and fungicides have consistent negative effects on biodiversity, including negative impact of insecticides on the potential for biological pest control[34]. The need for pesticides, especially fungicides and insecticides, is very low (or zero) in leys[35]. A change from annual crop rotations into more diversified ley-arable rotations would thus reduce the overall need for pesticides and reduce the biodiversity impacts of agriculture[36]. Increased crop diversity is also an important measure to increase biodiversity at landscape level[37]

Biomass cultivation systems are connected to, and interact with, surrounding and supporting systems, e.g., the soil system and adjacent landscapes. Such interactions are not well captured in environmental assessments conducted based on life cycle assessment (LCA). Partly because the product-based approach followed by this method focuses on the output of specific provisioning services, and partly because key aspects of sustainable agriculture, e.g., better soil health, lower biodiversity impacts, and lower pesticide-use impacts, are generally ignored[38]. Spatial modelling, such as in this study, can provide complementary information about biomass cultivation systems, including their output in terms of provisioning as well as maintaining and even cultural, ecosystem services. In particular, spatial modelling support assessment of multiple environmental effects from different land-use scenarios at a large scale, quantifying effects at different aggregation levels, while providing spatially explicit details at local to continental scales. However, the large scale also comes with a loss of precision, as local conditions cannot be fully considered. To understand how to optimize conditions for biodiversity and multiple ecosystem services, more detailed landscape level analyses are necessary [15,39,40].

The introduction of grass into annual crop rotations reduces the harvested area of cereal crops where grass is introduced. Displacement of soy meal with protein concentrate from grass-based biorefineries reduces this cropland displacement effect by an estimated 60-80%. But the effects of introducing grass cultivation in existing crop rotations depend on many factors and transcend regions as well as continents. Complementary studies, such as integrated assessment modelling, can provide important insights about land use consequences of widespread deployment of grass cultivation via changes in existing crop rotations.

Changes to more diversified crop rotations are well known to enhance the yield of grain crops, such as wheat. The principal mechanisms behind these yield gains include enhanced disease control and improved supply of nitrogen and water. There are, however, other “rotation effects” that are not yet fully understood[41]. Wheat yields preceded by a break crop instead of wheat increase between 0.5 t ha^{-1} (pre-crop: oats) to 1.2 t ha^{-1} (pre-crop: grain legumes). There are also yield increases in the second wheat harvest after a break crop, corresponding to 20-60% of the effect in the first year[42]. Understanding overall rotation effects on yields requires, as for SOC sequestration rates, data from long-term agricultural field experiments. Based on data from seven such experiments across Europe, Marini et al.[43] show that diversified crop rotations (e.g., including temporary leys) provided higher yields for both winter and spring cereals (average +0.86 and +0.39 t ha^{-1} yr^{-1}, respectively), compared with a continuous monoculture of cereals. Yield gains were higher in years with high temperatures and limited precipitation, i.e., conditions expected to become more frequent in the future climate, up to around 1 t ha^{-1} yr^{-1} compared to monocultures [43]. Angus et al. [42] estimate that on a global level, 40% of the wheat area is not preceded by an effective break crop, forage, or fallow, indicating a substantial potential for yield increases. In the EU, cereals (primarily wheat) are the dominating crops on arable land and estimates of potential yield increases from diversified crop rotations are lacking. These yield effects are however important to consider when assessing effects of crop rotation diversification on the agricultural system and associated food production. Here, research is urgently needed to build a stronger empirical, as well as theoretical, foundation.

A prerequisite for widespread deployment of in-rotation grass cultivation is a demand for products that can be produced from the grass biomass. There is an increasing interest in biorefineries, processing grass-clover mixes into protein concentrate and a multitude of other products, e.g., feed, fibers, heat, power, and biofuels[24]. Pig feeding trials in Denmark show that extracted grass protein with a high protein content (47% DM) can substitute soymeal without any adverse effects on animal performance and meat quality[44]. Beyond the mitigation of cropland displacement discussed above, protein feed production in Europe can substitute imported plant protein, mostly soymeal, which is a major import commodity to the EU food sector, both in terms of volume and use of agricultural land abroad[45]. Since this import is associated with substantial environmental concerns (deforestation, biodiversity loss, extensive pesticide use, etc.), the motives for developing a substitute feed protein source are strong[44]. This is highlighted by recent efforts by the European Commission to support EU-grown plant-based protein use, via support schemes in the new CAP and by boosting innovation and technology development[7]. Furthermore, the increased target goal in the recent proposal for a revision of the EU Renewable Energy Directive[25], where the share of renewable energy should amount to 40% in 2030, is likely to be a strong driver for increased production of biogas for heat, power and transportation fuel. Here, the outcome of the current process following the European Commission’s proposal[25] to revise the Renewable Energy Directive (RED) will likely influence how investors consider biorefineries. For example, treatment of biogas from biorefineries in the revised RED will depend on whether biogas is considered a main product or co-product of the biorefinery process.

Finally, European farmers may consider soil quality improvements sufficient motivation for in-rotation grass cultivation. Grass cultivation may also be an attractive option where intensive annual crop cultivation becomes restricted to protect the environment. In other places, incentives such as payments for soil carbon sequestration and other environmental benefits may be needed[16]. Such payments schemes require reliable methods for quantifying environmental effects with high detail, within individual landscapes.

Methods

In this study, a model was constructed to identify individual landscapes where the introduction of ley in annual crop rotations would increase SOC. To illustrate the effects of different management alternatives, different rotation systems were tested as well as two scenarios for large-scale deployment, a high- and a low estimate. In each case, the model identifies the total area under ley production in each landscape and the corresponding grass biomass production, in terms of dry matter (DM), energy (J), and protein (tonnes of extractable crude- and true protein, respectively). Furthermore, the model estimates corresponding SOC increases by 2030, 2050, and 2080, both relative 2020 and relative a business as usual scenario with a continuation of current land use. Finally, the model quantifies a number of co-benefits, i.e., environmental benefits other than SOC increases, for which there are no dedicated incentives in the model, including avoided soil loss by water and wind erosion, respectively, avoided nitrogen emissions to water, and mitigated flooding events.

Unless otherwise specified, "landscapes" refer here to polygons in a dataset containing over 81 000 sub-watersheds across EU28[15,17]. This dataset is an important basis for the modelling approach, as each landscape is profiled with information regarding, e.g., the area under annual crop production, degree of current environmental impact (N emissions to water, soil loss by water- and wind erosion, respectively, recurring floods, and accumulated losses of SOC), and the estimated effectiveness of strategic perennialization in mitigating these impacts, in general terms, for each individual landscape.

The term landscape is here defined as an intermediate integration level between the field and the physiographic region and is used synonymous to sub-watershed[46]. The unit is considered appropriate for this purpose since the anthropogenic processes (agricultural land use) within a sub-watershed, combined with hydrological processes that are constrained by a sub-watershed, determines (changes in) nutrient, water, and mass flows[17]. Using the term landscape also clarifies that implementation and impact mitigation is enabled by measures taken by multiple stakeholders at a greater scale than the individual field, thus applying a “landscape perspective” [47].

All GIS operations, including all database aggregation queries, were done in GRASS GIS [48] with projection EPSG:3035. All modelling, apart from input data preparation, was conducted using a python script with a dedicated GUI, facilitating execution of selected modules. Cartography was done in QGIS [49].

Basic production systems and scenarios for widespread deployment

The model introduces grass rotations into landscapes where the effectiveness of strategic perennialization was classified by Englund et al. [15] as medium or higher, based on accumulated losses of SOC in combination with the density of annual crops (Supplementary Figure 2). To illustrate the effects of different management alternatives, three rotation systems were modelled: two, three, and four years of ley, respectively, added to a 4-year rotation with the most dominant crops in the area, following the SOC simulations described below (Supplementary Figure 2). These systems are henceforth referred to as 2y, 3y, and 4y systems. Two scenarios for widespread deployment were then constructed: In the "low estimate" scenario, a 2y system was implemented on 100% of all agricultural fields where the accumulated losses of SOC is classified as "very high", on 50% of all fields where it is classified as "high", and on 25% of all fields where it is classified as "medium". In the "high estimate" deployment scenario, a 2y system was instead implemented on all land currently under annual crop production where the impact is classified as "medium", a 3y system where it is "high" and a 4y system where it is "very high". Based on this, areas, effects on SOC, biomass production and selected co-benefits were modelled for the three rotation systems and the two deployment scenarios, as follows.

Grassland area and corresponding biomass and protein production

Area with grassland was calculated as the product of annual crop area [15] and the share of grass relative to annual crops over time in the different systems, i.e., 1/3 for the 2y system, 3/7 for 3y, and ½ for 4y, at 100% implementation.

The corresponding biomass production was estimated for each individual landscape by multiplying the grassland area with simulated grass yields from a pan-European dataset at NUTS3 level [50]. The average yield for miscanthus, switchgrass, and reed canary grass, using a "medium" yield-input management level was calculated in each NUTS-3 region and identified for each landscape by first spatially joining landscapes to NUTS-3 regions, and then joining the database tables. The yields were then adjusted for each system assuming that the yield in the establishment year is 50% of the yield thereafter [51]. Yields for the different systems were thus adjusted as follows: 2y = (0.5 + 1) / 2 = 3/4; 3y = (0.5 + 2) / 3 = 5/6; and 4y = (0.5 + 3) / 4 = 7/8. Yields are expressed as t DM ha y^{-1} (Supplementary Figure 2). The energy output was calculated as the product of biomass production and energy content of the harvested biomass, 18.7 MJ/kg DM [17,52].

Crude protein yield was calculated by multiplying DM yield with the average concentration (g kg^{-1} DM) of crude protein (i.e., sum of average fractions A, B_1, B_2, and B_3) in seven lucerne harvests during field experiments [53]. True protein was similarly calculated by multiplying DM yield with the average concentration of true protein (i.e., sum of average fractions B_1, B_2, and B_3) from the same data source.

Biogas production and GHG savings from fossil fuel substitution

The greenhouse gas (GHG) emissions from biogas production based on ley crops has been estimated at 33 and 30 g CO_2^{eq} MJ^{-1} biogas, respectively, with and without upgrading of the biogas to natural gas quality[54], based on the methodology in the EU RED[8,55] but excluding changes in soil carbon content from grass cultivation and crediting for feed output. When upgraded biogas replaces petrol and diesel as transportation fuels in vehicles, GHG savings are about 61 g CO_2^{eq} MJ^{-1} biogas (65% reduction). The reference fuel-cycle GHG emissions for petrol and diesel[8] are 94 g CO_2^{eq} MJ^{-1} . When biogas (not upgraded) replaces natural gas for electricity production, GHG savings are about 38 g CO_2^{eq} MJ^{-1} biogas (56% reduction). Here, the reference fuel-cycle GHG emissions from natural gas[56] are 68 g CO_2^{eq} MJ^{-1}. The average methane yield per tonne DM grass-based feedstock[54] is 9.2 GJ. Thus, the GHG saving is approximately 560 and 350 kg $CO_{2\text{-eq}}$ t^{-1} DM grass when the feedstock is used for biogas production replacing petrol and diesel as vehicle fuel, and natural gas for electricity production, respectively.

Effects on soil organic carbon

The effects on SOC from the introduction of the different production systems were based on SOC simulations of 2-year ley systems and permanent grassland, respectively, in relation to SOC levels in 2020 as well as a business as usual (BAU) SOC scenario [27]. The input data is available for download at the Joint Research Centre European Soil Data Centre (ESDAC; https://esdac.jrc.ec.europa.eu/).

The SOC simulations are spatially explicit and provide BAU SOC estimates (t C ha^{-1}) for 2010, 2020, 2050, 2080, and 2100, assuming a continued rotation with the four most dominant crops in each area. They also provide SOC values in relation to these BAU values for multiple management options, including an in-rotation ley system, in which two years of lucerne are added to the BAU rotation, and a permanent grassland system, in which the BAU rotation is replaced by permanent grassland. The simulated SOC values were rasterized to match other input data (100 m) and new SOC values were calculated for the landscape dataset by identifying the median SOC value within each landscape. BAU values at specific points in time are referred to as "SOCbau_[year]", SOC increases relative BAU from implementation of in-rotation grass systems are referred to as "SOCinc_ley_[year], and SOC increases relative BAU from implementation of permanent grassland are referred to as "SOCinc_permgrass_[year]. Collectively, the latter two are referred to as "SOCinc_[year]" below.

"SOCinc" values are expressed in relation to 2010. They were therefore re-estimated with 2020 as base year, to be able to represent SOC changes from current levels while maintaining 2050, 2080, and 2100 as points in time for assessment. "SOCbau" did not require re-estimation as it represents a continuation of BAU land-use. "SOCbau_2020" was thus considered representative for current SOC. "SOCinc_ley" and "SOCinc_permgrass", however, needed to be re-estimated to represent a 10-year shorter time period than in the original simulations.

To reflect that SOC tends to increase more rapidly early after the introduction of a new land-use system [27], "SOCinc_2020" was assumed to represent the change in SOC during the first ten years, i.e., between 2020 and 2030 ("SOCinc_first10"). SOC changes during the remaining period (i.e., 20, 50, and 70 years, for 2010, 2080, and 2100, respectively) was calculated by subtracting SOCinc_first10 from SOCinc_2050/2080/2100, thus representing SOC changes in 30/60/80 years following the first 10 years ("SOCinc_last30/60/80"). Since SOC changes in 20/50/70 years are required, these values were downscaled by 20/30, 50/60, and 70/80, respectively ("SOCinc_last20/50/70"). Finally, SOC increases by 2050/2080/2100 relative BAU could be calculated as the sum of "SOCinc_first10" and "SOCinc_last20/50/70". These re-estimated SOC values are below referred to as SOCinc_ley/permgrass_new_[year], or collectively as SOCinc_new_[year].

At this point, SOC changes by 2050/2080/2100 relative BAU, with base year 2020, has been identified for the 2y system ("SOCinc_BAU_2y_2050/2080/2100"). To estimate SOC changes for the other systems, we assumed a linear correlation between SOC changes and the share of total area under annual crops that are used for grass production, on average over time. SOCinc_BAU_2y_lim50 and _lim25 are therefore estimated by multiplying SOCinc_BAU_2y with 0.5 and 0.25, respectively. Similarly, SOCinc_BAU_3y and _4y was estimated by multiplying SOCinc_BAU_2y by 9/7 and 3/2, respectively.

Total SOC changes were then calculated as the product of SOC changes per hectare and the total area under annual crops, for each system and in each landscape. Finally, the relative difference between "SOCinc_BAU" and "SOCbau" was calculated for the different assessment years. The same calculations (t C ha^{-1}, t C, and %) were also made relative 2020 instead of BAU. The first was done by adding the difference in BAU SOC between 2020 and the assessment year to the SOC increase relative BAU for the assessment year, e.g.: "SOCinc_2020_3y_2080" = "SOCinc_BAU_3y_2080" + ("SOCbau_2080" - "SOCbau_2020"). The latter two were calculated as described above. Finally, absolute SOC values for all assessment years and ley systems were calculated as the sum of SOC in 2020 and SOC change relative 2020. Finally, for each production system and assessment year, the share of maximum attainable SOC increase was estimated as the quotient of SOC increase relative 2020 in the different ley systems and in permanent grasslands.

Finally, annual C sequestration relative total GHG emissions from agriculture was estimated by first dividing total SOC increase by 2050, relative both 2020 levels and BAU, with 30 years and then dividing the quotients with total GHG emissions from agriculture in 2018 [26].

Environmental co-benefits

Four co-benefits were modelled: avoided (1) soil loss by water erosion, (2) soil loss by wind erosion, (3) nitrogen emissions to water, and (4) flooding events.

1. Soil loss by water erosion was indicated by "annual average soil loss by water erosion on land used for production of annual crops". Annual soil loss was retrieved from a published dataset for the year 2010 with 100 m resolution (available at ESDAC), based on the application of a modified version of the Revised Universal Soil Loss Equation (RUSLE) model [57]. Average values were then calculated for erosion values on land used for annual crop production, in each landscape.

2. Soil loss by wind erosion, indicated and calculated as for water erosion, based on a 1000 m dataset of soil loss by wind erosion derived using a GIS version (RWEQ-GIS) [58] of the Revised Wind Erosion Equation (RWEQ) model [59].

3. N emissions to water, indicated by "annual average diffuse nitrogen emissions to water"', retrieved by running v2 of the Geospatial Regression Equation for European Nutrient losses (GREEN) model [60] for the landscape dataset. Average values were then calculated for erosion values in each landscape.
4. Recurring floods, indicated by "share of landscape area subject to 10-year flooding". Data on 10-year flooding events were retrieved from a published flood hazard dataset with 100 m resolution. The data were derived using a cascading model simulation approach [61]. The share of the total area in each landscape subject to 10-year flooding events was then calculated for each landscape.

The four impacts were then classified on a five-step scale from "very low" to "very high". See Englund et al. [15] for more details on methods, thresholds, and underlying data. For impacts 1 and 2, an assumption was made that the impact is marginal on grassland [62]. This implies that replacing, e.g., 10% of annual crop production with grass would reduce the impact with 10%. The potential impact mitigation in each individual landscape was therefore calculated as the product of current impact and the share of grassland relative current area under annual crops, for the five system designs and the two deployment scenarios. For impact 3, an assumption was made that N emissions to water from grass production is 75% lower than current N emissions to water. This assumption was based on field experiments showing that perennial grasses reduce N leaching with 70-80% compared to traditional systems[63]. The potential impact mitigation was then calculated in each landscape as the product of current impact, the share of grassland relative current annual crop area, and the mitigation factor of 0.75, for the five system designs and the two deployment scenarios. It was also estimated to what extent in-rotation grass production could contribute to reducing impact 1-3 down to a "low" impact level. This was done by dividing potential impact mitigation by the difference between the upper threshold of the class “low impact”, as defined by Englund et al. [15], and the current impact.

Flood mitigation could not be estimated using the same approach. There is strong support for claiming that increased grass production in agricultural landscapes can mitigate flooding events[64]. However, the magnitude of this benefit depends on more landscape-specific characteristics and can thus not be generalized in the same way as for the other impacts. An attempt was instead made to indicate the likelihood of mitigated or avoided flooding events as a result of increased grass production in the landscape [17]. This was done by assuming that the likelihood is directly correlated with the previously estimated effectiveness of strategic perennialization in mitigating recurring floods[15]. A “medium” effectiveness thus corresponds to a “medium” likelihood, etc. The effectiveness of strategic perennialization in mitigating recurring floods was therefore identified for each landscape where the model introduces in-rotation grass systems.

Uncertainties and limitations

Where, and to what extent, implementation takes place, both in the base scenarios and in the high- and low estimates, is determined by the thresholds used for classification of impacts and impact mitigation effectiveness [15,17]. Different thresholds would thus yield different results. General spatial patterns would, however, be similar [15]. The use of average simulated yields for miscanthus, switchgrass, and reed canary grass to estimate ley yields, is justified by the lack of spatially explicit pan-European yield estimates specifically for ley crops. Visual assessment of the simulated yields across the study area suggests that reed canary grass yields are the most similar to ley yields, in spatial terms. In absolute numbers, however, miscanthus yields are more similar to what can be expected from ley crops. Using the average value for these three species provides both reasonable spatial patterns and reasonable yield levels. This approach can be further justified by the fact that selection of ley species will vary across Europe, given different biophysical conditions. It is therefore not reasonable to use simulated yields (if they existed) for one single species, or a specific combination of species, in all landscapes across Europe. See previous studies for additional general uncertainties related to the model, including co-benefits[15,17] and SOC simulations [27]

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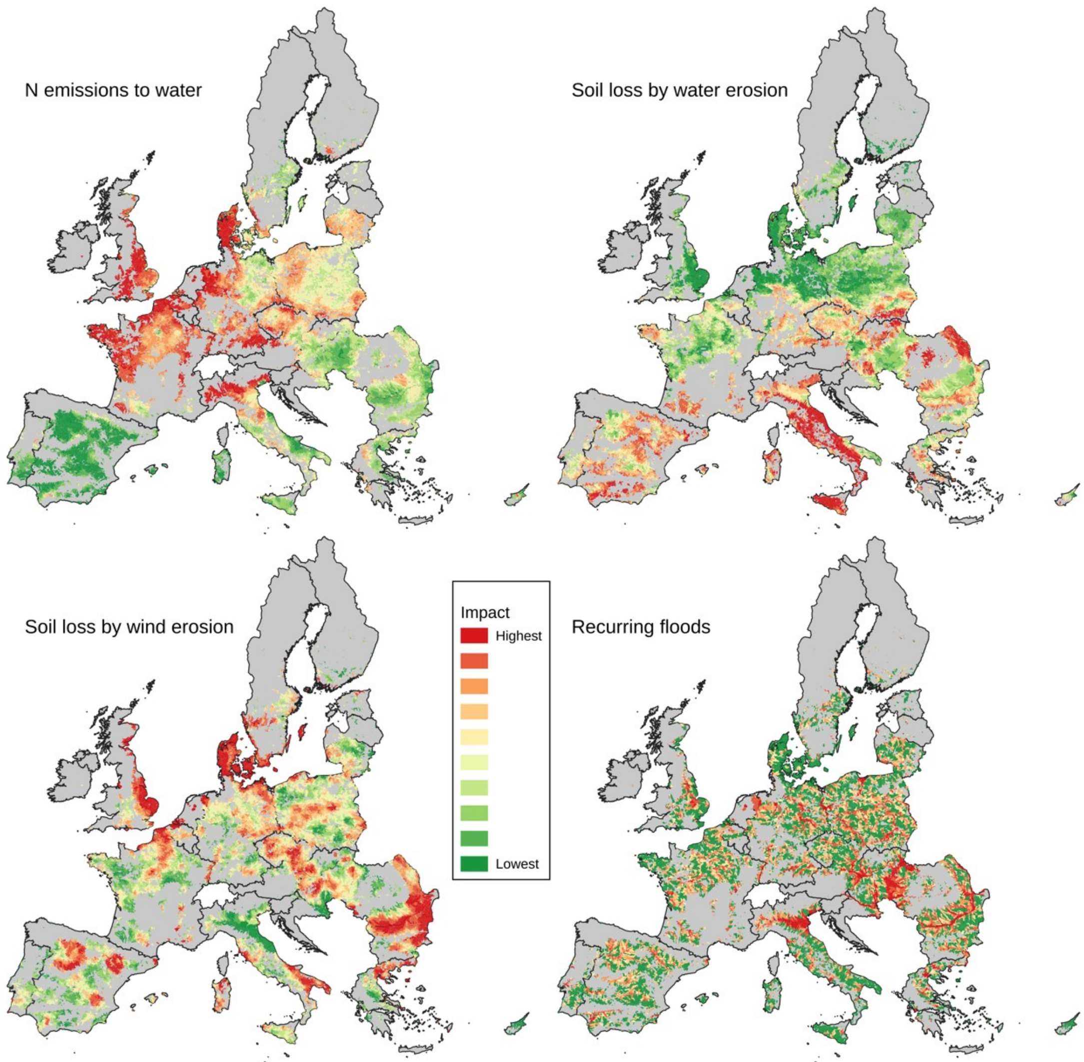
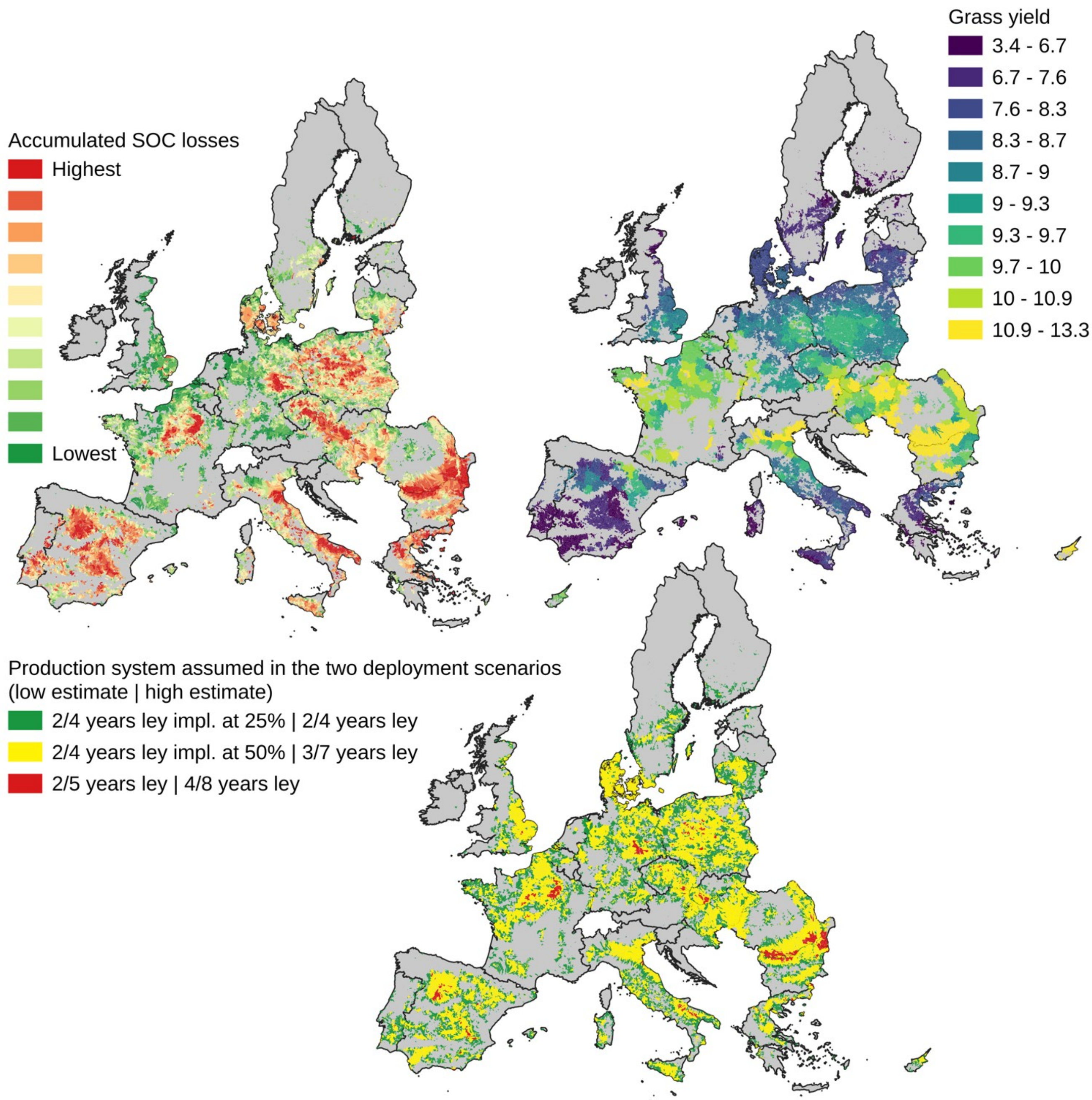
Supplementary information



Supplementary Figure 1: Current degree of N emissions to water, soil loss by wind erosion, soil loss by water erosion, and recurring floods, in the landscapes where grass is introduced in crop rotations to enhance soil organic carbon.



Supplementary Figure 2: Accumulated soil organic carbon (SOC) losses (top left), simulated grass yields (top right), and production systems assumed in the two deployment scenarios, based on estimated effectiveness to remediate accumulated SOC losses (bottom).

Supplementary Table 1. Calculated cropland area (Mha) of arable rotation with different inclusion of grass-clover leys based on the three modelled scenarios and average annual soil organic carbon sequestration rate (tC ha $^{-1}$ yr $^{-1}$) in the rotations

Case	Area of arable land with in-rotation grass production	Average annual SOC sequestration rate in ley-arable rotation, tC ha^{-1} yr^{-1}	Average annual SOC sequestration rate in ley-arable rotation, tC ha^{-1} yr^{-1}
yr ley/yr total rotation (share ley)	Mha	30 years	60 years
2/6 (0.33)	91.4	0.11	0.07
3/7 (0.44)		0.14	0.1
4/8 (0.5)		0.16	0.11

Supplementary Table 2*: Average area under ley production (kha). Country-level aggregates.*

Country	2y	3y	4y	low_est	high_est
AT	306	393	459	141	371
BE	155	200	233	58	177
BG	1,206	1,551	1,810	672	1,576
CY	70	91	106	30	85
CZ	895	1,150	1,342	491	1,158
DE	3,572	4,592	5,358	1,469	4,187
DK	922	1,186	1,384	442	1,163
EE	45	58	67	21	56
EL	623	801	934	345	815
ES	3,638	4,678	5,458	1,945	4,709
FI	101	129	151	36	113
FR	4,091	5,260	6,138	1,833	4,931
HR	82	105	123	40	105
HU	1,544	1,985	2,316	757	1,966
IE	3	4	5	0	0
IT	2,518	3,237	3,777	1,301	3,228
LT	647	831	970	310	816
LU	0	1	1	0	1
LV	103	133	155	34	112
NL	162	208	243	36	142
PL	4,245	5,458	6,369	2,106	5,383
PT	268	344	401	151	351
RO	2,596	3,338	3,895	1,479	3,383
SE	712	915	1,068	342	900
SI	9	11	13	2	9
SK	466	599	698	262	610
UK	1,473	1,894	2,210	461	1,488
EU28	**30,452**	**39,153**	**45,684**	**14,763**	**37,837**

Supplementary Table 3*:* Biomass output from ley production (kt). Country-level aggregates.

Country	2y	3y	4y	low_est	high_est
AT	2,528	3,612	4,425	1,178	3,401
BE	1,133	1,618	1,982	421	1,370
BG	9,648	13,783	16,884	5,385	14,093
CY	700	1,001	1,226	299	913
CZ	6,386	9,123	11,176	3,516	9,221
DE	24,245	34,637	42,430	10,034	30,607
DK	5,505	7,865	9,634	2,640	7,666
EE	225	321	394	104	307
EL	3,327	4,753	5,823	1,857	4,875
ES	20,618	29,455	36,083	11,068	29,748
FI	471	672	824	171	560
FR	30,792	43,989	53,887	13,811	40,302
HR	676	966	1,183	334	959
HU	11,891	16,987	20,809	5,832	16,778
IE	18	26	32	0	0
IT	16,979	24,257	29,715	8,729	24,120
LT	3,798	5,426	6,647	1,822	5,292
LU	3	4	5	2	4
LV	578	826	1,012	187	652
NL	1,081	1,544	1,892	244	957
PL	28,414	40,592	49,726	14,144	39,904
PT	1,355	1,936	2,372	773	1,996
RO	21,476	30,681	37,584	12,343	31,363
SE	3,827	5,468	6,698	1,844	5,348
SI	75	107	131	19	75
SK	3,637	5,196	6,365	2,062	5,342
UK	9,322	13,318	16,314	2,972	9,980
EU28	**208,711**	**298,164**	**365,254**	**101,792**	**285,832**

Supplementary Table 4*: Average SOC increase relative BAU in 2050. Country-level aggregates.*

Country	2y	3y	4y	low_est	high_est
AT	3	4	5	1	4
BE	5	6	8	2	6
BG	5	6	7	3	6
CY	3	4	5	1	4
CZ	3	4	4	1	3
DE	3	4	5	1	4
DK	2	3	4	1	3
EE	3	4	5	1	4
EL	3	4	4	2	4
ES	2	3	3	1	3
FI	2	3	3	1	3
FR	4	5	5	2	4
HR	3	4	4	1	4
HU	4	5	6	2	5
IE	3	4	5	1	3
IT	3	4	5	2	4
LT	3	3	4	1	3
LU	3	4	5	2	4
LV	4	5	6	1	4
NL	4	6	7	1	4
PL	3	4	5	1	4
PT	3	3	4	2	4
RO	4	6	6	2	5
SE	2	3	4	1	3
SI	3	4	5	1	3
SK	4	5	6	2	5
UK	3	4	5	1	3
EU28	**3**	**4**	**5**	**2**	**4**

Supplementary Table 5*: Average SOC increase relative BAU in 2080 (kt ha-1). Country-level aggregates.*

Country	2y	3y	4y	low_est	high_est
AT	5.0	6.4	7.4	2.2	6.0
BE	6.2	7.9	9.2	2.2	6.9
BG	7.0	9.0	10.5	3.7	9.1
CY	4.5	5.8	6.8	2.0	5.5
CZ	4.2	5.3	6.2	2.2	5.3
DE	4.1	5.2	6.1	1.6	4.7
DK	3.5	4.5	5.2	1.7	4.4
EE	5.4	7.0	8.2	2.3	6.5
EL	4.1	5.3	6.1	2.4	5.4
ES	2.5	3.3	3.8	1.3	3.3
FI	2.8	3.6	4.2	1.3	3.4
FR	4.1	5.3	6.2	1.7	4.9
HR	3.8	4.9	5.8	1.8	4.8
HU	6.1	7.8	9.1	2.9	7.6
IE	4.1	5.3	6.2	1.0	4.1
IT	4.7	6.0	7.0	2.6	6.1
LT	4.0	5.1	5.9	1.9	5.0
LU	4.0	5.2	6.1	2.0	5.2
LV	6.2	7.9	9.3	2.1	6.8
NL	6.2	8.0	9.4	1.7	6.2
PL	4.6	6.0	7.0	2.2	5.8
PT	3.1	4.0	4.7	1.8	4.1
RO	6.7	8.6	10.0	3.4	8.4
SE	3.7	4.7	5.5	1.8	4.6
SI	4.2	5.5	6.4	1.1	4.2
SK	6.2	7.9	9.2	3.3	7.9
UK	4.3	5.5	6.4	1.3	4.4
EU28	**4.4**	**5.7**	**6.6**	**2.1**	**5.5**

Supplementary Table 6: *Average SOC increase relative BAU in 2100 (kt ha-1). Country-level aggregates.*

Country	2y	3y	4y	low_est	high_est
AT	5.0	6.4	7.4	2.2	6.0
BE	6.0	7.7	9.0	2.2	6.8
BG	6.6	8.5	9.9	3.5	8.5
CY	4.3	5.5	6.4	1.9	5.2
CZ	3.9	5.0	5.9	2.1	5.0
DE	3.7	4.8	5.6	1.5	4.3
DK	3.5	4.5	5.2	1.7	4.4
EE	5.7	7.3	8.6	2.4	6.8
EL	3.8	4.9	5.7	2.2	5.0
ES	2.4	3.1	3.6	1.2	3.1
FI	3.1	4.0	4.7	1.5	3.8
FR	3.8	4.9	5.7	1.6	4.5
HR	3.8	4.9	5.8	1.8	4.8
HU	6.4	8.2	9.6	3.1	8.0
IE	3.9	5.0	5.8	0.9	3.8
IT	4.8	6.2	7.2	2.7	6.3
LT	3.9	5.1	5.9	1.9	5.0
LU	2.9	3.7	4.3	1.4	3.7
LV	6.3	8.1	9.5	2.2	7.0
NL	5.8	7.4	8.7	1.5	5.8
PL	4.8	6.1	7.2	2.3	6.0
PT	2.5	3.2	3.7	1.4	3.3
RO	6.9	8.9	10.4	3.5	8.7
SE	3.7	4.7	5.5	1.8	4.6
SI	3.5	4.5	5.2	0.9	3.5
SK	6.6	8.4	9.8	3.5	8.4
UK	4.1	5.3	6.2	1.2	4.2
EU28	**4.4**	**5.6**	**6.5**	**2.1**	**5.4**

Supplementary Table 7*: Total SOC increase relative BAU in 2050 (kt). Country-level aggregates.*

Country	2y	3y	4y	low_est	high_est
AT	2,891	3,717	4,336	1,255	3,385
BE	2,292	2,947	3,438	849	2,608
BG	16,702	21,473	25,052	8,993	21,672
CY	682	877	1,023	292	820
CZ	7,433	9,557	11,150	4,009	9,586
DE	32,686	42,025	49,029	13,186	38,003
DK	6,682	8,591	10,022	3,188	8,412
EE	450	579	675	207	558
EL	5,835	7,502	8,752	3,233	7,632
ES	22,128	28,450	33,192	11,389	28,394
FI	669	861	1,004	228	738
FR	44,688	57,456	67,032	19,372	53,378
HR	671	863	1,006	327	853
HU	18,255	23,470	27,382	8,932	23,236
IE	36	46	53	0	1
IT	24,085	30,966	36,127	12,588	30,944
LT	4,984	6,408	7,476	2,346	6,240
LU	5	6	7	2	6
LV	1,250	1,607	1,875	379	1,326
NL	1,931	2,483	2,896	409	1,585
PL	36,913	47,459	55,369	17,863	46,460
PT	2,013	2,588	3,019	1,104	2,624
RO	35,913	46,174	53,870	20,553	46,856
SE	5,322	6,842	7,983	2,554	6,719
SI	85	109	127	21	84
SK	5,924	7,617	8,886	3,279	7,739
UK	13,842	17,796	20,762	4,126	13,597
EU28	**294,364**	**378,469**	**441,547**	**140,685**	**363,458**

Supplementary Table 8: Total SOC increase relative BAU in 2080 (kt). Country-level aggregates.

Country	**2y**	**3y**	**4y**	**low_est**	**high_est**
AT	4,306	5,537	6,460	1,886	5,070
BE	2,770	3,562	4,156	1,025	3,150
BG	24,220	31,140	36,329	13,126	31,465
CY	955	1,227	1,432	408	1,148
CZ	11,235	14,445	16,852	6,021	14,463
DE	43,301	55,672	64,951	17,399	50,282
DK	9,432	12,127	14,148	4,487	11,859
EE	755	970	1,132	348	936
EL	7,802	10,031	11,703	4,347	10,216
ES	23,164	29,782	34,746	11,837	29,686
FI	851	1,094	1,276	295	943
FR	49,857	64,102	74,786	21,491	59,438
HR	872	1,121	1,308	425	1,109
HU	28,010	36,013	42,016	13,708	35,654
IE	42	54	63	0	1
IT	33,289	42,801	49,934	17,439	42,810
LT	7,640	9,823	11,460	3,580	9,546
LU	6	7	8	3	7
LV	2,048	2,633	3,071	616	2,166
NL	2,753	3,539	4,129	581	2,257
PL	56,300	72,385	84,450	27,179	70,809
PT	2,231	2,869	3,347	1,216	2,904
RO	54,637	70,247	81,955	31,407	71,372
SE	7,879	10,131	11,819	3,776	9,943
SI	111	143	167	28	111
SK	8,982	11,548	13,473	4,973	11,734
UK	18,722	24,072	28,084	5,469	18,182
EU28	**402,170**	**517,075**	**603,255**	**193,069**	**497,260**

Supplementary Table 9: Total SOC increase relative BAU in 2100 (kt). Country-level aggregates.

Country	**2y**	**3y**	**4y**	**low_est**	**high_est**
AT	4,316	5,549	6,474	1,892	5,087
BE	2,691	3,460	4,037	995	3,060
BG	22,700	29,186	34,051	12,223	29,453
CY	901	1,158	1,351	385	1,084
CZ	10,549	13,563	15,824	5,652	13,583
DE	40,281	51,790	60,421	16,279	46,845
DK	9,470	12,175	14,204	4,493	11,894
EE	781	1,005	1,172	359	968
EL	7,052	9,067	10,579	3,927	9,232
ES	21,783	28,007	32,675	11,098	27,878
FI	958	1,232	1,437	330	1,060
FR	45,850	58,950	68,775	19,616	54,540
HR	871	1,120	1,307	424	1,107
HU	29,876	38,411	44,813	14,616	38,023
IE	41	52	61	0	1
IT	33,817	43,478	50,725	17,771	43,540
LT	7,433	9,556	11,149	3,490	9,296
LU	4	5	6	2	5
LV	2,065	2,655	3,098	619	2,182
NL	2,555	3,284	3,832	537	2,086
PL	57,252	73,610	85,879	27,593	71,971
PT	1,722	2,214	2,583	939	2,240
RO	56,733	72,942	85,099	32,391	74,008
SE	7,852	10,095	11,778	3,763	9,909
SI	86	110	129	21	86
SK	9,407	12,095	14,110	5,192	12,281
UK	17,752	22,824	26,627	5,104	17,053
EU28	**394,797**	**507,596**	**592,195**	**189,712**	**488,469**

Supplementary Table 10: Annual avoided soil loss by water erosion (kt y^{-1}). Country-level aggregates.

Country	2y	3y	4y	low_est	high_est
AT	852	1,095	1,278	355	975
BE	297	382	445	110	338
BG	2,845	3,658	4,268	1,579	3,717
CY	103	133	155	45	125
CZ	2,145	2,758	3,218	1,173	2,773
DE	5,226	6,720	7,840	1,952	5,937
DK	554	712	831	266	699
EE	28	36	42	13	34
EL	1,540	1,980	2,310	859	2,016
ES	12,508	16,083	18,763	6,467	16,064
FI	39	50	58	15	45
FR	7,340	9,437	11,011	2,982	8,574
HR	110	141	165	54	140
HU	3,032	3,898	4,547	1,478	3,853
IE	1	2	2	0	0
IT	20,480	26,332	30,721	10,589	26,360
LT	570	733	855	275	721
LU	1	1	2	1	1
LV	77	99	116	25	83
NL	86	110	128	20	76
PL	6,298	8,098	9,448	3,064	7,955
PT	600	771	900	334	786
RO	7,953	10,225	11,929	4,078	10,087
SE	647	832	970	310	816
SI	16	20	24	4	16
SK	1,419	1,824	2,128	763	1,842
UK	956	1,229	1,434	290	936
EU28	**75,721**	**97,359**	**113,587**	**37,100**	**94,969**

Supplementary Table 11: Annual avoided soil loss by wind erosion (kt y^{-1}). Country-level aggregates.

Country	2y	3y	4y	low_est	high_est
AT	102	131	153	52	131
BE	64	82	96	22	71
BG	2,380	3,061	3,571	1,519	3,202
CY	0	0	0	0	0
CZ	440	566	661	252	577
DE	972	1,250	1,458	390	1,129
DK	2,815	3,619	4,222	1,357	3,560
EE	14	18	21	7	18
EL	333	429	500	175	433
ES	1,679	2,159	2,520	903	2,177
FI	21	26	31	10	25
FR	918	1,180	1,377	385	1,086
HR	0	0	0	0	0
HU	433	557	649	213	551
IE	0	0	0	0	0
IT	759	976	1,139	454	1,007
LT	67	86	101	32	85
LU	0	0	0	0	0
LV	8	10	11	3	9
NL	429	551	643	93	373
PL	775	997	1,163	390	986
PT	20	26	30	11	27
RO	2,525	3,246	3,787	1,810	3,480
SE	605	779	908	289	763
SI	0	0	0	0	0
SK	199	256	298	124	266
UK	2,107	2,709	3,160	717	2,258
EU28	**17,664**	**22,714**	**26,501**	**9,209**	**22,212**

1 **Supplementary Table 12:** Annual avoided N emissions to water (t N y^{-1}). Country-level aggregates.

Country	2y	3y	4y	low_est	high_est
AT	3,454	4,441	5,181	1,410	3,902
BE	5,169	6,646	7,753	1,896	5,858
BG	4,883	6,278	7,324	2,543	6,300
CY	309	398	464	130	369
CZ	9,665	12,427	14,498	5,169	12,435
DE	40,643	52,256	60,966	15,237	46,250
DK	14,155	18,199	21,232	6,751	17,822
EE	377	485	565	178	473
EL	3,689	4,743	5,534	2,220	4,899
ES	5,604	7,206	8,407	2,895	7,177
FI	1,323	1,701	1,985	504	1,514
FR	59,194	76,107	88,791	24,926	70,215
HR	639	822	959	314	815
HU	5,374	6,909	8,061	2,620	6,827
IE	88	113	132	1	2
IT	25,777	33,143	38,667	12,719	32,493
LT	7,349	9,449	11,024	3,581	9,331
LU	23	29	34	11	29
LV	703	904	1,055	245	783
NL	3,317	4,265	4,975	785	3,015
PL	33,759	43,405	50,640	16,714	42,816
PT	1,199	1,542	1,799	755	1,608
RO	11,071	14,234	16,607	5,791	14,164
SE	5,839	7,507	8,759	2,791	7,360
SI	131	168	196	33	131
SK	2,956	3,800	4,434	1,567	3,824
UK	23,899	30,728	35,849	7,128	23,338
EU28	**270,590**	**347,904**	**405,890**	**118,914**	**323,752**