Beneficial land use change: Strategic expansion of new biomass plantations can reduce environmental impacts from EU agriculture

Oskar Englund*[a,b], Pål Börjesson[c], Göran Berndes[a], Nicolae Scarlat[d], Jean-Francois Dallemand[d], Bruna Grizzetti[d], Ioannis Dimitriou[e], Blas Mola-Yudego[e,f], Fernando Fahl[d]

[a] Div. of Physical Resource Theory, Dept. of Space, Earth and Environment, Chalmers University of Technology, Sweden
[b] Englund GeoLab, Dept. of Ecotechnology and Sustainable Building Engineering, Mid Sweden University, Östersund, Sweden
[c] Div. of Environmental and Energy Systems Studies, Dept. of Technology and Society, Lund University, Lund, Sweden
[d] European Commission. Joint Research Centre (JRC), Ispra, Italy
[e] Dept. of Crop Production Ecology, Swedish University of Agricultural Sciences, Uppsala, Sweden
[f] University of Eastern Finland, Joensuu, Finland

* Corresponding author: englund@geolab.bio

Keywords: Land use, LULUCF, CAP, biomass, environmental impacts, perennial crops, spatial planning

Abstract

Society faces the double challenge of addressing negative impacts of current land use, while increasing biomass production to meet the future demands for food, materials and bioenergy. Potential impacts of increasing the biomass supply are subject to debate. In the discourse, land use change (LUC) has often been considered as negative, referring to impacts of deforestation and cropland expansion. At the same time, LUC is considered necessary for mitigating impacts of existing land use. Strategic establishment of suitable crop cultivation systems in agricultural landscapes can mitigate environmental impacts of current crop production, while providing biomass for the bioeconomy. Here, we explore the potential for such "beneficial LUC" in EU28, based on high-resolution land use modeling. First, we map and quantify the degree of accumulated soil organic carbon losses, wind and water erosion, nitrogen emissions to water, and recurring flooding, in ~81.000 individual sub-watersheds in EU28. We then estimate the effectiveness in mitigating these impacts through establishment of perennial plants, in each sub-watershed. Finally, we identify areas where perennialization may be particularly beneficial from an environmental point of view. The results indicate that there is a substantial potential for effective mitigation, regarding all the assessed impacts. Depending on criteria selection, some 10-46% of the land used for annual crop production in EU28 is located in landscapes that could be considered priority areas for beneficial LUC. While some recent policy development is favorable for promoting beneficial LUC, the effectiveness could be increased by seeking synergies between climate change mitigation, energy security, and other societal goals. One way forward can be to identify and promote options for biomass production in the context of SDG implementation.

1 Introduction

The exploitation of fossil fuels has been a powerful driver of societal development in the twentieth century, and the relative dependency on biomass has declined. The food sector has undergone large changes: most of our food still comes from agriculture, but often produced in an intensive manner, relying on fossil fuels and petroleum-based chemicals. The access to fossil fuels and the intensification of agriculture have limited the need for expanding agriculture land. Nevertheless, biomass resources are of major significance for the economy in many countries. The demand for land and biomass is expected to increase, as a growing and wealthier global population requires more food, paper, construction wood, etc. Additional biomass demand arises as countries, organizations and companies adopt policies, regulations and strategies aligned with visions about a biobased circular economy, formulated in response to concerns about resource scarcity and impacts associated with the use of fossil fuels and other non-renewable resources – not the least climate change.

However, much of current environmental impacts are caused by the intensified land use and the use of fossil resources. Human societies have put almost half of the world's land surface to their service, and have caused extensive land degradation and loss of biodiversity worldwide. As we manage landscapes and associated ecosystems for the production of biomass, we often alter their capacity to support other ecosystem services (ES) that are essential for human well-being [1]. Many ecosystems are currently being degraded or used unsustainably, jeopardizing their capacity to support multiple ES over time [2]. The cultivation of annual crops is an important example; nutrient and agrochemical runoff to water bodies, soil carbon losses, and erosion can cause impacts such as eutrophication, climate change and soil degradation unless there is sufficient ES supplies for regulating these stressors (i.e., nutrient retention, soil carbon sequestration and regulation of mass flows).

Society thus faces the double challenge of addressing negative impacts of current land use, while increasing biomass production to meet the future demands for food, materials and bioenergy. Implications of an increased biomass supply have been debated for many decades, primarily focusing on bioenergy, with key issues being land use impacts and uncertain climate benefits [1,3-7]. One example is the debate and research activity following the biomass intensive scenario (LESS) in the Second Assessment Report of IPCC. More recently, a similar debate has arisen following IPCC AR5 [8] and IPCC SR1.5 [9], in which bioenergy with carbon capture and storage is relied upon in most of the considered scenarios where the mean temperature increase is limited to 1.5 °C or 2 °C above the pre-industrial level. In relation to the IPCC AR6 cycle, Smith and Porter [10] identify key emerging issues to be (i) trade-offs between the use of land for bioenergy production, food and fibre production, and conservation of ecosystem integrity and (ii) the codelivery of bioenergy based climate change mitigation (with or without carbon capture and storage) and the UN Sustainable Development Goals (SDGs).

In the discourse, land use change (LUC) has often been considered as negative, referring to environmental and socio-economic impacts of deforestation and cropland expansion on previously uncultivated land, e.g., habitat loss, greenhouse gas (GHG) emissions, soil degradation, water pollution, etc. There is however a growing body of literature that investigates opportunities for achieving “beneficial LUC”, where a strategic integration of perennial plants (“perennials”) into agricultural landscapes enhances, e.g., landscape diversity, habitat quality, retention of nutrients and sediment, erosion control, climate regulation, pollination, pest and disease control, and flood regulation. Such LUC can thereby mitigate environmental impacts from intensive agriculture [11-17]. Perennial grasses (e.g. Miscanthus, reed canary grass, switchgrass) as well as woody plants (e.g., short-rotation coppice willow or poplar) can be used for such purposes. There is significant experience of this type of biomass supply systems from both practical field trials and commercial applications [17-27]. As many of the SDGs are closely linked to land use, the identification and promotion of beneficial LUC can support a growing use of bioenergy and other bio-based products while advancing several SDGs, e.g., SDG2 “Zero hunger”, SDG6 “Clean water and sanitation”, SDG7 “Affordable and Clean Energy” and SDG15 “Life on Land”.

Most earlier studies of beneficial LUC are conceptual or adopts a limited geographical scope. Few have investigated the possible extent and spatial distribution at larger scales. This article presents the first attempt to explore the potential for beneficial LUC across EU28, based on high-resolution land use modeling. We identify and quantify:

(1) The degree of selected environmental impacts associated with agriculture (soil loss by wind and water erosion, nitrogen emissions to water, accumulated loss of soil organic carbon (SOC), and recurring floods) in each of the ~81 000 sub-watersheds (from here on referred to as “landscapes”) in EU28

(2) The extent to which strategic introduction of perennials in landscapes (from here on referred to as “perennialization”) may mitigate these impacts

(3) Agricultural areas where perennialization may be particularly beneficial from an environmental point of view.

Finally, we discuss policy implications for realizing beneficial LUC on a large scale in EU28.

2 Material and Methods

2.1 Spatial analysis unit

The spatial analysis unit for the assessment is equivalent to functional elementary catchments (FECs) from the ECRINS database [28], modified as specified below. FEC is equivalent to sub-watershed. This unit was selected based on the importance of hydrological processes, constrained by a watershed, in determining how nutrient and sediment retention and the control of water and mass flows can be affected by a change in land use. It was also considered an appropriate size for identifying where local measures to mitigate negative environmental impacts can be introduced.

Throughout this article, the analysis units are also referred to as *landscapes*. While there are varying meanings of the term landscape, it is here defined as an intermediate integration level between the field and the physiographic region [29,30], with an extent depending on the spatial range of the biophysical and anthropogenic processes driving the processes under study [31]. A thorough discussion on the use of the terms *landscape* and *landscape scale* is provided by Englund et al. [32].

2.1.1 Data preparation

All GIS operations were made using the coordinate reference system ETRS89-LAEA Europe (EPSG:3035). The following modifications were made to the original FEC dataset[1]:

1. All FECs outside of EU-28 + Norway + Switzerland were deleted. This resulted in a total of 81301 features.
2. Due to methodological issues in the production of the original FEC dataset [28], several FECs consists of more than one polygon (i.e., the dataset is “multipart”). Since one landscape cannot consist of several polygons, the dataset was converted into “single part” by splitting multipart FECs into multiple individual landscapes. This increased the number of features to 95086.
3. Original FECs enveloped waterbodies. It was considered more appropriate to consider landscapes as land units. Also, it was observed that large lakes were split between several different surrounding FECs, which is unrealistic. To resolve this, a lake dataset from the ECRINS project [28] was used to exclude all lakes from the landscape dataset. This increased the number of features to 115804.
4. In the construction of the original FEC dataset, many very small polygons were created, e.g., in FEC intersections. At the time, the complexity of correcting this was considered to outweigh the benefit [28]. An effort was therefore made here to delete polygons that could be considered noise, to decrease computation time and to avoid unrealistic quantifications. This was done by deleting all 26560 features smaller than 5 ha (of which 12366 features < 1 ha, 10988 = 1 ha, 1729 = 2 ha, 922 = 3 ha, and 575 = 4 ha). The threshold of 5 ha was determined based on visual inspection of randomly selected features of different sizes. This operation may have resulted in the removal of a few actual landscapes, e.g., very small islands, from the dataset, but that would have no measurable negative effect on the results. This decreased the number of features to 89244.

---

[1] In the below description, “FEC” refers to features in the original dataset while “landscape” refers to features in the resulting dataset.

5. Finally, all landscapes in Norway (6645) and Switzerland (1127) were deleted from the dataset, to consider only landscapes subject to CAP regulations within EU28. The remaining and final number of landscape units was then 81472.[2]

2.2 Classification of the degree of negative environmental impacts

Five environmental impacts that could be mitigated by the introduction of perennials into intensive arable landscapes were included in this assessment (Table 1). Each impact can be attributed to insufficient supply of, or degraded, ecosystem services (ES) under current agricultural practices. The relationship between ES, environmental impacts, and the spatial indicator used for impact classification is available in Table 1.

Each landscape was classified as having *very low*, *low*, *medium*, *high*, or *very high* (i) nutrient emissions to water, (ii) soil loss by water erosion, (iii) soil loss by wind erosion, (iv) recurring floods, and (v) accumulated loss in soil organic carbon (SOC). This classification was made using spatial indicators, as summarized in Table 1 and described below.

Table 1: Units and thresholds for classifying landscapes as having varying degrees of negative environmental impacts, and the corresponding ecosystem service required to mitigate the impact.

Degraded ecosystem service	**Environmental impact**	**Spatial indicator**	**Unit**	**Degree of environmental impact**				
				Very low	**Low**	**Medium**	**High**	**Very high**
Nutrient retention	Nitrogen emissions to water	Diffuse nitrogen emissions to water	kg N / ha / y (Average value for entire landscape)	≤5	(5,10]	(10,15]	(15,20]	>20
Mass flow regulation	Soil loss by water erosion	Soil loss by water erosion on land used for production of annual crops	t soil loss / ha / y (Average value on land used for production of annual crops)	0	(0,2]	(2,5]	(5,10]	>10
Mass flow regulation	Soil loss by wind erosion	As above, but for wind erosion	as above.					
Water flow regulation	Recurring floods	Share of landscape area subject to 10-year flooding	% of landscape area	0	(0,5]	(5,10]	(10,25]	>25
Soil organic matter formation and composition	Loss of soil organic carbon (SOC)	SOC saturation capacity	Ratio of current SOC divided by theoretical max SOC (Average value on land used for production of annual crops)	>0.844 + null	(0.688, 0.844]	(0.532, 0.688]	(0.376, 0.532]	≤0.376

---

[2] This was done as step 5 instead of step 1 due to an initial aim of including these countries in the assessment.

The degree of nitrogen emissions from land to rivers, including atmospheric deposition, was classified for each landscape by running version 2 of the GREEN model [33] for the landscape dataset. For each polygon, annual average diffuse nitrogen emissions to water per hectare was quantified (kgN/ha). Thresholds based on expert (i.e., data provider) advice was used to classify individual landscapes (Table 1).

The degree of soil loss from erosion by (i) water, (ii) wind, and (iii) water and wind combined, was classified for each landscape by averaging modelled annual soil loss from water [34] and wind [35] erosion, respectively, on land classified as annual crop production [36] (see Table 3) within each landscape. Thresholds were then applied based on Panagos et al. [34,37] as specified in Table 1.

The degree of recurring floods was classified for each landscape by estimating the share of total area in each landscape expected to be subject to 10-year flooding events [38] and applying thresholds as specified in Table 1.

The degree of accumulated SOC loss, i.e., current SOC relative to the theoretical potential, was identified for each landscape using the indicator "SOC saturation capacity" (expressed as the ratio between the actual and the potential SOC content at pixel level). Values close to 0 indicate a great potential of soil to store more carbon [39,40]. For each landscape, the average SOC saturation capacity on land used for annual crop production was calculated, and thresholds were applied as specified in Table 1. Based on data provider advice, the thresholds were set to define five equal intervals between the min and max aggregated average SOC saturation capacity values.

2.3 Estimating the effectiveness of mitigating negative environmental impacts by perennialization

The introduction of perennial crops for mitigating environmental impacts can only be effective in landscapes dominated by the production of annual crops, which has caused the environmental impacts by degrading the regulating ES supply. To estimate the effectiveness of perennialization, the *annual crop dominance*, i.e., the share of land in each landscape used for the production of annual crops compared with the total vegetated area, was calculated for each landscape. This was combined with the impact indicators to define four levels of expected effectiveness of perennialization, thus considering both the degree of environmental impact and the dominance of annual crops, as illustrated in Table 2.

Table 2: Expected effectiveness of perennialization in mitigating negative environmental impacts by enhancing corresponding ecosystem services. Colours indicate marginal (blue), low (purple), medium (light red), high, (orange), and very high (yellow) expected effectiveness. Colours are identical as in Fig. 1 and Fig. 2.

		Environmental impact				
		Very low	Low	Medium	High	Very high
Annual crop dominance	Very low	🟦	🟦	🟦	🟦	🟪
	Low	🟦	🟦	🟦	🟪	🟥
	Medium	🟦	🟦	🟪	🟥	🟧
	High	🟦	🟪	🟥	🟧	🟨
	Very high	🟪	🟥	🟧	🟨	🟨

The share of annual crops in each landscape was calculated using the CORINE 2012 100 m LULC dataset. The CORINE raster was first reclassified from 47 to four land use classes, “annual crops”, “other agriculture”, “other vegetation” and “unvegetated” (Table 3). The number of 100m cells was then calculated for each of the four land use classes within each landscape unit. Finally, the share of annual crops of all vegetation was calculated in each landscape (annual crops / (annual crops + other agriculture + other vegetation)).

Table 3: Reclassification of land use classes in CORINE 2012

Aggregated land use class	**CORINE land use class (GRID_CODE)**
1: Annual crops	12, 13
2: Other agriculture	14-22
3: Other vegetation	10-11, 23-29, 32-33, 35-39, 49
4: Unvegetated	1-9, 30-31, 34, 40-44, 50
null[1)]	48

1) Refers to cells classified as “NODATA” in the original dataset.

Thresholds for *annual crop dominance* classes were defined based on univariate statistics, as specified in Table 4. The distribution was skewed (mean: 0.33, median: 0.27, skewness: 0.62) so quantiles were used to define reasonable thresholds. Note that landscapes without annual crops were excluded in the computation of quantiles but still (naturally) classified as *very low* annual crop production dominance. This class therefore has significantly more observations than other classes.

Table 4: Definitions of annual crop dominance classes and resulting number of landscapes, corresponding landscape area, and affected area under annual crop production

Annual crop dominance	**% annual crops of total vegetated area within landscape**	**Percentile**	**Landscapes**		**Total area**		**Area with annual crop production**	
			#	**% of total #**	**Thousand hectares**	**% of total**	**Thousand hectares**	**% of total ha**
Very low	≤ 3.38983	0-15	39 595	49%	138 980	33%	637	1%
Low	(3.38983,14.1245]	15-35	9 854	12%	60 626	14%	4 692	4%
Medium	(14.1245,41.8919]	35-65	14 780	18%	94 613	22%	24 163	22%
High	(41.8919,66.8304]	65-85	9 853	12%	73 444	17%	36 915	34%
Very high	> 66.8304	85-100	7 390	9%	57 869	14%	43 191	39%

2.4 Identification of priority areas for beneficial LUC

Priority areas for beneficial LUC are conceptually referred to as landscape units where the environmental effects of perennialization are estimated to be particularly beneficial. In the modeling framework, priority areas are defined as landscapes where

1. any given environmental impact could be mitigated with *very high* effectiveness, or
2. multiple impacts could be mitigated with either *high* or *very high* effectiveness

To identify the latter, the number of impacts for which perennialization was classified as having a *high* and *very high* expected effectiveness, respectively, were identified (see section 2.3) and counted for each landscape unit.

3 Theory

3.1 Options for strategic perennialization

Perennialization in the form of wind breaks can increase yields for annual crops on land protected from wind, due to reduced crop damages (e.g., plant blasting, coverage of plants, uncovered roots and seeds), while also avoiding losses of organic matter and fine soil particles that can lead to decreased soil fertility. To be effective, windbreak cultivations need to be several meters high, hence preferably based on woody crops. For example, 50-meter wide willow plantations located 100 meters apart can provide continuous sheltering in areas exposed to wind erosion and on sensitive soils, if half of the plantation width is harvested at a time [25].

Perennial cultivations can be used as riparian buffer strips and filter zones reducing nutrient (and other agrochemical) emissions from arable land. Plantations designed and managed similarly as for windbreaks can be located along open waterways to continuously capture nutrients [11,17]. Riparian buffer zones may consist of perennial grass cultivations and/or short-rotation woody plantations. On arable land with covered drainage systems, nutrient-rich drainage water can be collected in storage ponds and used for irrigation. Besides efficient nutrient retention and water purification, the irrigation can improve yield levels and reduce the need for commercial fertilizers [27]. Vegetation zones, or strips of perennial crop cultivations, can also be located in areas sensitive to rill erosion, particularly on fields with clayey and silty soils in hilly areas [25]. Prevention of water erosion requires continuous soil cover, which can make perennial grass cultivations preferable to short-rotation woody plantations. Similar types of vegetation zones can also be used for flood prevention [17]. Besides the onsite benefits of reduced soil losses, there are also offsite benefits, such as reduced sediment loading in reservoirs and irrigation channels, as well as reduced deterioration in the quality of river water due to the suspended load that accompanies flood waters formed mostly by runoff.

Independently of the type of perennial cultivation, replacement of annual crops with perennial crops normally leads to increased soil carbon sequestration [41]. This is due to a combination of an increased input of organic matter to the soil and reduced soil tillage, leading to decreased decomposition of soil organic matter by microorganisms. Thus, this benefit will normally be provided in all situations where annual crops are replaced [17]. The extent may however vary geographically, due to local and regional climate conditions as well as the historical land use, e.g., the intensity in previous cultivation of annual crops [42]. This is also illustrated in the concept of SOC saturation capacity [39,40], used as indicator for accumulated SOC losses in this study.

4 Results

4.1 Environmental impacts at sub-watershed scale

About 70% of the area cultivated with annual crops is within landscapes classified as having *high* (65%) or *very high* (5%) accumulated loss of soil organic carbon (Fig. 1, Table 5). Furthermore, significant shares of the area under annual crops are located in landscapes with *high* or *very high* negative impacts concerning water erosion (12%), nitrogen emissions to water (11%), and recurring floods (14%). Wind erosion is an overall less severe problem (1%).

Fig. 1C and 1E together indicate that the production of annual crops is an important determinant for accumulated loss in SOC. For other impacts, the spatial correlation is weaker, indicating that there are additional important biophysical factors influencing the degree of soil erosion, nitrogen emissions to water, and recurring floods. For example, nitrogen emissions to water can be very high in areas with high precipitation and/or intensive livestock production, even if the land is largely covered by perennials (see, e.g., Ireland in Fig. 1B). The same can be seen for soil loss by water erosion which can be high in mountainous areas or on land with steep slopes, regardless of the land use. Soil loss by wind erosion, the least severe impact overall, is largely driven by wind exposure, hence mainly limited to coastal areas or higher altitudes. It can be observed that where several contributing parameters co-exist, the degree of environmental impacts is particularly high.

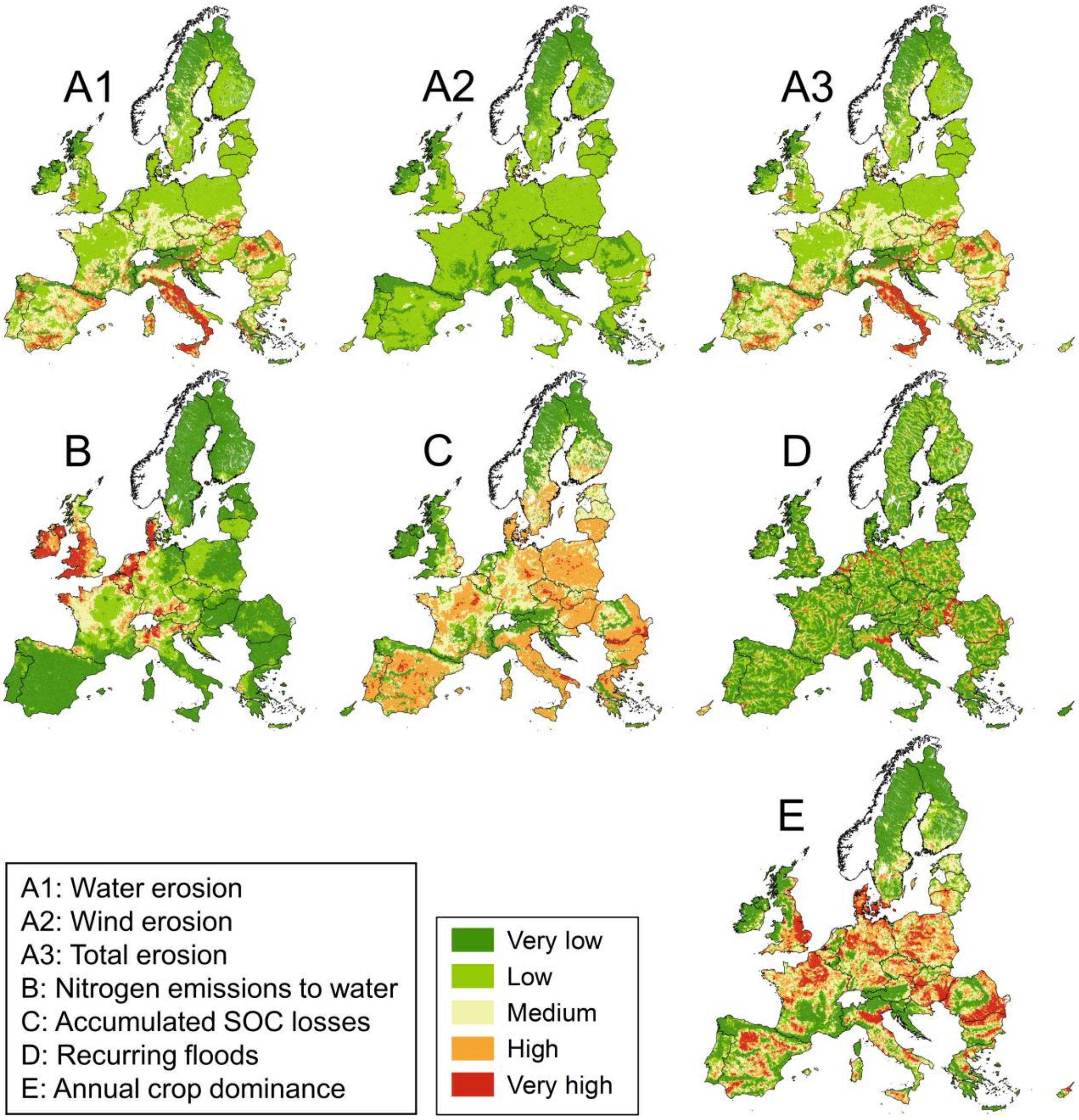

Figure 1: Environmental impacts (A-D) and annual crop dominance (E) at sub-watershed level.

Table 5: The total number of landscapes, corresponding landscape areas, and areas under annual crop production classified as having *very low* to *very high* degree of selected environmental impacts. Areas rounded to thousand hectares.

Environmental impact	**Degree**	**Landscapes**		**Total area**		**Area with annual crop production**	
		#	**% of total**	**Thousand hectares**	**% of total**	**Thousand hectares**	**% of total**
Nitrogen emissions to water	**Very low**	48 786	60%	241 823	57%	56 589	52%
	Low	17 832	22%	97 233	23%	28 925	26%
	Medium	7 382	9%	42 139	10%	12 865	12%
	High	3 564	4%	21 455	5%	6 193	6%
	Very high	3 908	5%	22 882	5%	5 025	5%
Water erosion	**Very low**	32 356	40%	88 746	21%	44	0%
	Low	24 192	30%	182 750	43%	67 222	61%
	Medium	15 092	19%	97 948	23%	29 928	27%
	High	6 185	8%	36 775	9%	8 503	8%
	Very high	3 647	4%	19 313	5%	3 901	4%
Wind erosion	**Very low**	41 049	50%	128 996	30%	2 873	3%
	Low	38 602	47%	281 986	66%	99 288	91%
	Medium	1 494	2%	11 913	3%	6 025	5%
	High	271	0.3%	2 246	1%	1 196	1%
	Very high	56	0.1%	391	0.1%	216	0%
Total erosion 1)	**Very low**	32 353	40%	88 744	21%	44	0%
	Low	21 004	26%	155 478	37%	53 169	49%
	Medium	16 997	21%	116 108	27%	39 735	36%
	High	7 292	9%	44 851	11%	12 245	11%
	Very high	3 826	5%	20 351	5%	4 404	4%
Recurring floods	**Very low**	51 806	64%	238 454	56%	51 303	47%
	Low	15 867	19%	122 587	29%	33 500	31%
	Medium	4 674	6%	28 784	7%	9 464	9%
	High	5 112	6%	23 131	5%	9 121	8%
	Very high	4 013	5%	12 576	3%	6 210	6%
Accumulated soil organic carbon losses	**Very low**	35 852	44,0%	109 285	26%	1 726	2%
	Low	4 383	5,4%	28 162	7%	4 631	4%
	Medium	14 984	18,4%	102 581	24%	26 149	24%
	High	24 367	29,9%	174 171	41%	71 399	65%
	Very high	1 886	2,3%	11 333	3%	5 692	5%

1) Refers to the sum of soil loss by water and wind erosion. For example, a landscape may have “high” water erosion and “high” wind erosion resulting in either a “high” or “very high” total erosion, depending on the total amount of soil loss compared with the classification thresholds.

4.2 Effectiveness of strategic perennialization

The extent to which the assessed environmental impacts can be mitigated by perennialization depends on the degree of environmental impact in the landscape, and the dominance of annual crops relative to other vegetation. As detailed below, the results indicate that there is a substantial potential for effective mitigation regarding all the assessed impacts.

Mitigation of accumulated SOC losses could be achieved with *high* or *very high* effectiveness on 63% of the total area used for the cultivation of annual crops (Table 6). This is logical since it is the most common environmental impact, having a high spatial correlation with the production of annual crops (Fig. 1). The largest potential for mitigating accumulated SOC losses is found in eastern UK, northern France, and large parts of Denmark, Spain, Germany, Poland, Lithuania, Czech Republic, Hungary, Romania and Bulgaria (Fig. 2).

The effectiveness in reducing soil loss by wind and water erosion is estimated as *high* or *very high* in landscapes containing about a quarter of the total area under annual crops (Table 6). The largest potential is indicated in eastern UK, and large areas in Denmark, Spain, Italy, Romania and Bulgaria (Fig. 2).

Mitigation of recurring floods could be achieved with *high* or *very high* effectiveness in landscapes containing 16% of the total area under annual crops (Table 6). The largest potential is indicated in the Po Valley in Italy and along the Danube basin, although areas with *high* and *very high* effectiveness can be seen around rivers all over Europe (Fig. 2).

Reduction of nitrogen emissions to water could be achieved with *high* or *very high* effectiveness in landscapes containing 12% of the total area under annual crops (Table 6). Contrary to other impacts where mitigation could be effective all over Europe, the potential for reducing nitrogen emissions to water is significant mainly in north-western Europe, primarily in large parts of UK and Denmark, parts of the Netherlands and Belgium, northern France, and western Germany, but also in the Po Valley in Italy and in the western parts of the Danube basin (Fig. 2).

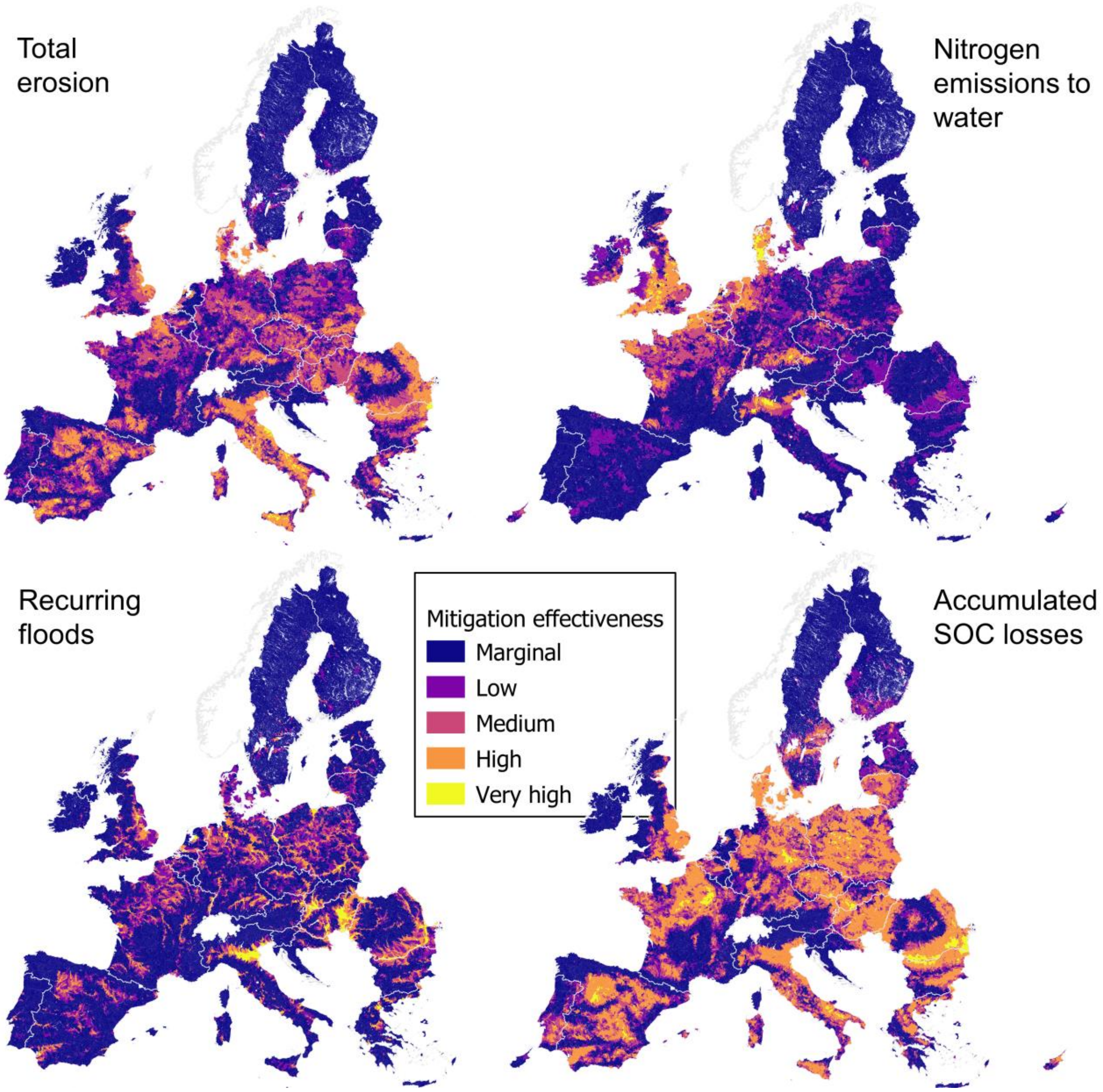

Figure 2: Estimated effectiveness of mitigating selected environmental impacts caused by the cultivation of annual crops, by a strategic introduction of perennials into landscapes.

Table 6: Estimated effectiveness of mitigating selected environmental impacts caused by the cultivation of annuals crops, by a strategic introduction of perennials into landscapes. Areas rounded to thousand hectares.

Environmental impact	Effectiveness of perennialization	Landscapes		Total area		Area with annual crop production	
		#	% of total	Thousand hectares	% of total	Thousand hectares	% of total
Nitrogen emissions to water	Marginal	62 837	77%	292 840	69%	41 247	38%
	Low	11 057	14%	74 852	18%	37 214	34%
	Medium	4 392	5%	32 712	8%	16 960	15%
	High	2 895	4%	22 907	5%	12 552	11%
	Very high	291	0,4%	2 221	1%	1 626	1%
Water erosion	Marginal	52 795	65%	227 021	53%	16 061	15%
	Low	12 550	15%	88 705	21%	30 639	28%
	Medium	10 873	13%	78 728	19%	44 921	41%
	High	5 073	6%	30 287	7%	17 380	16%
	Very high	181	0,2%	791	0,2%	596	0,5%
Wind erosion	Marginal	64147	79%	292 420	69%	29 382	27%
	Low	9842	12%	73 077	17%	36 256	33%
	Medium	6680	8%	52 865	12%	38 507	35%
	High	769	1%	6 942	2%	5 266	5%
	Very high	34	0,04%	228	0,1%	187	0,2%
Total erosion	Marginal	51 950	64%	221 176	52%	14 804	14%
	Low	12 302	15%	86 301	20%	28 314	26%
	Medium	10 323	13%	72 324	17%	37 797	34%
	High	6 645	8%	44 516	10%	27 742	25%
	Very high	252	0,3%	1 215	0,3%	941	0,9%
Recurring floods	Marginal	63 838	78%	307 892	72%	42 470	39%
	Low	9 017	11%	57 594	14%	31 579	29%
	Medium	3 990	5%	31 821	7%	18 198	17%
	High	3 809	5%	22 987	5%	13 373	12%
	Very high	818	1%	5 237	1%	3 978	4%
Accumulated soil organic carbon losses	Marginal	47 312	58%	187 222	44%	6 491	6%
	Low	9 621	12%	60 078	14%	11 724	11%
	Medium	10 531	13%	68 817	16%	22 458	20%
	High	13 405	16%	104 334	25%	64 876	59%
	Very high	603	1%	5 080	1%	4 049	4%

4.3 Priority areas for beneficial LUC

Perennialization may help mitigating environmental impacts in tenth of thousands of landscapes across Europe, as shown in the previous section. The majority of annual crops cultivated in EU is located in such landscapes. Areas where perennialization can be particularly beneficial, from an environmental perspective, is here identified as *Priority areas* for beneficial LUC.

A total of 1764 landscapes, harboring 9% of total annual crop production in EU, can be considered priority areas, due to expected mitigation of a single environmental impact by perennialization with *very high* effectiveness (Table 7).

Priority areas could also be defined as landscapes where multiple impacts can be mitigated with either *high* or *very high* effectiveness. Depending on the required number of impacts to be mitigated, such priority areas contain 1% (for four mitigated impacts), 9% (at least three impacts), or 37% (at least two impacts) of total annual crop production in EU, respectively (Table 7).

Combined, these two types of priority areas cover 15-60 million hectares, harboring 10-46% of total annual crop production in EU. As seen in Figure 3, these areas are scattered all over Europe, but there are notable “hot-spots” where priority areas are concentrated. This can be seen in, e.g., large parts of Denmark, western UK, The Po valley in Italy, and the Danube basin, but also in northern France, and several regions in, e.g., Spain, Germany, and Italy.

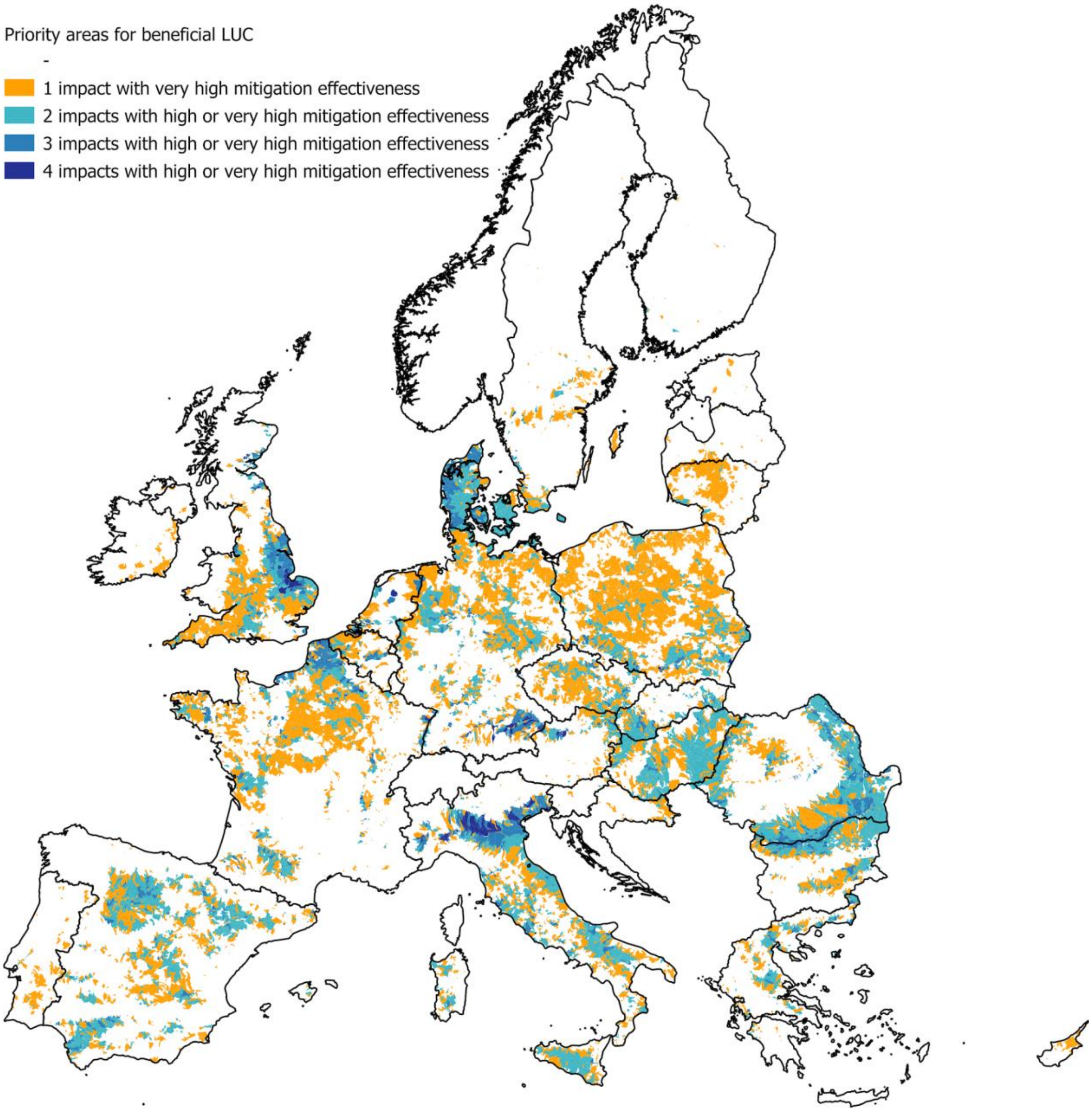

Figure 2: Priority areas for beneficial LUC. In case a landscape appears in both the orange "*very high*" category and any of the blue "*high* to *very high*" categories (cf. Table 7), the latter is prioritized for visualization.

Table 7: The total number of landscapes, corresponding landscape areas, and areas under annual crops where perennialization can help mitigate different numbers of environmental impacts, with a high and/or very high effectiveness. Numbers in the coloured rows can be linked to identically coloured areas in Fig 3. Area numbers are rounded to thousand hectares.

Effectiveness of perennialization	**Number of impacts**	**Landscapes**		**Total area**		**Area with annual crop production**	
		#	**% of total #**	**Thousand hectares**	**% of total**	**Thousand hectares**	**% of total**
High	**0**	63516	78%	294 880	69%	33 814	31%
	1	10636	13%	78 107	18%	41 217	38%
	2	5939	7%	42 038	10%	27 140	25%
	3	1284	2%	9 468	2%	6 661	6%
	4	97	0,1%	1 039	0,2%	765	0,7%
Very high	**0**	79608	98%	412 117	97%	99 266	91%
	1	1764	2%	13 076	3%	10 070	9%
	2 1)	100	0,1%	339	0,1%	262	0,2%
	3	-	-	-	-	-	-
	4	-	-	-	-	-	-
High or very high 2)	**0**	63199	78%	292 683	69%	32 055	29%
	1	9893	12%	72 908	17%	37 326	34%
	2	6492 2)	8%	45 971	11%	30 151	28%
	3	1711 3)	2%	12 231	3%	8 757	8%
	4	177 4)	0,2%	1 739	0,4%	1 309	1%

1. These landscapes are only visualized as part of the “high or very high” category with 2-4 impacts. Overlaps are specified in table notes 2-4.
2. Of which 47 have two “very high” and zero “high”
3. Of which 38 have two “very high” and one “high”
4. Of which 15 have two “very high” and two “high”

5 Discussion

5.1 Methodological considerations

The data supporting the selection of spatial indicators, and associated indicator datasets, are considered to be of high quality. The results are however sensitive to the threshold values used for the classification of negative impacts and annual crop dominance. All impacts have been classified based on advice from the providers of indicator datasets, besides in the case of *recurring floods*, where the classification was based on arbitrarily defined thresholds. Thresholds for *annual crop dominance* classes were also arbitrarily defined based on univariate statistics. While results for individual landscapes are sensitive to threshold definitions, spatial patterns are generally not. The results presented here are therefore considered particularly useful for indicating relative differences between areas, and for identifying locations where perennialization can be particularly interesting from an environmental point of view. The effects of introducing perennials in agricultural landscapes depend on what type of crop is used, its location in the landscape, and other biotic and abiotic landscape characteristics. To fully understand—quantitatively as well as spatially—the effects of perennialization, high-resolution spatially explicit analysis within individual landscapes is required [32].

5.2 Policy considerations

Policies and regulations put in place to establish a societal transition towards the Paris targets will likely lead to an increased biomass demand for bioenergy and other bio-based products. Yet, despite that knowledge and practical experience from field trials and commercial applications have existed for several decades, perennialization activities of the type described in this study rarely takes place in EU. Studies commonly find significant socioeconomic values [17,27,43], but the incentives for farmers to achieve such beneficial LUC have not been sufficiently strong. The Common Agricultural Policy (CAP) of the EU has historically not provided direct support for perennial plantations producing biomass feedstock for, e.g., energy purposes. Inadequate knowledge support, low biomass prices and market uncertainty are other reasons behind slow development for perennial grasses and woody crops.

The effectiveness in promoting beneficial LUC may increase if policies and regulations seek synergies between climate change mitigation, energy security, and other societal goals, e.g., related to SDGs. Recent policy development is favorable in some areas. For example, the CAP currently requires that all arable areas exceeding 15 ha must set aside 5% of the area for "ecologically beneficial elements" (Ecological Focus Areas, EFAs). The main purpose of EFAs is to enhance biodiversity, but also to provide other environmental benefits. EFAs can be in the form of, e.g., fallow land, terraces, landscape features, buffer strips, agroforestry, strips along forest edges, short rotation coppice with no use of fertilizers and/or plant protection products, catch crops, and nitrogen-fixing crops [44]. The biomass produced on these areas is allowed to be used as feedstock for various purposes, including energy. This may act as a driver for increased perennialization in agricultural landscapes, hence beneficial LUC.

Localization of EFAs in the landscape will be determined by biotic and abiotic landscape characteristics as well as stakeholder preferences. In some cases, EFAs may provide the highest environmental benefits by being scattered across the landscape, while in other cases it may be more beneficial to connect EFAs to provide green infrastructure and simplify potential biomass harvesting. The approach presented in this article can be further developed to provide more detailed information on how to localize EFAs to meet different objectives in individual landscapes. Such information can facilitate processes where landowners, local decision makers, and other relevant stakeholders jointly develop strategies for beneficial LUC that reflect local conditions and preferences [45].

If achievement of beneficial LUC causes losses in the production of agriculture commodities, the production of the same commodities will need to increase elsewhere, unless changes in demand and efficiency improvements along supply chains can fully buffer the losses. Effects of such indirect LUC (iLUC) need to be considered in relation to any measure that aim to reduce land use impacts, e.g., changes from conventional to organic agriculture, restrictions of fertilizer use to protect water, or lower stocking densities in animal agriculture.

In response to concerns that iLUC will cause large negative effects, various approaches to identify so-called low iLUC risk options have been developed [46]. Options for achieving beneficial LUC through perennialization can provide opportunities to reduce land use impacts while achieving high biomass yields. The biomass can then be refined to multiple products, including biofuels and animal feed, hence substituting conventional (cultivated) feed and reducing grazing requirements [47-52]. Such options can help maintain or increase agriculture production in a region while limiting environmental impacts, or reduce imports of agriculture commodities that are associated with negative impacts where they are produced. In other cases, when reduced food commodity production will be compensated by increased production elsewhere, this need not imply adverse environmental impacts; outcomes critically depend on the context where production increases, including governance of land use.

Beneficial LUC need not be premised on the requirement that the production of agriculture commodities in a region is not reduced. However, it remains important to consider possible iLUC impacts when evaluating how options for achieving beneficial LUC contribute to set policy objectives, such as GHG gas emissions reduction. These issues are further addressed in subsequent ongoing studies, quantifying biomass supply potentials and GHG mitigation associated with strategies for achieving beneficial LUC in EU.

References

1. Smith, P., Haberl, H., Popp, A., Erb, K.-H., Lauk, C., Harper, R., Tubiello, F. N., de Siqueira Pinto, A., Jafari, M., Sohi, S., Masera, O., Böttcher, H., Berndes, G., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E. A., Mbow, C., Ravindranath, N. H., Rice, C. W., Robledo Abad, C., Romanovskaya, A., Sperling, F., Herrero, M., House, J. I. & Rose, S. How much land-based greenhouse gas mitigation can be achieved without compromising food security and environmental goals? *Glob Chang Biol* **19,** 2285–2302 (2013).
2. Costanza, R., de Groot, R., Sutton, P., van der Ploeg, S., Anderson, S. J., Kubiszewski, I., Farber, S. & Turner, R. K. Changes in the global value of ecosystem services. *Global Environmental Change* **26,** 152–158 (2014).
3. Leemans, R., van Amstel, A., Battjes, C., Kreileman, E. & Toet, S. The land cover and carbon cycle consequences of large-scale utilizations of biomass as an energy source. *Global Environmental Change* **6,** 335–357 (1996).
4. Berndes, G., Hoogwijk, M. & van den Broek, R. The contribution of biomass in the future global energy supply: a review of 17 studies. *Biomass and Bioenergy* **25,** 1–28 (2003).
5. Slade, R., Bauen, A. & Gross, R. Global bioenergy resources. *Nature Climate Change* **4,** 99–105 (2014).
6. Creutzig, F., Ravindranath, N. H., Berndes, G., Bolwig, S., Bright, R., Cherubini, F., Chum, H., Corbera, E., Delucchi, M., Faaij, A., Fargione, J., Haberl, H., Heath, G., Lucon, O., Plevin, R., Popp, A., Abad, C. R., Rose, S., Smith, P., Stromman, A., Suh, S. & Masera, O. Bioenergy and climate change mitigation: an assessment. *GCB Bioenergy* **7,** 916–944 (2015).
7. Abad, C. R., Althaus, H. J., Berndes, G., Bolwig, S., Corbera, E., Creutzig, F., Ulloa, J. G., Geddes, A., Gregg, J. S., Haberl, H., Hanger, S., Harper, R. J., Hunsberger, C., Larsen, R. K., Lauk, C., Leitner, S., Lilliestam, J., Campen, H. L., Muys, B., Nordborg, M., Ölund, M., Orlowsky, B., Popp, A., Pereira, J. P., Reinhard, J., Scheiffle, L. & Smith, P. Bioenergy production and sustainable development: science base for policymaking remains limited. *GCB Bioenergy* **9,** 541–556 (2017).
8. IPCC (2014) Summary for Policymakers. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Edenhofer, O., R. Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlmer,S., von Stechow, S., Zwickel, T. and J.C. Minx (eds.) Cambridge and New York: Cambridge University
9. IPCC. *Global Warming of 1.5 °C*. (IPCC, 2018). at <http://www.ipcc.ch/report/sr15/>
10. Smith, P. & Porter, J. R. Bioenergy in the IPCC Assessments. *GCB Bioenergy* **10,** 428–431 (2018).
11. Styles, D., Börjesson, P., D'Hertefeldt, T., Birkhofer, K., Dauber, J., Adams, P., Patil, S., Pagella, T., Pettersson, L. B., Peck, P., Vaneeckhaute, C. & Rosenqvist, H. Climate regulation, energy provisioning and water purification: Quantifying ecosystem service delivery of bioenergy willow grown on riparian buffer zones using life cycle assessment. *Ambio* **45,** 872–884 (2016).
12. Holland, R. A., Eigenbrod, F., Muggeridge, A., Brown, G., Clarke, D. & Taylor, G. A synthesis of the ecosystem services impact of second generation bioenergy crop production. *Renewable and Sustainable Energy Reviews* **46,** 30–40 (2015).

13. Milner, S., Holland, R. A., Lovett, A., Sunnenberg, G., Hastings, A., Smith, P., Wang, S. & Taylor, G. Potential impacts on ecosystem services of land use transitions to second-generation bioenergy crops in GB. *GCB Bioenergy* **8,** 317–333 (2016).
14. Asbjornsen, H., Hernandez-Santana, V., Liebman, M., Bayala, J., Chen, J., Helmers, M., Ong, C. K. & Schulte, L. A. Targeting perennial vegetation in agricultural landscapes for enhancing ecosystem services. *Renewable Agriculture and Food Systems* **29,** 101–125 (2014).
15. Dauber, J. & Miyake, S. To integrate or to segregate food crop and energy crop cultivation at the landscape scale? Perspectives on biodiversity conservation in agriculture in Europe. *Energy, Sustainability and Society 2016 6:1* **6,** 25 (2016).
16. Christen, B. & Dalgaard, T. Buffers for biomass production in temperate European agriculture: A review and synthesis on function, ecosystem services and implementation. *Biomass and Bioenergy* **55,** 53–67 (2013).
17. Berndes, G., Börjesson, P., Ostwald, M. & Palm, M. Multifunctional biomass production systems –an overview with presentation of specific applications in India and Sweden. *Biofuels, Bioprod. Bioref.* **2,** 16–25 (2008).
18. Gustafsson, L. Plant Conservation Aspects of Energy Forestry - a New Type of Land-Use in Sweden. *Forest Ecology and Management* **21,** 141–161 (1987).
19. Rijtema, P. E. & DeVries, W. Differences in Precipitation Excess and Nitrogen Leaching From Agricultural Lands and Forest Plantations. *Biomass and Bioenergy* **6,** 103–113 (1994).
20. Goransson, G. Bird Fauna of Cultivated Energy Shrub Forests at Different Heights. *Biomass and Bioenergy* **6,** 49–52 (1994).
21. Christian, D. P., Niemi, G. J., Hanowski, J. M. & Collins, P. Perspectives on Biomass Energy Tree Plantations and Changes in Habitat for Biological Organisms. *Biomass and Bioenergy* **6,** 31–39 (1994).
22. Perttu, K. L. & Kowalik, P. J. Salix vegetation filters for purification of waters and soils. *Biomass and Bioenergy* **12,** 9–19 (1997).
23. Kort, J., Collins, M. & Ditsch, D. A review of soil erosion potential associated with biomass crops. *Biomass and Bioenergy* **14,** 351–359 (1998).
24. Grigal, D. F. & Berguson, W. E. Soil carbon changes associated with short-rotation systems. *Biomass and Bioenergy* **14,** 371–377 (1998).
25. Börjesson, P. Environmental effects of energy crop cultivation in Sweden - I: Identification and quantification. *Biomass and Bioenergy* **16,** 137–154 (1999).
26. Berndes, G., Fredrikson, F. & Börjesson, P. Cadmium accumulation and Salix-based phytoextraction on arable land in Sweden. *Agriculture, Ecosystems & Environment* **103,** 207–223 (2004).
27. Börjesson, P. & Berndes, G. The prospects for willow plantations for wastewater treatment in Sweden. *Biomass and Bioenergy* **30,** 428–438 (2006).
28. European Environment Agency. *European catchments and Rivers network system (Ecrins)*. (European Environment Agency (EEA), 2012). at <www.eea.europa.eu/data-and-maps/data/european-catchments-and-rivers-network>
29. Turner, M. G. Landscape Ecology - the Effect of Pattern on Process. *Annual Review of Ecology and Systematics* **20,** 171–197 (1989).
30. Burel, F. & Baudry, J. *Landscape Ecology*. (Science Publishers, 2003).
31. Lacoste, M., Minasny, B., McBratney, A., Michot, D., Viaud, V. & Walter, C. High resolution 3D mapping of soil organic carbon in a heterogeneous agricultural landscape. *Geoderma* **213,** 296–311 (2014).
32. Englund, O., Berndes, G. & Cederberg, C. How to analyse ecosystem services in landscapes—A systematic review. *Ecological Indicators* **73,** 492–504 (2017).

33. Grizzetti, B., Bouraoui, F. & Aloe, A. Changes of nitrogen and phosphorus loads to European seas. *Glob Chang Biol* **18,** 769–782 (2012).
34. Panagos, P., Borrelli, P., Poesen, J., Ballabio, C., Lugato, E., Meusburger, K., Montanarella, L. & Alewell, C. The new assessment of soil loss by water erosion in Europe. *Environmental Science & Policy* **54,** 438–447 (2015).
35. Borrelli, P., Lugato, E., Montanarella, L. & Panagos, P. A New Assessment of Soil Loss Due to Wind Erosion in European Agricultural Soils Using a Quantitative Spatially Distributed Modelling Approach. *Land Degradation & Development* **28,** 335–344 (2017).
36. Copernicus Land Monitoring Service. CLC 2012. (2018). at <https://land.copernicus.eu/pan-european/corine-land-cover/clc-2012>
37. Panagos, P., Imeson, A., Meusburger, K., Borrelli, P., Poesen, J. & Alewell, C. Soil Conservation in Europe: Wish or Reality? *Land Degradation & Development* **27,** 1547–1551 (2016).
38. Alfieri, L., Salamon, P., Bianchi, A., Neal, J., Bates, P. & Feyen, L. Advances in pan-European flood hazard mapping. *Hydrological Processes* **28,** 4067–4077 (2014).
39. Lugato, E., Panagos, P., Bampa, F., Jones, A. & Montanarella, L. A new baseline of organic carbon stock in European agricultural soils using a modelling approach. *Glob Chang Biol* **20,** 313–326 (2014).
40. 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. *Glob Chang Biol* **20,** 3557–3567 (2014).
41. Whitaker, J., Field, J. L., Bernacchi, C. J., Cerri, C. E. P., Ceulemans, R., Davies, C. A., DeLucia, E. H., Donnison, I. S., McCalmont, J. P., Paustian, K., Rowe, R. L., Smith, P., Thornley, P. & McNamara, N. P. Consensus, uncertainties and challenges for perennial bioenergy crops and land use. *GCB Bioenergy* **10,** 150–164 (2018).
42. Berndes, G., Ahlgren, S., Börjesson, P. & Cowie, A. L. Bioenergy and land use change-state of the art. *WENE* **2,** 282–303 (2012).
43. Börjesson, P. Environmental effects of energy crop cultivation in Sweden - II: Economic valuation. *Biomass and Bioenergy* **16,** 155–170 (1999).
44. European Parliament and the Council. *Regulation (EU) No 1307/2013 of the European Parliament and of the Council*. (2013).
45. Busch, G. A spatial explicit scenario method to support participative regional land-use decisions regarding economic and ecological options of short rotation coppice (SRC) for renewable energy production on arable land: case study application for the Göttingen district, Germany. *Energy, Sustainability and Society 2016 6:1* **7,** 2
46. Peters, D., Spöttle, M., Hähl, T., Kuhner, A. K., Cuijpers, M., Stomph, T. J., van der Werf, W. & Grass, M. *Methodologies for the identification and certification of Low ILUC risk biofuels*. (European Commission, 2016).
47. Manevski, K., Lærke, P. E., Jiao, X., Santhome, S. & Jørgensen, U. Biomass productivity and radiation utilisation of innovative cropping systems for biorefinery. *Agricultural and Forest Meteorology* **233,** 250–264 (2017).
48. Solati, Z., Manevski, K., Jørgensen, U., Labouriau, R., Shahbazi, S. & Lærke, P. E. Crude protein yield and theoretical extractable true protein of potential biorefinery feedstocks. *Industrial Crops and Products* **115,** 214–226 (2018).
49. Manevski, K., Lærke, P. E., Olesen, J. E. & Jørgensen, U. Nitrogen balances of innovative cropping systems for feedstock production to future biorefineries. *Science of The Total Environment* **633,** 372–390 (2018).
50. Larsen, S., Bentsen, N. S., Dalgaard, T., Jørgensen, U., Olesen, J. E. & Felby, C. Possibilities for near-term bioenergy production and GHG-mitigation through

sustainable intensification of agriculture and forestry in Denmark. *Environ Res Lett* **12,** 114032 (2017).

51. Sparovek, G., Berndes, G., Egeskog, A., de Freitas, F. L. M., Gustafsson, S. & Hansson, J. Sugarcane ethanol production in Brazil: an expansion model sensitive to socioeconomic and environmental concerns. *Biofuels, Bioprod. Bioref.* **1,** 270–282 (2007).
52. Egeskog, A., Berndes, G., Freitas, F., Gustafsson, S. & Sparovek, G. Integrating bioenergy and food production-A case study of combined ethanol and dairy production in Pontal, Brazil. *Energy for Sustainable Development* **15,** 8–16 (2011).