Large-scale deployment of grass in crop rotations as a multifunctional soil-based climate mitigation strategy

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Abstract

The agriculture sector can contribute to climate change mitigation by reducing its own greenhouse gas (GHG) emissions, sequestering atmospheric carbon in vegetation and soils, and providing biomass to substitute for fossil fuels and other GHG intensive products (1). New policies at the EU level provide incentives for more sustainable land-use practices, including cultivation systems with perennial species that provide biomass along with land carbon sequestration and other environmental benefits (2–6). One such system is the inclusion of grass in crop rotations with annual crops, a common practice in northern Europe (7). Here, we estimate the effects of widespread deployment of such systems to remediate soil organic carbon (SOC) losses from historic land use while producing biomass and additional environmental benefits. Based on spatial modeling across more than 81,000 sub-watersheds in Europe, we find a substantial SOC sequestration potential for European cropland when introducing two to four years of grass into a four-year rotation with annual crops to create new six- to eight-year mixed rotations. The environmental co-benefits, including reduced wind and water erosion, reduced nitrogen emissions to water, and mitigated flooding events, are notable—in some cases exceeding the estimated mitigation needs. The combined annual GHG savings from soil-carbon sequestration and use of biogas from grass-based biorefineries are equivalent to 13-48% of current GHG emissions from agriculture. Incentivizing widespread deployment will require supportive policy measures as well as new markets for grass biomass, e.g., as feedstock for biofuels and protein concentrate.

Introduction

The recently published IPCC WG1 AR6 report (8) concludes 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 (9, 10). The agriculture sector can contribute to climate change mitigation by reducing greenhouse gas (GHG) emissions and by CDR via carbon sequestration in vegetation and soils. The sector can also provide biomass for mitigation in the energy, industry, and transport sectors by substituting for fossil fuels and other GHG-intensive products (1). Meanwhile, the agriculture sector needs to address water, soil, and biodiversity impacts caused by historic and current practices (11, 12). The sector also needs to adapt to climate change, which is expected to cause new stresses on agricultural systems and exacerbate risks to human health, ecosystem health, food systems, and livelihoods (1).

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 (2). Other EU policies that are likely to influence agricultural practices include the Renewable Energy Directive (3), the European Green Deal (4), the Biodiversity Strategy for 2030 (5), and the Farm to Fork Strategy (6). Changing agricultural practices toward a greater share of perennial species, e.g., perennial grasses and legumes (here, "grass"), 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 the environmental impacts from agriculture (13–18).

Biomass production in species-rich mixtures of perennial grasses on marginal land has the potential to enhance biodiversity and carbon sequestration in soils (19). Another promising option is to include grass in crop rotations with annual crops in mixed farming systems, a common practice in cold or humid climates (7), primarily in northern Europe. This practice can have multiple environmental benefits, such as increasing the soil organic carbon (SOC) content, but can also enhance crop yields in the longer term (20). Interest is also growing in biorefineries that process grass-clover mixes into protein concentrate and a multitude of other products, e.g., feed, fibers, heat, power, and biofuels (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, with multiple co-products (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).

Here, we estimate the effects of producing perennial grass in rotation with annual crops at large scale on biomass production, remediation of SOC losses from historic land use, and mitigation of additional environmental problems. We model the introduction of grass in crop rotations with annual crops in more than 81,000 sub-watersheds ("landscapes", see Methods) across Europe (EU27+UK). We then quantify grass biomass production —in terms of dry matter (DM), extractable protein, energy content, and biogas output— and increases in SOC and the corresponding GHG emission savings from carbon sequestration and fossil fuel substitution. Finally, we quantify or indicate multiple environmental co-benefits: (i) reduced wind erosion, (ii) reduced water erosion, (iii) reduced nitrogen emissions to water, and (iv) mitigated flooding events.

The results show that widespread deployment of perennial grass in rotation with annual crops would result in significant carbon sequestration in agricultural soils. The annual carbon sequestration by 2050 in two illustrative deployment scenarios corresponds to about 5-10% of current GHG emissions from agriculture in EU27+UK. The combined annual GHG savings from soil carbon sequestration and biogas use are equivalent to 13-48% of current GHG emissions from agriculture. Environmental co-benefits are notable—in some cases exceeding the estimated mitigation needs.

Results

The model introduces perennial grass in crop rotations on 91 million hectares (Mha) of arable land, in 24,363 of the ~81,000 assessed landscapes, encompassing about 80% of all land in Europe currently used to cultivate annual crops. Most of these landscapes (76%) are classified as having a "high" level of accumulated SOC losses, 17% are "medium" and 7% are "very high." Adding two years of grass cultivation to four-year crop rotations (2/6-grass system) in these landscapes results in 30 Mha of land being used for cultivation of grass instead of annual crops, on average over time. Adding one additional year of grass in the crop rotation (3/7-grass system) increases the grass area to 39 Mha; adding two additional years (4/8-grass system) results in 46 Mha. The corresponding grass production is about 210, 300, and 370 Mt DM y^{-1}, for the 2/6, 3/7, and 4/8 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 protein and true protein amount to about 40-80 Mt and 30-50 Mt, respectively.

In our "low estimate" scenario, the 2/6 system is implemented on all land under annual crop production where SOC loss is classified as "very high", on 50% of the land where it is "high", and on 25% where it is "medium." In this scenario, 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 an energy content of about 1.9 EJ and a biogas output of 1 EJ. Extractable crude protein and true protein amount to about 20 Mt and 10 Mt, respectively.

In our "high estimate" scenario, the 2/6 system is implemented on all land under annual crop production for which the accumulated SOC loss is classified as "medium," with the 3/7 and 4/8 systems implemented where the loss is classified as "high" and "very high," respectively. Here, 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}, equivalent to an energy content of about 5.3 EJ and a biogas output of 2.6 EJ. Extractable crude protein and true protein amount to about 60 Mt and 40 Mt, respectively.

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

Table 1: Model results for large-scale introduction of grass into crop rotations, aggregated at the European (EU27+UK) scale. BAU = Land use continues as per business as usual. Numbers are rounded. See Supplementary Table 2-12 for country-level aggregates.

		2/6 system	**3/7-grass system**	**4/8-grass system**	**Low estimate scenario**	**High estimate 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 relative to BAU | relative to 2020 (tC ha^{-1} of total cropland area)	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 relative to BAU | relative to 2020 (Mt)	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 to BAU | relative to 2020 (as % of total current GHG emissions from agriculture)		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 for gasoline and diesel in cars (Mt C yr^{-1} | as % of total current GHG emissions from agriculture)		32 | 27	46 | 39	56 | 47	16 |14	44 | 37
Annual GHG savings when biogas substitutes for natural gas for electricity (Mt C yr^{-1} | as % of 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

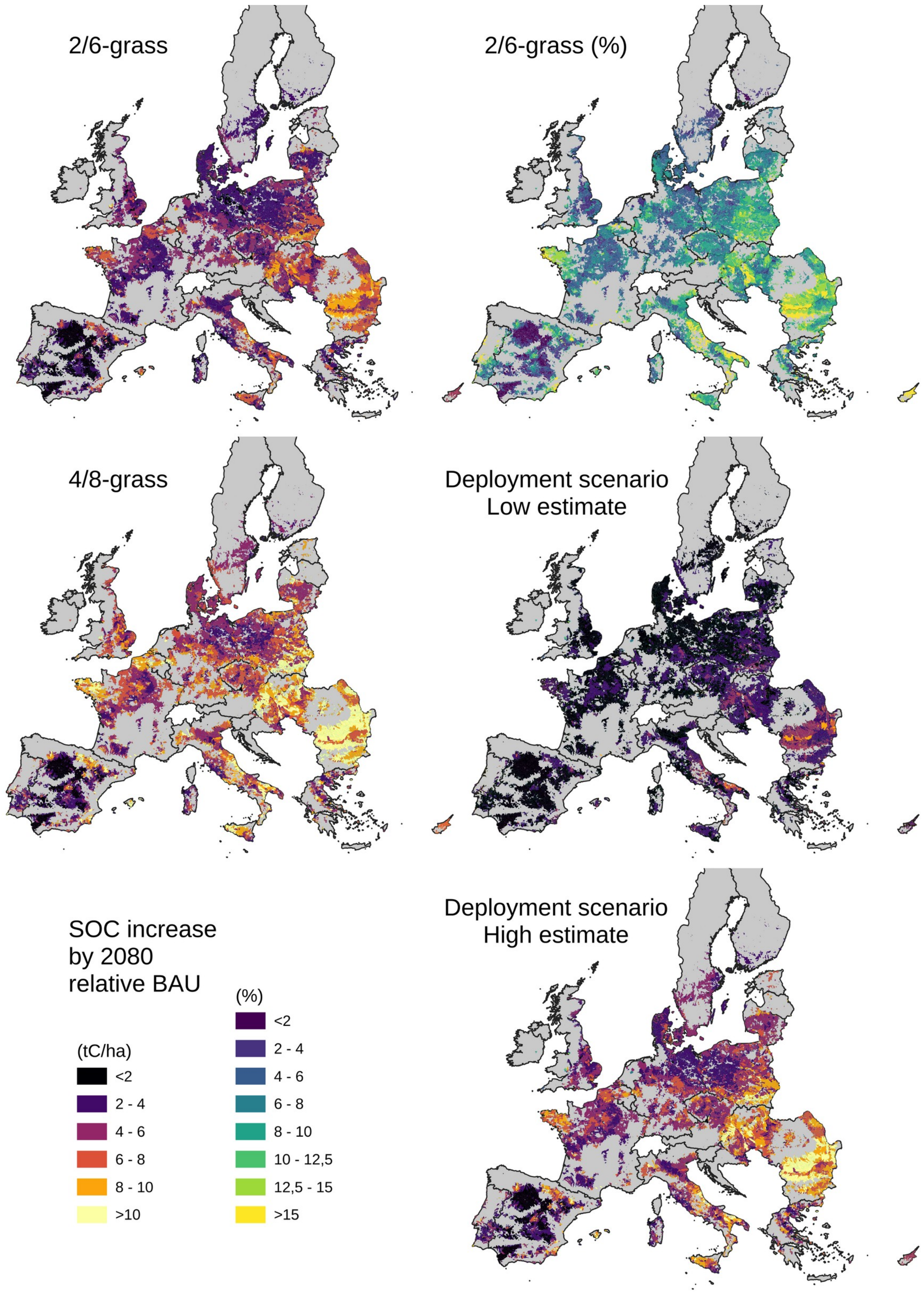

Figure 1: Increase in soil organic carbon (SOC) from the introduction of grass in crop rotations, relative to a business as usual (BAU) scenario.

Effects on SOC are consistently positive. If two, three, or four years of grass are added to a four-year crop rotation with annual crops, the corresponding SOC increase is about 300, 510, or 600 Mt C by 2080, relative to a business-as-usual scenario in which current land use continues as is (BAU). In the low and high estimate scenarios in which implementation depends on the degree of accumulated SOC losses, the total SOC increase by 2080 is 190 and 500 Mt C, respectively. There are, however, substantial variations between different regions and individual landscapes. For example, while the average landscape in the high estimate scenario achieves an increase in SOC (by 2080) of 5.1 t ha^{-1}, the 20th percentile is 2.2 and the 80th percentile is 6.3 t ha^{-1}.

In the high estimate scenario, the total average annual SOC sequestration by 2050 amounts to 12.1 Mt C y^{-1} relative to BAU; in the low, it amounts to 4.7 Mt C y^{-1}. This is equivalent to 4.0-10.3% of the total current GHG emissions from agriculture in EU27+UK(24). Comparing with 2020 levels instead of BAU results in slightly higher values. The combined GHG savings from increases in SOC and from decreases in fossil fuels due to an increased use of biogas amount 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 are estimated relative to BAU or 2020 levels, see Table 1.

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 modeled SOC increase takes place in France, Romania, Poland, Denmark, Italy, Spain, Hungary, and Bulgaria (Figure 1 and Supplementary Table 7-9).

Co-benefits

The other relevant environmental problems differ in magnitude across Europe (Supplementary Figure 1; see also previous work (16, 18)). For example, nitrogen emissions to water are high in the northwest and central parts of Europe. Water erosion is primarily a problem in the southern and central parts. Wind erosion is primarily a problem in coastal areas in northern and eastern Europe, and recurring floods are problematic all over Europe, mainly around major rivers. While all these problems could theoretically be mitigated by growing more grass, the mitigation potential is, naturally, determined by the location and magnitude of the problem (Figure 2).

In the low estimate scenario, nitrogen emissions to water decrease by a total of 119 kt N y^{-1}; in the high estimate scenario, the figure is 324 kt N y^{-1} (Table 1). In the low estimate scenario, grass rotations contribute 34% of the reduction necessary to reduce the impact level down to a "low" level, in the median landscape. In the high estimate scenario, the same contribution surpasses 100%.

A substantial mitigation potential is also seen for soil loss by water erosion, which is reduced by 37 and 95 Mt annually in the low and high estimate scenarios, respectively (Table 1). For the median landscape, this translates into 33% of the reduction necessary to reach the "low" impact level in the low estimate scenario, and 85% in the high estimate scenario.

Soil loss by wind erosion is generally a smaller 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). For the median landscape, this corresponds to 48% of the reduction necessary to reach the "low" impact level in the low estimate scenario. In the high estimate scenario, the reduction surpasses 100%.

The co-benefits are thus considerable. In the high estimate scenario, no further measures are needed to reduce nitrogen emissions to water nor soil loss by wind erosion in most landscapes where grass production is included in annual crop rotations. In addition to the co-benefits described above, there are multiple other co-benefits that are possible, and even likely, that have not been quantified, such as a reduced need for pesticides. Furthermore, mitigated flooding events have not been modeled explicitly, but an indicative assessment shows that the likelihood of mitigated flooding events is classified as "medium" in 12% of the landscapes where grass is included in the rotation, "high" in 13%, and "very high" in 3% (Figure 3). Potential additional co-benefits thus need to be better understood and quantified to get a more complete picture of the positive effects of large-scale deployment of grass production in crop rotations.

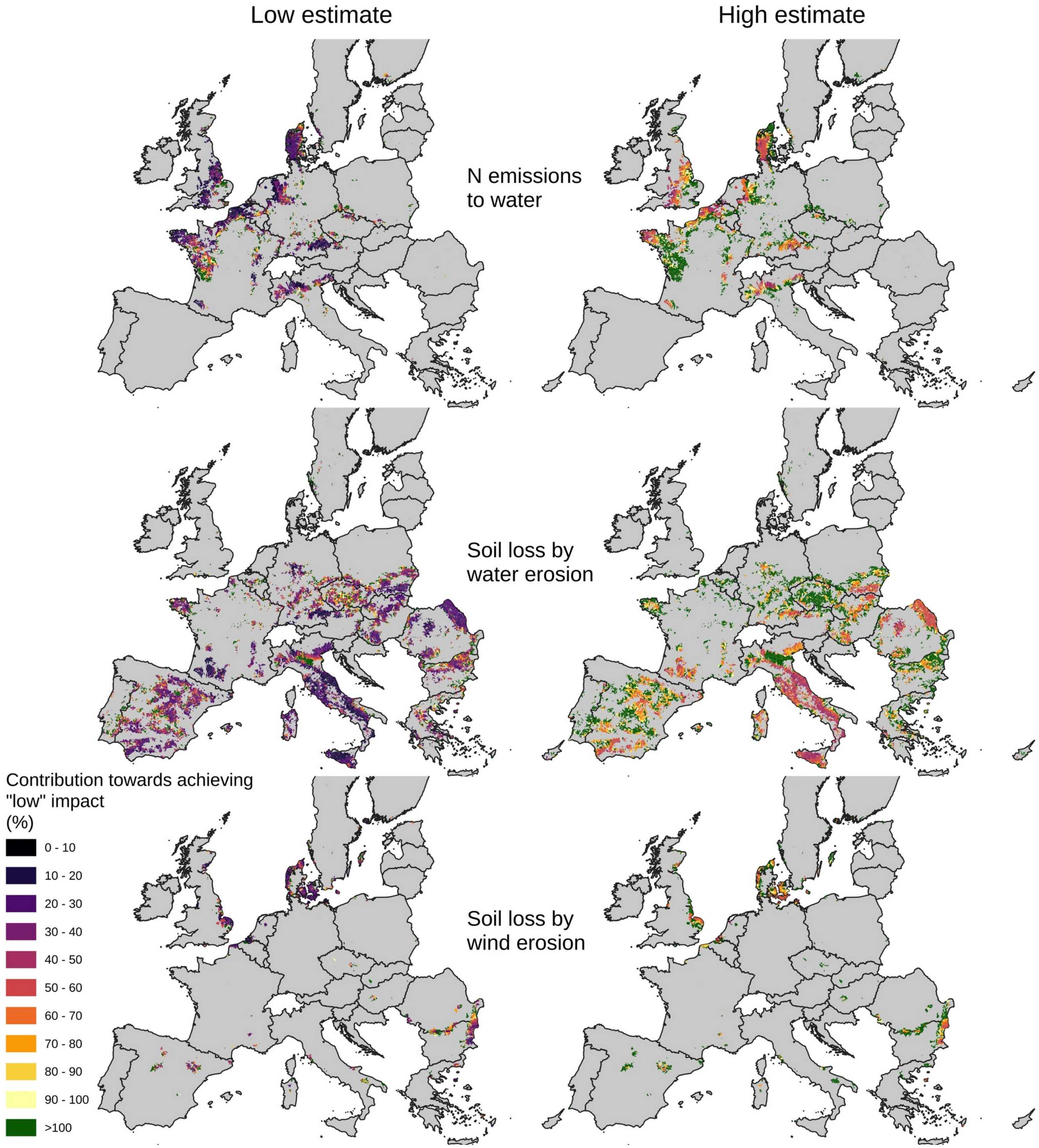

Figure 2: Co-benefits of introducing grass production in crop rotations with the primary objective of enhancing soil organic carbon. The figure shows the relative contribution toward reaching the classification "low impact" at the landscape scale for nitrogen emissions to water, soil loss by water erosion,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

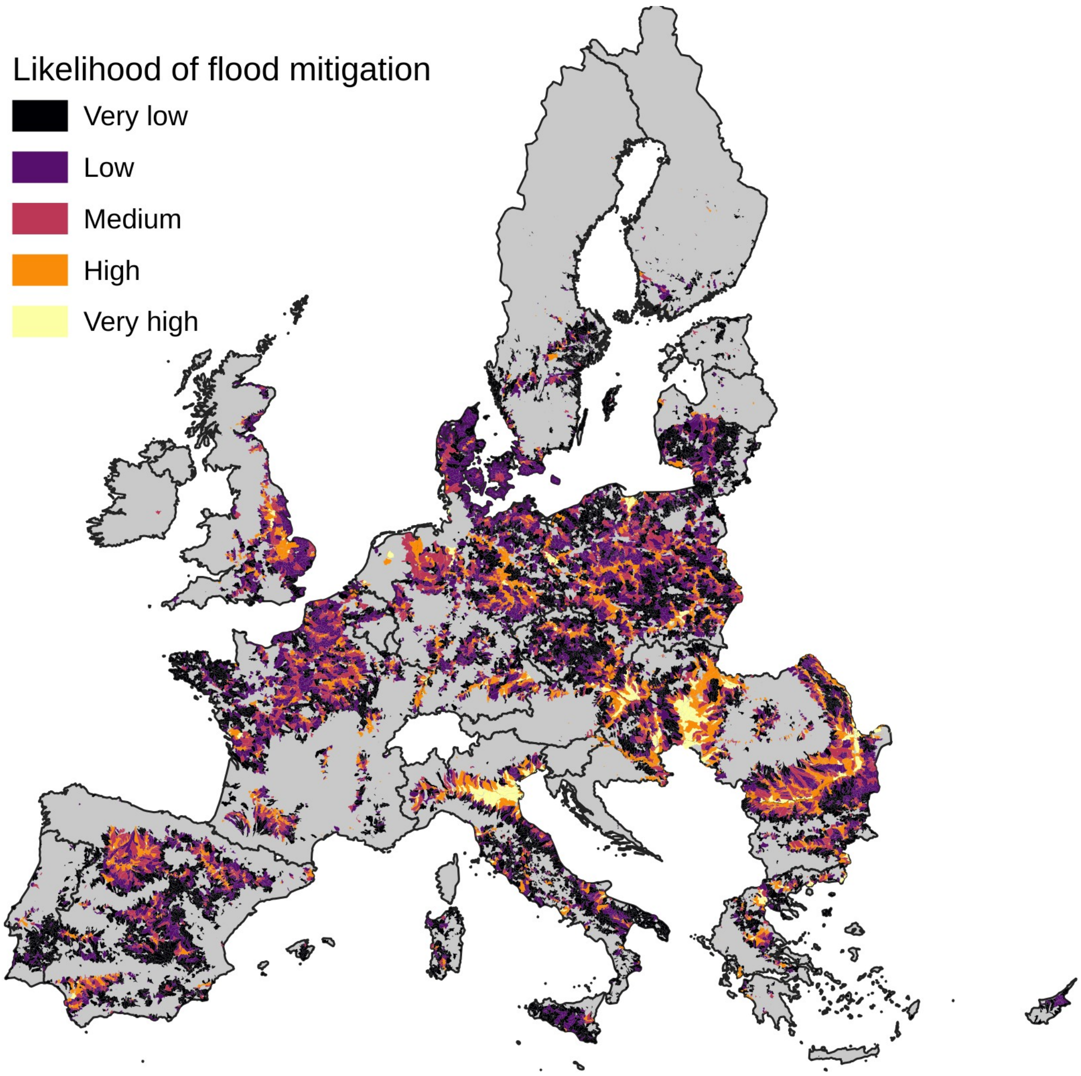

Figure 3: Likelihood of mitigated flooding events as a result of widespread deployment of grass in crop rotations. Note that this is a general indication of how problems with flooding in a landscape can be mitigated by increased cultivation of perennials, and that there is no distinction made between the different deployment scenarios.

Discussion

In line with previous research (25), we find a substantial SOC sequestration potential on European cropland when adding two to four years of grass to a four-year rotation with annual crops (for a total rotation of six to eight years) at a large scale. We also find substantial environmental co-benefits, including reduced wind and water erosion and reduced nitrogen emissions to water. Our results also indicate the possible mitigation of flooding events.

The combined GHG savings from increases in SOC and from decreases in fossil fuel use due to an increased use of biogas amount to 13-48% of current GHG emissions from agriculture in Europe. This estimate does not consider potential increases in N_2O emissions due to incorporation of residues in soil, which depend on how the biomass is treated. If harvested and removed (e.g., as feedstock to biorefineries and/or anaerobic digesters), a small amount of above-ground residues are left in the field, and only below-ground residues, i.e., nitrogen in root systems, will contribute to N_2O emissions (26). Recent research indicates that these effects are negligible, primarily due to reduced fertilizer needs (27). Furthermore, crops that offer cover during a longer time period (as with grass cultivation for more than a single year) increase surface albedo compared with bare soil and thus reduce albedo-driven radiative forcing. This can provide additional, more immediate, climate benefits (27).

Grass/legume species are commonly included in crop rotations in mixed farming systems in cold or humid climate (7), thus primarily in northern Europe. To validate modeled 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 five-year rotation with cereals and root crops was changed into a rotation with three years of grass and two years of cereal crops (i.e., a 60% share of grass 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 (28). Börjesson et. al (29) report long-term field measurements for two sites in southern Sweden with different climate and soil characteristics. Here, a four-year rotation with cereals was changed into a mixed rotation with three years of grass and one year of cereals around 1980. After 35 years, significant increases in SOC concentrations and stocks were found in the grass-dominated rotations compared with cereal monoculture, 0.36-0.59 tC ha^{-1} yr^{-1} (topsoil, 0–20 cm). The results reported in the current study appear to be conservative compared with these field trials. The results also illustrate that SOC sequestration increases with the share of grass in the total crop rotation (7, 30) and confirm that SOC sequestration tends to be greater in the years following deployment, then declining toward a new equilibrium level as the carbon sink saturates (31).

Biodiversity is rapidly declining (32). One important cause is the extensive use of insecticides and fungicides, which consistently have negative effects on biodiversity and on the potential for biological pest control (33). Grass production in crop rotations has a very low (or zero) need for pesticides, especially fungicides and insecticides (34). Including grass in crop rotations with annual crops would thus reduce the overall need for pesticides and consequently reduce impacts on biodiversity from agriculture (35). Increased crop diversity is also an important measure to increase biodiversity at the landscape level (36).

The introduction of grass/legume species into annual crop rotations reduces the harvested area of cereal crops. This cropland displacement may counteract environmental benefits, including reduced pesticide use, by causing cropland intensification or expansion elsewhere. However, this effect can to some extent be counterbalanced. 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 (37). Wheat yields preceded by a break crop have been shown to increase from 0.5 t ha^{-1} (pre-crop: oats) to 1.2 t ha^{-1} (pre-crop: grain legumes) compared to when preceded by wheat (38), corresponding to 12-29% of the average wheat yields in 2020. The effect in the second wheat harvest after a break crop corresponds to 20-60% of that in the first year (38). As with SOC sequestration rates, confirming overall rotation effects on yields requires data from long-term agricultural field trials. In an analysis from seven such trials across Europe with consecutive yield data for time periods ranging 20-55 years, Marini et al. (39) show that diversified crop rotations including two to three years of grass/legumes in overall six- to seven-year rotations provided higher yields for both winter and spring cereals (on average +0.86 and +0.39 t ha^{-1} yr^{-1}, respectively), compared with a continuous monoculture of cereals. The yield gains were higher, up to around 1 t ha^{-1} yr^{-1}, in years with high temperatures and limited precipitation (39). Diversifying crop rotations thus appears to be an interesting adaptation measure under a changing climate. Angus et al. (38) estimate that at the 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) dominate among crops on arable land, but estimates of the potential yield increases from diversified crop rotations are lacking. Such yield effects are important to consider when assessing the 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.

The food/feed crop displacement effect is further reduced when grass biomass is used in biorefineries that can produce food and feed along with bioenergy and other biobased products (21, 40, 41). For example, lactic acid bacteria can facilitate the use of grass biomass for production of a protein concentrate, suitable for feeding monogastric animals as well as ruminants, with multiple co-products (22). Trials in Denmark show that grass protein with a high protein content (47% DM) can substitute for soymeal in pig feed without any adverse effects on animal performance or meat quality (42). Such solutions using alternatives to high-input and high-emission annual grain and seed crops as feedstock can enable sustainable intensification of agricultural systems with reduced environmental impacts (23). To illustrate, grass production on one hectare of cropland in the EU (assuming 10 t DM annual yield) can support protein concentrate production in a biorefinery equivalent to soy meal from 0.8 hectare of soybean cultivation in the 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 by 60-80%. Higher crop yields from improved soil fertility would reduce the effect even further. When factoring in other biorefinery outputs, such as biogas and biobased products, deploying grass in crop rotations even result in net cropland savings in some regions. However, the effects depend on many factors and transcend regions as well as continents. Complementary studies, such as integrated assessment modeling, can provide important insights about land-use consequences of widespread deployment of grass cultivation via changes in existing crop rotations.

Beyond mitigation of cropland displacement, protein feed production in Europe can substitute for 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 (43). Since this import is associated with substantial environmental concerns (deforestation, biodiversity loss, extensive pesticide use, etc.), the motives for developing a substitute source of feed protein are strong (42). 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 (2). Furthermore, the increased target goal in the recent proposal for a revision of the EU Renewable Energy Directive (44), 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 (44) 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.

A prerequisite for widespread deployment of grasses in crop rotations is a demand for products that can be produced from the grass biomass (17), although some farmers may consider soil quality improvements sufficient motivation. 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 (17). Such payment schemes require reliable methods for quantifying environmental effects with high detail, within individual landscapes.

Finally, 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). This is 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 (45). Spatial modeling, such as in this study, can provide complementary information about biomass cultivation systems, including their output in terms of provisioning, maintaining, and cultural ecosystem services. Spatial modeling can support assessment of multiple environmental effects from different land-use scenarios over a large geographic area while quantifying effects at different aggregation levels and providing spatially explicit details at multiple scales. However, a large geographic area typically comes with a loss of precision, as local conditions cannot be fully considered. Understanding how to optimize conditions for biodiversity and multiple ecosystem services will require more attention to more detailed landscape-level analyses (16, 46, 47).

Methods

We constructed a model to identify sub-watersheds ("landscapes") where the introduction of grass into crop rotations with annual crops could increase SOC. We designed three grass rotation options to include in the model and two scenarios (a high and a low estimate) for large-scale deployment using combinations of these rotations, with separate sets of conditions for the implementation of the two scenarios depending on the current accumulated SOC losses in the landscape. For each alternative and scenario, the model calculates the total area under grass production in each landscape and the corresponding grass biomass production, in terms of dry matter, energy (J), and protein (metric tons of extractable crude and true protein, respectively). Furthermore, the model estimates the corresponding SOC increases by 2030, 2050, and 2080, both relative to 2020 and relative to 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 that do not incentivize implementation. These include (i) avoided soil loss by water, (ii) avoided wind erosion, (iii) avoided nitrogen emissions to water, and (iv) mitigated flooding events.

The analysis and aggregation unit is equivalent to sub-catchment or sub-watershed and is also referred to here as a "landscape". A previously published pan-European dataset containing >81,000 polygons (16), based on functional elementary catchments from the ECRINS database (48), was used. For each landscape, we have previously estimated, e.g., the area under annual crop production, degree of current environmental impact (nitrogen emissions to water, soil loss by water erosion and by wind erosion, recurring floods, and accumulated losses of SOC), and the estimated effectiveness of strategic perennialization in mitigating these impacts, in general terms (16).

The term "landscape" is here defined as an intermediate integration level between the field and the physiographic region (49). The use of the term is considered appropriate since the anthropogenic processes (agricultural land use) within a sub-watershed, combined with hydrological processes that are constrained by a sub-watershed, determine (changes in) nutrient, water, and mass flows (18). Using the term landscape also clarifies that implementation and impact mitigation are enabled by measures taken by multiple stakeholders at a greater scale than the individual field, thus applying a "landscape perspective" (50).

All GIS operations, including all database aggregation queries, were done in GRASS GIS (51) with projection EPSG:3035. All modeling, apart from input data preparation, was conducted using a Python script with a GUI that facilitates execution of selected modules. Cartography was done in QGIS (52).

Grass production in crop rotation systems and scenarios for widespread deployment

The model first selects landscapes where the effectiveness of strategic perennialization has been classified as "medium" or higher (16), based on accumulated losses of SOC in combination with the density of annual crops (Supplementary Figure 2). For each landscape, the model then makes calculations for three management alternatives where grass is included in crop rotations with annual crops and two scenarios for "widespread deployment". The management alternatives are:

- **2/6-grass**: Two years of grass added to a four-year rotation of the most dominant crops in the region.
- **3/7-grass**: Three years of grass added to a four-year rotation of the most dominant crops in the region.
- **4/8-grass**: Four years of grass added to a four-year rotation of the most dominant crops in the region.

We constructed two scenarios for widespread deployment, where the introduction of grass in crop rotations is conditioned by the degree of accumulated SOC losses in each landscape:

- **Low estimate:** The 2/6-grass system is implemented on all fields currently under annual crop production where the accumulated SOC loss is classified as "very high,", on 50% of all fields where it is "high," and on 25% of all fields where it is classified as "medium."
- **High estimate**: The 2/4-grass system is implemented on all fields currently under annual crop production where the impact is classified as "medium," the 3/7-grass system is implemented where it is "high," and the 4/8-grass system is implemented where it is classified as "very high."

Grassland area and corresponding biomass and protein production

For the three production systems and two deployment scenarios, the average area under grass production in each landscape was calculated as the product of annual crop area (16) and the share of grass relative to annual crops over time in the different systems, i.e., 1/3 for the 2/6-grass system, 3/7 for the 3/7-grass system, and 4/8 for the 4/8-grass system. The area was then multiplied by 25% and 50%, respectively, to calculate the areas under 25% and 50% implementation, for the low estimate scenario.

Having calculated the areas, the corresponding biomass production was estimated for each landscape by multiplying the area under grass production with simulated grass yields from a pan-European dataset at NUTS3 level (53). 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 subsequent yields (54). Yields for the different systems were thus adjusted as follows. Yields are expressed as t DM ha y^{-1} and are visualized in Supplementary Figure 2.

- $2/6\text{-grass}_{yield} = (0.5 + 1) / 2 * \text{yield}_{avg}$
- $3/7\text{-grass}_{yield} = (0.5 + 2) / 3 * \text{yield}_{avg}$
- $4/8\text{-grass}_{yield} = (0.5 + 3) / 4 * \text{yield}_{avg}$

The energy output was calculated as the product of biomass production and energy content of the harvested biomass, estimated at 18.7 MJ/kg DM (18, 55).

Crude protein yield was calculated by multiplying DM yield with the average concentration (g kg^{-1} DM) of crude protein (i.e., the sum of average fractions A, B_1, B_2, and B_3, see reference) in seven lucerne harvests during field experiments (56). True protein was similarly calculated by multiplying DM yield with the average concentration of true protein (i.e., the sum of average fractions B_1, B_2, and B_3) based on the same source.

Biogas production and GHG savings from fossil fuel substitution

Greenhouse gas (GHG) emissions from biogas production based on biomass from grass production in crop rotations have been estimated at 33 and 30 g CO_2eq MJ^{-1} biogas, with and without upgrading the biogas to natural gas quality, respectively (57). The estimates were based on the methodology in the EU RED (3, 58) but exclude changes in soil carbon content from grass cultivation and credit for feed output. When upgraded biogas replaces petrol or diesel as transportation fuel in vehicles, the GHG savings are about 61 g CO_2eq MJ^{-1} biogas (a 65% reduction). The reference-fuel lifecycle GHG emissions for petrol and diesel are 94 g CO_2eq MJ^{-1} (3). When biogas (not upgraded) replaces natural gas for electricity production, GHG savings are about 38 g CO_2eq MJ^{-1} biogas (a 56% reduction), using reference lifecycle GHG emissions from natural gas of 68 g CO_2eq MJ^{-1} (59). The average methane yield per metric ton DM grass-based feedstock (57) is 9.2 GJ. Thus, the GHG savings are approximately 560 and 350 kg CO_2eq 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 are based on previous SOC simulations of multiple agricultural management practices (25). The input data are available for download at the Joint Research Centre European Soil Data Centre (ESDAC; https://esdac.jrc.ec.europa.eu/). The SOC simulation output data are spatially explicit and provide SOC estimates (t C ha $^{-1}$) for 2010, 2020, 2050, 2080, and 2100, for a business-as usual scenario (BAU) assuming a continued rotation with the four most dominant crops in each area. They also provide SOC values in relation to BAU for multiple management options, including a grass/annual crop rotation system in which two years of lucerne are added to the four-year BAU rotation. These simulations data were here used as a basis for calculating SOC effects from the different management options and, consequently, the deployment scenarios, as detailed in Supplementary Information. Simulation data for a permanent grassland system, in which the BAU rotation is replaced by permanent grassland, are also available. These are here used to assess how SOC increases from the modelled grass/cereal rotations relate to the, assumed, theoretical maximum.

The simulated SOC values were rasterized to match other input data (100 m) and aggregated SOC values were calculated for each landscape by calculating median SOC values. As detailed in Supplementary Information, the following information was then calculated for each landscape, management system alternative, and deployment scenario, for 2050, 2080, and 2100, relative to SOC values in 2020 and relative to BAU:

- SOC change per hectare (t C ha^{-1})
- Total SOC (t C)
- Relative SOC change (%)
- SOC change relative to current GHG emissions from agriculture (24).

Environmental co-benefits

Three co-benefits were modeled for each landscape: avoided (i) soil loss by water erosion, (ii) soil loss by wind erosion, and (iii) nitrogen emissions to water. In addition, we indicate potential (iv) mitigated flooding events. Impact i-iv was quantified for each landscape:

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, see above), based on the application of a modified version of the Revised Universal Soil Loss Equation (RUSLE) model (59). 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) (60) of the Revised Wind Erosion Equation (RWEQ) model (61).
3. Nitrogen emissions to water, indicated by "annual average diffuse nitrogen emissions to water", were retrieved by running v2 of the Geospatial Regression Equation for European Nutrient losses (GREEN) model (62) 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 (63). 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 classified on a five-step scale from "very low" to "very high". For more details on methods, thresholds, and underlying data, see previous work (16). For impacts 1 and 2, we assumed that the impact is negligible on grassland (64). 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 the current impact and the share of grassland relative to the current area under annual crops, for the five system designs and the two deployment scenarios. For impact 3, we assumed that nitrogen emissions to water from grass production are 75% lower than current nitrogen emissions to water. This assumption is based on field experiments showing that perennial grasses reduce nitrogen leaching by 70-80% compared to traditional systems (65). The potential impact mitigation is then calculated in each landscape as the product of current impact, the share of grassland relative to the current annual crop area, and the mitigation factor of 0.75, for the five system designs and the two deployment scenarios. We also estimated to what extent introducing grass production in crop rotations could contribute to reducing impacts 1-3 to a "low" impact level. This was calculated as the quotient of potential impact mitigation by the difference between the upper threshold of the class "low impact" (16) 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 intensively managed agricultural landscapes can mitigate flooding events (66). However, the magnitude of this benefit depends on landscape-specific characteristics and can thus not be generalized in the same way as for the other impacts. We instead attempted to indicate the likelihood of mitigating flooding events as a result of increased grass production in the landscape (18). This was done by assuming that the likelihood is directly correlated with the estimated effectiveness of strategic perennialization in mitigating recurring floods (16). 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 grass into crop rotations with annual crops.

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 (16, 18). Different thresholds would thus yield different results. General spatial patterns would, however, be similar (16). The use of average simulated yields for miscanthus, switchgrass, and reed canary grass to estimate grass yields, is justified by the lack of spatially explicit pan-European yield data for grass/clover species that are traditionally used in rotations with annual crops. Visual assessment of the simulated yields across the study area, based on in-house experience, suggests that reed canary grass yields are the most similar to traditional species, in spatial terms. In absolute numbers, however, miscanthus yields are more similar to what can be expected. 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 grass species are likely to 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 general uncertainties related to the underlying models, including co-benefits (16, 18) and SOC simulations (25). See also the Discussion section where model results are evaluated.

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Large-scale deployment of grass in crop rotations as a multifunctional soil-based climate mitigation strategy

Supplementary information

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Effects on soil organic carbon

The simulated SOC values[1] were rasterized to match other input data (100 m) and aggregated SOC values were calculated for each landscape by calculating median SOC values. In the method sequence below, the following codes apply:

- $\mathrm{SOC}_{\mathrm{bau\_[year]}}$ = SOC BAU values at specific points in time.
- $\mathrm{SOC}_{\mathrm{inc\_grass\_[year]}}$ = SOC increases relative BAU from implementation of in-rotation grass systems at specific points in time
- $\mathrm{SOC}_{\mathrm{inc\_permgrass\_[year]}}$ = SOC increases relative BAU from implementation of permanent grassland at specific points in time
- $\mathrm{SOC}_{\mathrm{inc}}$ and $\mathrm{SOC}_{\mathrm{inc[year]}}$ = collectively used below for the above two codes

$\mathrm{SOC}_{\mathrm{inc}}$ 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. $\mathrm{SOC}_{\mathrm{bau}}$ did not require re-estimation as it represents a continuation of BAU land-use. $\mathrm{SOC}_{\mathrm{bau\_2020}}$ was thus considered representative for current SOC. $\mathrm{SOC}_{\mathrm{inc}}$ values, however, needed to be re-estimated to represent a 10-year shorter time period than in the original dataset.

To reflect that SOC tends to increase more rapidly early after the introduction of a new land-use system[1], $\mathrm{SOC}_{\mathrm{inc\_2020}}$ was assumed to represent the change in SOC during the first ten years, i.e., between 2020 and 2030:

- $SOC_{inc\_first10} = SOC_{inc\_2020}$

SOC changes during the remaining period (i.e., 20, 50, and 70 years, for 2010, 2080, and 2100, respectively) was calculated by subtracting $\mathrm{SOC}_{\mathrm{inc\_first10}}$ from $\mathrm{SOC}_{\mathrm{inc\_2050|2080|2100}}$, thus representing SOC changes in 30|60|80 years following the first 10 years:

- $SOC_{inc\_last30|60|80} = SOC_{inc\_\ 2050|2080|2100} - SOC_{inc\_first10}$

Since SOC changes in 20/50/70 years are required, these values were downscaled by 2/3, 5/6, and 7/8, respectively:

- $\mathrm{SOC}_{\mathrm{inc\_last20|50|70}} = SOC_{inc\_last30|60|80} * 2/3 \mid 5/6 \mid 7/8$

Finally, SOC increases by 2050 | 2080 | 2100 relative BAU could be calculated as:

- $SOC_{inc\_2050|2080|2100} = SOC_{inc\_first10} + SOC_{inc\_last20|50|70}$

These re-estimated SOC values are below referred to as $\mathrm{SOC}_{\mathrm{inc\_grass|permgrass\_new\_[year]}}$, or collectively as $\mathrm{SOC}_{\mathrm{inc\_new\_[year]}}$.

At this point, SOC changes by 2050|2080|2100 relative BAU (t C ha^{-1}), with base year 2020, has been identified for the 2/6-grass system. 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 relative the 2/6-grass system, on average over time. This approach was selected based on discussions with the developer of the underlying SOC dataset:

$SOC_{inc\_BAU\_2y\_lim50|lim\_25} = SOC_{inc\_BAU\_2y} * 0.5|0.25$

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[1] Lugato, E., Bampa, F., Panagos, P., Montanarella, L. & Jones, A. Potential carbon sequestration of European arable soils estimated by modelling a comprehensive set of management practices. *Global Change Biology* **20**, 3557–3567 (2014).

$SOC_{inc\_BAU\_3y|4y} = SOC_{inc\_BAU\_2y} * 9/7|3/2$

Total SOC changes (t C) were then calculated for each management alternative and in each landscape:

$SOC_{inc\_total} = SOC_{inc} * area_{annual\ crops}$

Finally, the relative SOC changes (%) were calculated for the different assessment years, e.g.:

$\mathrm{SOC}_{\mathrm{diff\_2y\_2050}} = (\mathrm{SOC}_{\mathrm{bau\_2050}} + \mathrm{SOC}_{\mathrm{inc\_2y\_2050}} / \mathrm{SOC}_{\mathrm{bau\_2050}}) - 1$

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.:

$\mathrm{SOCinc}_{\mathrm{\_2020\_3y\_2080}} = \mathrm{SOC}_{\mathrm{inc\_BAU\_3y\_2080}} + (\mathrm{SOC}_{\mathrm{bau\_2080}} - \mathrm{SOC}_{\mathrm{bau\_2020}})$.

The latter two were calculated as described above. Finally, absolute SOC values for all assessment years and ley systems were calculated, e.g. for the 2/6-grass system by 2050:

$\mathrm{SOC}_{\mathrm{total\_2050}} = \mathrm{SOC}_{\mathrm{bau\_2020}} + \mathrm{SOC}_{\mathrm{inc\_2020\_2y\_2050}}$

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 in-rotation grass systems and in permanent grasslands, respectively, e.g.:

$\mathrm{SOC}_{\mathrm{inc\_share\_potential\_2y\_2050}} = \mathrm{SOC}_{\mathrm{inc\_2020\_2y\_2050}} / \mathrm{SOC}_{\mathrm{inc\_2020\_permgrass\_2050}}$

Finally, annual C sequestration relative total GHG emissions from agriculture[2] (%) was estimated, e.g.:

$\mathrm{C\_seq}_{\mathrm{total\_2y\_2050\_relBAU}} = (\mathrm{SOC}_{\mathrm{inc\_total\_2y\_2050}} / 30) / \mathrm{GHG\_emissions}_{\mathrm{current}}$

$\mathrm{C\_seq}_{\mathrm{total\_2y\_2050\_rel2020}} = (\mathrm{SOC}_{\mathrm{inc\_total\_2020\_2y\_2050}} / 30) / \mathrm{GHG\_emissions}_{\mathrm{current}}$

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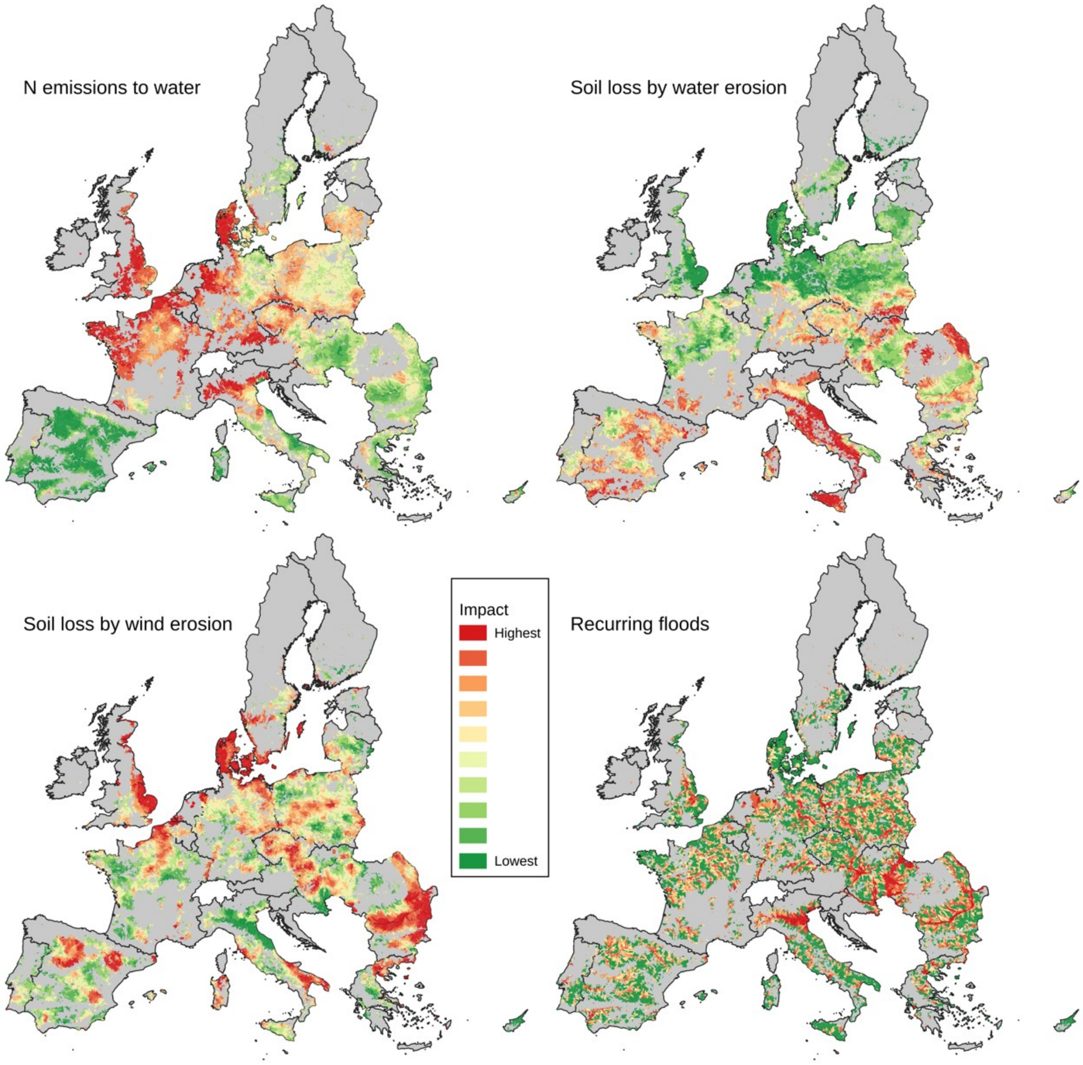
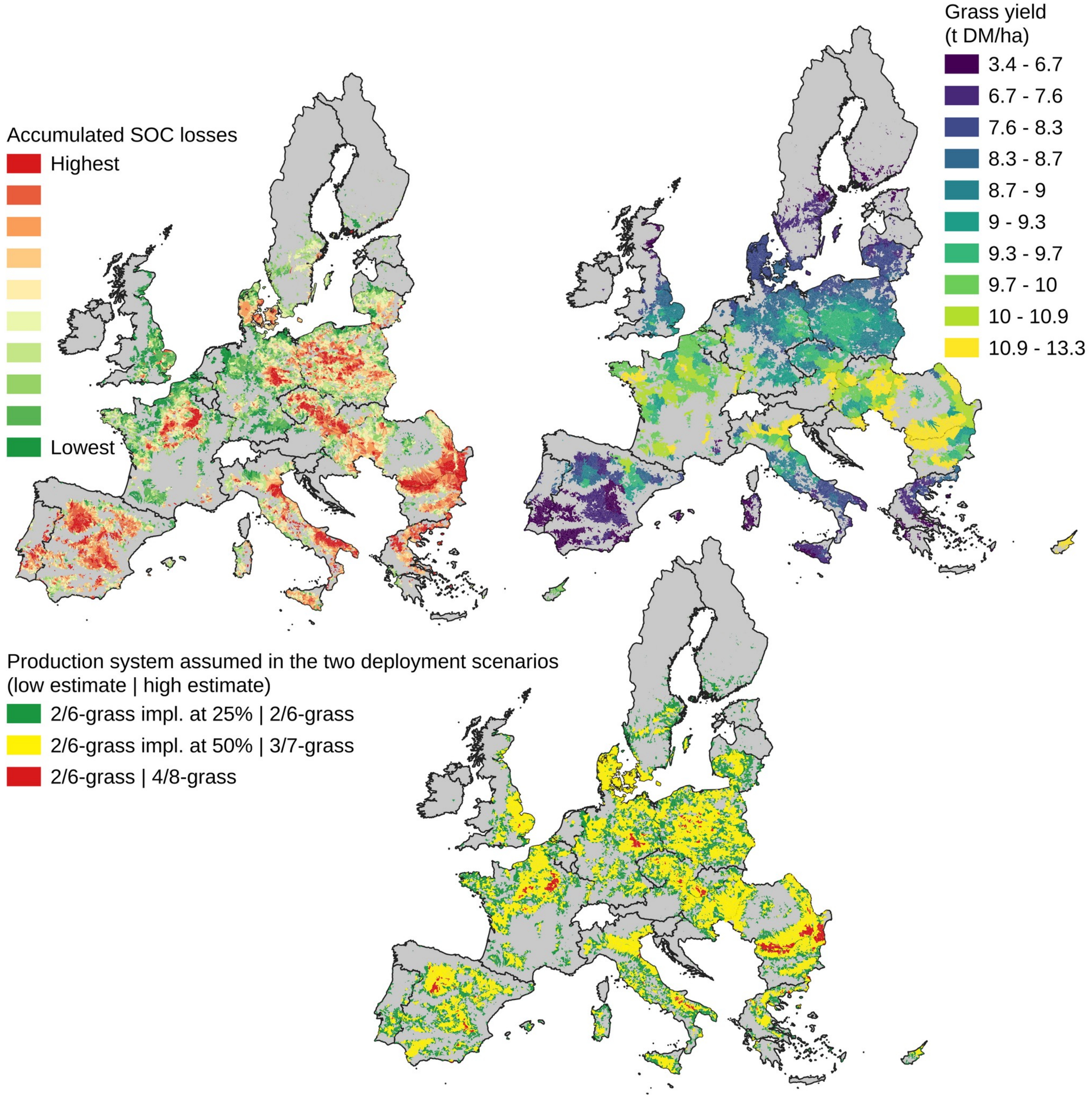
[2] EEA. *Greenhouse gas emissions by source sector*. https://appsso.eurostat.ec.europa.eu/nui/submitViewTableAction.do (2021).

Supplementary figures



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 implemented in the two deployment scenarios (bottom), based on estimated effectiveness to remediate accumulated SOC losses.

Supplementary tables

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

Case yr grass/yr total rotation (share grass)	**Area of arable land with grass in crop rotations (Mha)**	**Average annual SOC sequestration rate in mixed rotations (tC ha^{-1} yr^{-1})**	
		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 grass 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 grass 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**

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**