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Strategic deployment of riparian buffers and windbreaks in Europe can co-deliver biomass and environmental benefits

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Within the scope of the new Common Agricultural Policy of the European Union, in coherence with other EU policies, new incentives are developed for farmers to deploy practices that are beneficial for climate, water, soil, air, and biodiversity. Such practices include establishment of multifunctional biomass production systems, designed to reduce environmental impacts while providing biomass for food, feed, bioenergy, and other biobased products. Here, we model three scenarios of large-scale deployment for two such systems, riparian buffers and windbreaks, across over 81,000 landscapes in Europe, and quantify the corresponding areas, biomass output, and environmental benefits. The results show that these systems can effectively reduce nitrogen emissions to water and soil loss by wind erosion, while simultaneously providing substantial environmental co-benefits, having limited negative effects on current agricultural production. This kind of beneficial land-use change using strategic perennialization is important for meeting environmental objectives while advancing towards a sustainable bioeconomy.

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Climate change and increasing biomass demand for food, bioenergy and a multitude of other biobased products, are projected to add further pressure on managed as well as natural and semi-natural ecosystems^{1,2}. The agriculture sector is at the same time expected to reduce its greenhouse gas (GHG) emissions and provide carbon storage in soils and vegetation², while reducing also other environmental impacts³. Thus, the agriculture sector needs to increase biomass production to meet multiple demands while adapting to climate change, reducing negative land use impacts, enhancing land carbon sinks, and reducing GHG emissions^{2,4}.

Multiple policies are being developed in the European Union (EU) to take on this double challenge⁵. For example: (i) the European Green Deal⁶ has a vision of achieving multiple sustainability and climate neutrality goals by 2050. To decarbonize the energy system, the EU will, e.g., prioritize solutions based on sustainable bioenergy that needs to comply with sustainability criteria⁷; (ii) the Biodiversity Strategy for 2030⁸ includes general goals for the protection and restoration of nature and biodiversity, requiring high-diversity landscape features on at least 10% of the agricultural area; and (iii) the Farm to Fork Strategy⁹ aims to promote the transition to sustainable food production. Connected to these policies is the new EU Common Agricultural Policy (CAP) for the period 2021–2027, which aims to drive the sustainability transition in agriculture¹⁰.

Three of CAP's nine specific objectives will concern the climate and environment, namely (i) contribute to climate change mitigation and adaptation, as well as sustainable energy; (ii) foster sustainable development and efficient management of natural resources, such as water, soil and air; and (iii) contribute to the protection of biodiversity, enhance ecosystem services and preserve habitats and landscapes¹¹. The new CAP also introduces *Eco-schemes* to incentivize farmers to adopt measures for contributing to the environmental and climate objectives. The schemes offer the possibility to grant direct payments for implementing practices beneficial for climate, water, soil, air, and biodiversity¹¹. Member States will be free to define such schemes, but they are voluntary for farmers.

Multifunctional biomass production systems are designed, located and managed to reduce environmental impacts from agriculture while providing biomass for the bioeconomy^{3,12–15}. Such systems could therefore contribute to the objectives of the emerging EU policies and be eligible for compensation within the EU Eco-scheme framework. In the previous CAP, economical support has also been available for farmers for environmental investments and measures that, e.g., reduce eutrophication and improve biodiversity, but these regulations have been based on criteria set at EU level. The new CAP opens up for an enhanced toolbox, leading to a more efficient mix of voluntary and mandatory measures that are adapted to local conditions. Thus, it is up to the Member States to set specific criteria to meet the objectives on a local and regional level. This, in turn, could lead to more effective and dedicated incentives for farmers to realize investments in, for example, multifunctional biomass production systems. These systems can be designed to focus on the most critical environmental impacts in the specific region, while at the same time deliver biomass for replacing fossil fuels and thereby contribute to climate change mitigation. Recently, an assessment of the potential for multifunctional biomass production systems in Europe indicated a substantial potential for effective mitigation regarding soil loss by wind and water erosion, nitrogen emission to water, losses of soil organic carbon (SOC), and recurring floods³. This assessment did not, however, provide any quantitative estimates concerning large-scale deployment of specific systems, such as impact mitigation and biomass output.

Two examples of systems to explore further in this context are riparian buffers and windbreaks. Riparian buffers can consist of

woody and/or herbaceous crops, located along watercourses with the primary purpose of retaining nutrients^{12–14}. Buffer strips can deliver additional multiple benefits associated with the characteristics of the perennial crops, most notably flood mitigation and reduced streambank erosion. They are also likely to enhance SOC if established on land historically used for annual crop production, enhance conditions for biodiversity by, e.g., improving landscape connectivity, and protect agricultural fields from wind and water erosion³. Windbreaks are strips of woody crops, such as poplar or willow, cultivated in short rotation coppice (SRC) or -forestry (SRF) systems, located within or between fields to protect agricultural land from wind erosion¹⁶. Similar to riparian buffers, windbreaks can provide co-benefits such as enhanced SOC and reduced nutrient leaching³. Both riparian buffers and windbreaks can be designed using high-yielding species and harvested for biomass, thus increasing land-use efficiency by maintaining agricultural productivity in the landscape while providing environmental benefits. Buffer strips are also recognised as acceptable options by the EU to help protect soil fertility and increase soil organic matter, reduce nutrient losses and soil erosion and enhance carbon sequestration. Buffer strips also contribute to ensure connectivity among habitats, thus avoiding habitat fragmentation through the implementation of the Birds and Habitats Directive^{17,18}.

Here, we model the implementation of multifunctional riparian buffers, with the primary objective to reduce nitrogen emissions to water, and windbreaks, with the primary objective to reduce soil loss by wind erosion, in over 81,000 landscapes in Europe (i.e., EU27 + UK), aiming to quantify resulting ecosystem services and environmental benefits, considering three deployment scenarios with different incentives for implementation. We also estimate GHG emissions savings that could be achieved by replacing fossil fuels with biomass produced in the multifunctional systems, combined with increases in SOC. Finally, we discuss implications associated with the land-use change, such as for current agricultural production, and relevant land-use policies that may incentivize deployment.

The results show that multifunctional biomass production systems in the form of energy crop cultivations, designed and utilised as riparian buffers and windbreaks, can lead to substantial environmental benefits with limited negative effects on current agricultural production. These systems can reduce N emissions to water and soil loss by wind erosion in Europe down to a low-impact level, while simultaneously providing substantial environmental co-benefits, utilizing <1% of the area under annual crops in the EU.

Results and discussion

Multifunctional riparian buffers and windbreaks are modelled to achieve a primary objective, i.e., to mitigate a specific environmental impact (nitrogen emissions to water for buffers and soil loss by wind erosion for windbreaks), motivated by specific incentives. This mitigation effect is designated primary benefit. In many cases, additional co-benefits are likely, i.e., the perennialization will contribute positively also to other objectives, thereby increasing the total benefits for the environment and society¹⁹.

The multifunctional systems can have different designs, be located differently in the landscape, and be implemented to varying degrees. The outcome of widespread deployment will depend on the incentives (and disincentives) to establish these systems, in combination with farmer preferences and other factors. To illustrate the variation of possible outcomes, three deployment scenarios were designed, as further described in the “Methods” section. The first scenario (Biomass) assumes that the

design that has the highest biomass output from the multi-functional system, as well as the highest default mitigation potential, is used. The second scenario (Low-impact) allows for greater flexibility in system design but assumes that there are no incentives to reduce the primary impact below a predefined level. The third scenario (Food-first) resembles Low impact but with the addition that impacts on food production are disincentivized, thus minimizing the area used for the multifunctional system to achieve the predefined impact mitigation. The Biomass scenario can thus be considered a high estimate and the Food-first scenario a low estimate of widespread deployment. In all scenarios, a certain degree of effectiveness of impact mitigation and/or current impact (both classified on a scale from very low to very high, see Table 1), is required by the model to enable implementation.

Throughout the analysis, landscapes are used as the aggregation unit. In this case, landscape is synonymous to sub-watershed, as further defined and justified in the “Methods” section. Since catchments vary in size, so does the aggregation unit. All results have therefore also been quantified in terms of hectares.

Large-scale deployment of riparian buffers. The primary benefit of riparian buffers is avoided N emissions to water. Co-benefits that are quantified by the model include enhanced SOC, avoided soil loss by water erosion, and sediment retention.

A total of 7574 landscapes, covering a total of about 58 million hectares (Mha), were identified as suitable for riparian buffers in the Biomass scenario (Fig. 1b). In the Low-impact (Fig. 1c) and Food-first (Fig. 1d) scenarios, fewer ($n = 5705$) landscapes, covering about 43 Mha, were identified. The reason for this difference is that, in the latter scenarios, a higher degree of existing N emissions to water is required by the model to enable buffer establishment. In all scenarios, suitable landscapes are predominantly located in north-western Europe (Fig. 1b–d). In most locations, SRC was identified as the highest yielding buffer option, with willow as the most suitable SRC species, in terms of productivity. In some areas, however, grass was identified as the highest yielding buffer option, most notably in France, Belgium, and Italy (Fig. 1c).

The degree of N emissions to water in suitable landscapes, and the degree of impact mitigation using different buffer designs, vary substantially—both within and between countries (Fig. 1a; see also the previous results³). On 25% of the total area with suitable landscapes (1870 of the 7574 landscapes) in the Biomass scenario, the impact is already at a low level (see Table 1 for definitions of thresholds for the classification of current impacts). However, on 12% of the total area (1031 of the 7545 landscapes) it cannot even be reduced to a low level using the narrow buffer type. The geographical distribution follows previous estimates^{13,19} considering, e.g., mineral and organic nitrogen application rates in agriculture, and atmospheric deposition¹⁹. These estimates indicate low impacts in large areas, particularly the Iberian Peninsula and Eastern Europe, that are consequently not identified by the model as suitable for these kinds of buffer plantations.

In the Biomass scenario, 1.4 Mha of double-wide SRC buffers are established, corresponding to 4.6% of the area under annual crops in the affected landscapes and 1.3% of the total area under annual crops in EU27 + UK. These buffers result in about 900 kt y^{-1} of avoided N emissions to water, while delivering over 16 Mt DM y^{-1} biomass. (Table 2; Supplementary Table 1).

In the Low-impact scenario, there is a large spread in the total buffer area, since farmers can freely decide which buffer option to implement. It ranges from about 69 kha (if only narrow buffers are implemented) to 431 kha (if only double-wide buffers are implemented), corresponding to 0.3–2.1% of the area under annual crops in the affected landscapes and 0.1–0.4% of the total

Table 1 Thresholds for classifying existing environmental impacts. Adapted from Englund et al.³

Impact	Indicator	Unit	Thresholds	Very low	Low	Medium	High	Very high
N emissions to water	Annual average diffuse nitrogen emissions to water in landscape	Kg N ha ⁻¹ y ⁻¹	Very low ≤5	(5, 10]	(10, 15]	(15, 20]	>20	
Soil loss by erosion	Annual average soil loss by water erosion on land used for production of annual crops	t soil loss ha ⁻¹ y ⁻¹	0	(0, 2]	(2, 5]	(5, 10]	>10	
Recurring floods	Share of landscape area subject to 10-year flooding events	% of landscape area	0	(0, 5]	(5, 10]	(10, 25]	>25	
Accumulated loss of soil organic carbon	Average soil organic carbon saturation capacity on land used for production of annual crops	Ratio of current SOC divided by the theoretical maximum	>0.844 + null	(0.688, 0.844]	(0.532, 0.688]	(0.376, 0.532]	≤0.376	

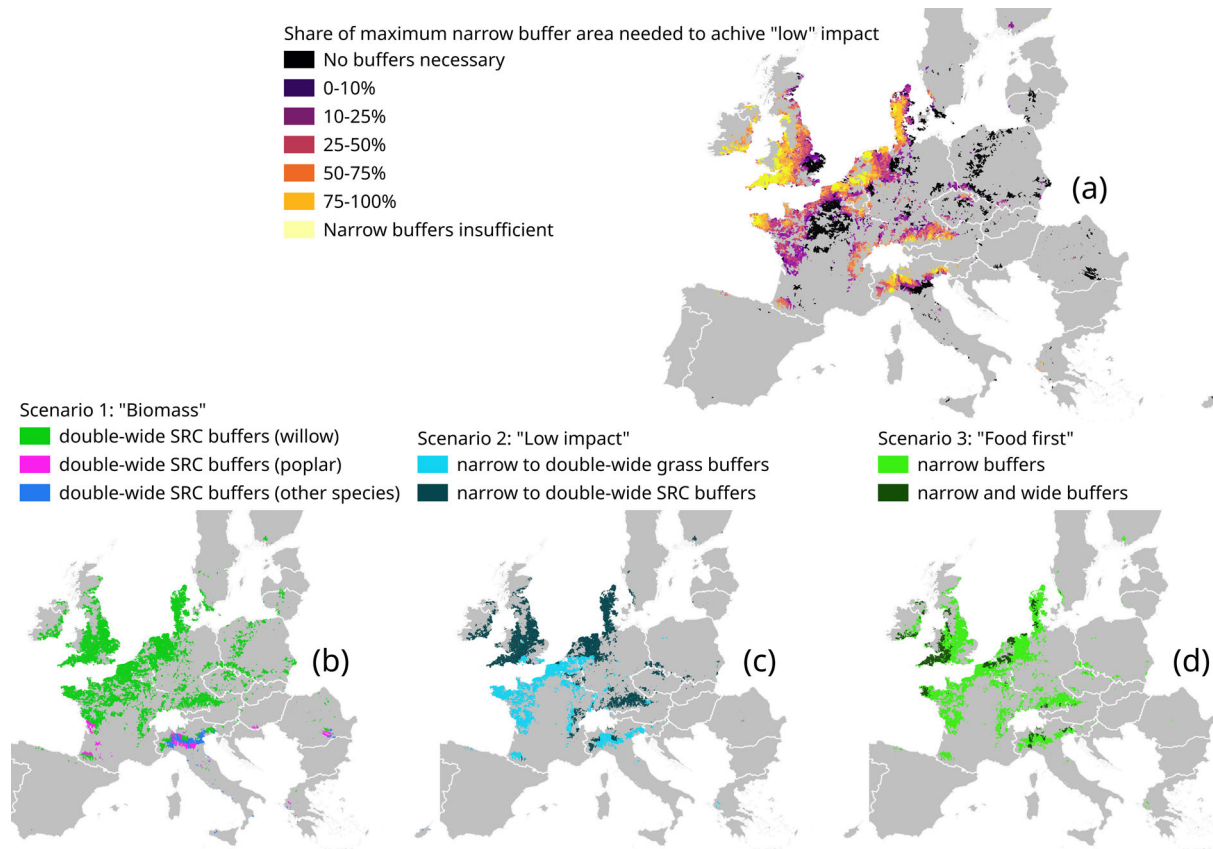


Fig. 1 Strategic deployment of riparian buffers. Share of maximum narrow buffer area needed to achieve a low level of nitrogen emissions to water (a), and the type of riparian buffers established in the three deployment scenarios (b-d). See "Methods" for information about what determines the buffer type in each landscape and scenario.

Table 2 Model output for riparian buffers and windbreaks for the three deployment scenarios All values aggregated to EU27 + UK.

Production system	Model output	Deployment scenario		
		Biomass	Low-impact	Food-first
Riparian buffers	Buffer area (kha)	1424	70-431	101
	Biomass production SRC (Mt DM PJ)	16.1 301	0.8-4.9 15-91	1.2 22
	Biomass production grass (Mt DM PJ)	-	0.8-2 15-39	1.2 22
	Buffer area relative area under annual crops in landscapes where riparian buffers could be established (%)	4.6	0.3-2.1	0.5
	Buffer area relative total area under annual crops in EU27 + UK (%)	1.3	0.1-0.4	0.1
	Avoided N emissions to water (kt N % of total N emissions in EU27 + UK)	908 32.9	371 13.4	
	SOC increase by 2050 (Mt C average kt C y ⁻¹)	32.8 1094	1.1-6.3 35-211	2.2 74
	Avoided soil erosion by water (Mt median % of mitigation necessary for achieving a low-impact level)	3.3 26	0.2-1.2 1.9-11	0.3 2.2
	Retained sediment (Mt)	49	12.7-16.5	15.6
	Windbreaks	Windbreak area (kha)	1685-2261	185-555
Biomass production (Mt PJ)		18.1-24.2 338-453	1.8-5.9 34-110	3.2 60
Windbreak area relative area under annual crops in landscapes where windbreaks are established (%)		30-33	2.7-8.2	4.6
Windbreak area relative total area under annual crops in EU27 + UK (%)		1.6-2.1	0.2-0.5	0.3
Avoided soil loss by wind erosion (kt % of total in EU27 + UK)		13,094 23	13,335 23	
Avoided N emissions to water (kt N)		20.2-21.8	1.6-4.8	2.9
SOC increase by 2050 (Mt C average kt C y ⁻¹)		38-45 1253-1507	4-11 118-353	6 206
Avoided soil erosion by water (kt median % of mitigation necessary for achieving a low-impact level)		1870-3175 44-95	213-639 4-12	289 10

area under annual crops in EU27 + UK. These buffers result in 371 kt y⁻¹ avoided N emissions to water, while delivering 0.8-4.9 Mt DM y⁻¹ of SRC biomass or 0.8-2.1 Mt DM y⁻¹ of grass biomass. (Table 2; Supplementary Table 1).

In the Food-first scenario, a total of 101 kha of narrow (49 Kha) and wide (52 kha) buffers are established, corresponding to 0.5% of the area under annual crops in the affected landscapes and 0.1% of the total area under annual crops in EU27 + UK. As in the Low-impact scenario, these buffers result in 371 kt y⁻¹ of avoided N emissions to water. The biomass output is, however, lower, at about 1.2 Mt DM y⁻¹ (Table 2; Supplementary Table 1).

For comparison, the gross nitrogen balance per hectare on agricultural land in EU-27 + UK, or the gross surplus of nitrogen between total inputs and total outputs, was estimated to, on average, 49 kg N in 2015²⁰. In total, this is equivalent to some 8500 kt N, based on 173 million hectares of agricultural land in EU-27 + UK²¹. Not this entire surplus of nitrogen will be leached to surface water; the degree depends on specific local and regional conditions (see Fig. 1). The 900 kt y⁻¹ avoided N emissions to water in the Biomass scenario thus represent some 11% of the gross surplus of nitrogen on agricultural land, and 33% of total N emissions to water, in EU-27 + UK. Avoided N emissions to water in the low-impact and

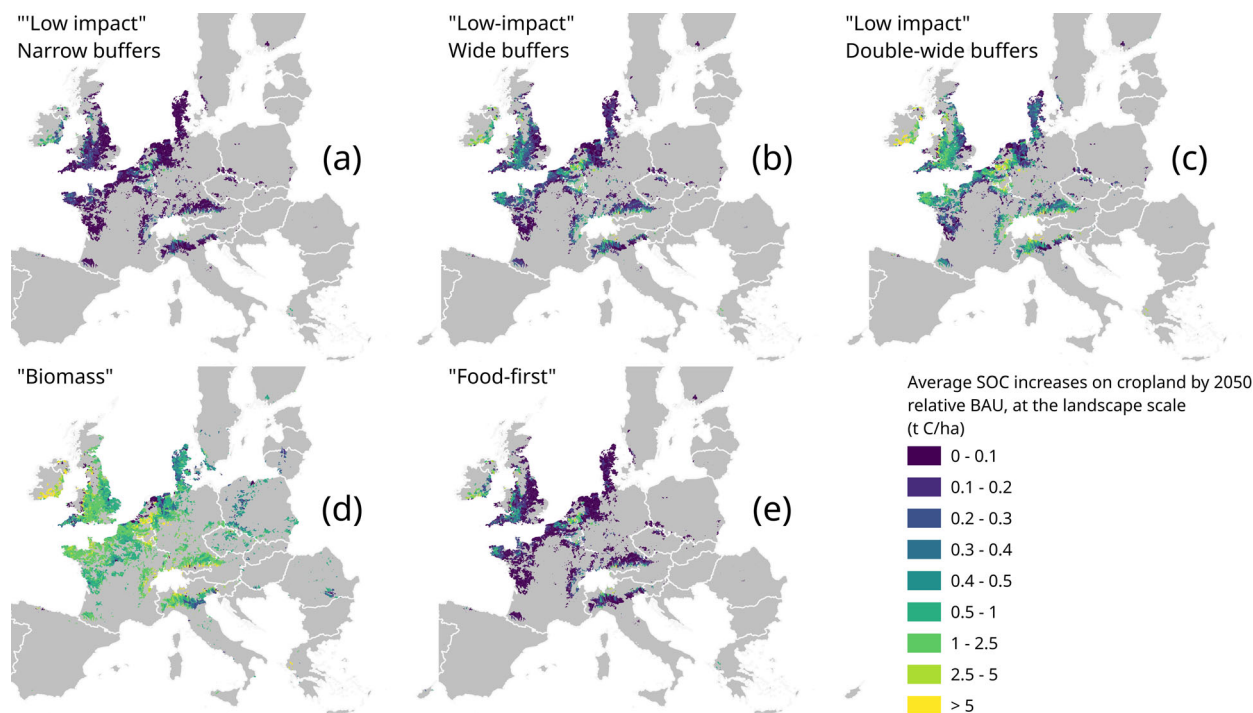


Fig. 2 Increase in soil organic carbon due to implementation of riparian buffers. Average increase in SOC on cropland by 2050, relative a business-as-usual (BAU) scenario with continued existing land-use, in each landscape, for the different deployment scenarios (a–e), with different riparian buffer options for the Low-impact scenario (a–c).

food-first scenarios, equivalent to 371 kt N y^{-1} , represent about 4% of total gross N surplus and 13% of total N emissions to water.

Enhanced SOC as a co-benefit of riparian buffer deployment.

The potential of riparian buffers to enhance SOC depends on existing accumulated SOC losses and thus the potential to increase SOC by establishing perennials, combined with the total buffer area. Given the large variation of both factors, there is also a large variation in the degree to which riparian buffers can contribute to enhancing SOC (Fig. 2).

In the Biomass scenario (Fig. 2d), given the large buffer areas relative to the other scenarios, SOC increases are the greatest. By 2050, the SOC increase relative a business-as-usual (BAU) scenario with continued existing land-use, amounts to almost 33 Mt C (Table 2), corresponding to avoided GHG emissions of $4 \text{ Mt CO}_2\text{-eq y}^{-1}$. In the other scenarios (Fig. 2a–c, e) the corresponding numbers are $1.1\text{--}6.3 \text{ Mt C}$ and $0.1\text{--}0.8 \text{ kt Mt CO}_2\text{-eq y}^{-1}$ for Low-impact and 2.2 Mt C and $0.3 \text{ Mt CO}_2\text{-eq y}^{-1}$ for Food-first (Table 2). It should be noted that the annual GHG emissions savings presented here are average values over 30 years. In reality, SOC increases are greater during the first 10 years after establishment²², meaning higher short-term GHG emissions savings from increased SOC than what is indicated here. However, relative total GHG emissions (all sectors) in 2018, these emissions savings are marginal; 0.1% in the biomass scenario.

While these SOC increases can be considered substantial in absolute terms, riparian buffers are unlikely to play an important role in restoring accumulated losses of SOC across Europe. SOC losses are widespread and substantial, and riparian buffers only enhance SOC in the location where they are established, meaning that the majority of landscapes in Europe are unaffected, and also the majority of land within the landscapes where buffers are established. To effectively restore SOC on a large scale, changes in crop-rotation practices are necessary, e.g., using ley crops²². This

also entails that riparian buffers cannot contribute substantially to achieving climate neutrality goals.

Avoided soil loss by water erosion and sediment retention as co-benefits of riparian buffer deployment.

In the Biomass scenario, avoided soil loss by water erosion due to buffer establishment amounts to 3.3 Mt y^{-1} , corresponding to 6.3% of current soil loss by water erosion on cropland in landscapes where buffers are established, and 1.2% of current soil loss by water erosion on cropland in EU27 + UK. The median landscape contributes with 26% of the reductions in soil loss by water erosion necessary to achieve a low-impact level, at the landscape scale. In addition to these direct erosion reductions, buffers retain 49 Mt of soil that is eroded on nearby cropland. At the European level, buffers retain 19% of all soil loss by water on cropland. (Fig. 3d, Table 2; Supplementary Table 1).

In the Low-impact scenario, total avoided soil loss by water erosion ranges from 192 kt (only narrow buffers) to 1150 kt (only double-wide buffers), corresponding to 0.5–3.1% of all soil loss by water erosion on cropland where buffers are established, and 0.1–0.4% of total soil loss by water erosion on cropland in EU27 + UK. In the median landscape, avoided water erosion amounts to 2–11% of what is necessary to achieve a low-impact level at the landscape scale. Additional sediment retention amounts to $13\text{--}16 \text{ Mt y}^{-1}$, thus totalling 38–50% direct and indirect avoided soil loss by water erosion within the buffer landscapes. At the European level, buffers retain 5–6% of all soil loss by water on cropland. (Fig. 3a–c; Table 2; Supplementary Table 1).

In the Food-first scenario, avoided water erosion amounts to 291 kt y^{-1} , from narrow (126 kt) and wide (165 kt) buffers combined, corresponding to 0.8% of total soil loss by water erosion on cropland where buffers are established, and 0.1% of total soil loss by water erosion on cropland in EU27 + UK. In the median landscape, avoided water erosion amounts to 2.2% of

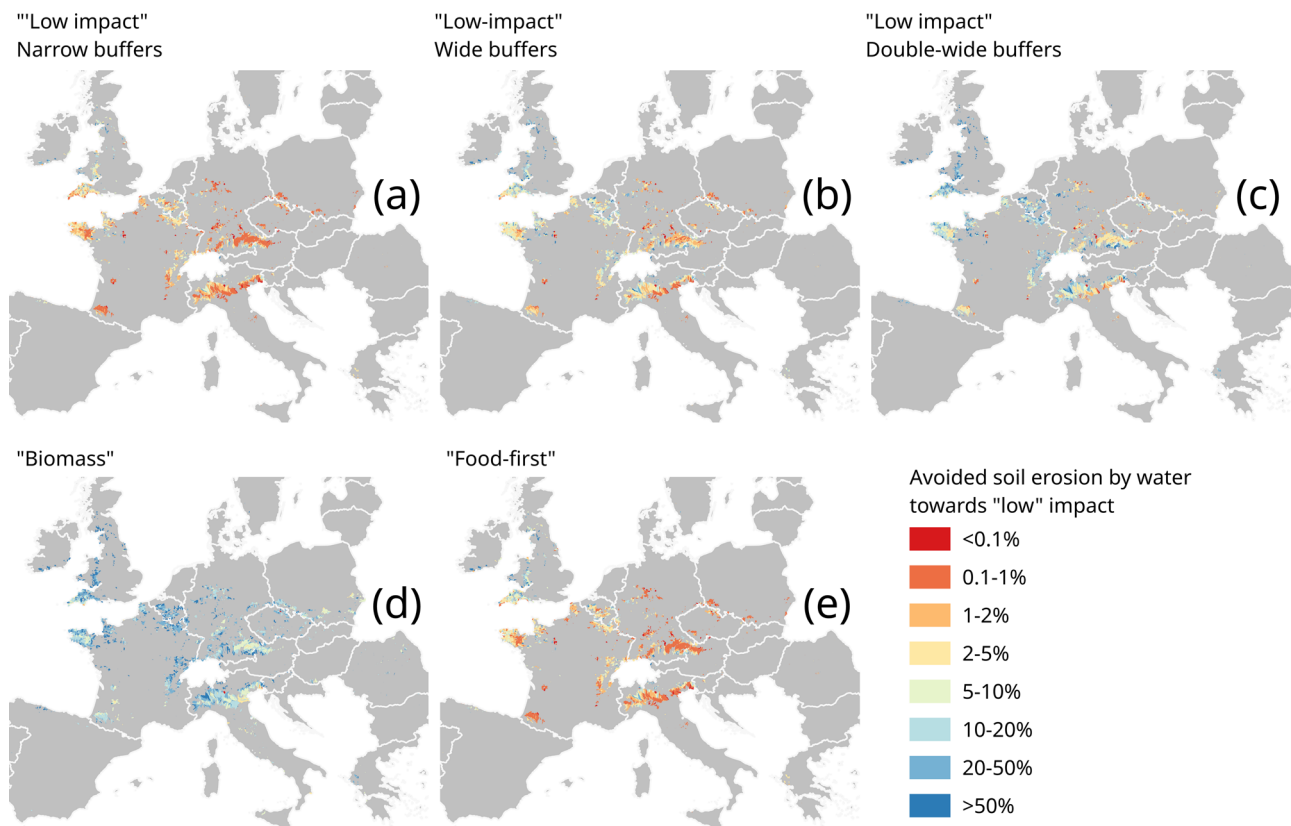


Fig. 3 Avoided soil erosion due to implementation of riparian buffers. Degree to which establishment of riparian buffers contribute towards reducing soil loss by water erosion down to a low-impact level, for the different deployment scenarios (a–c, d, e), and different riparian buffer options for the Low-impact scenario (a–c).

what is necessary to achieve a low-impact level at the landscape scale. Additional sediment retention amounts to 16 Mt y^{-1} , totalling 42.6% direct and indirect avoided soil loss by water erosion within the buffer landscapes. At the European level, buffers retain 5.6% of all soil loss by water on cropland. (Fig. 3e; Table 2; Supplementary Table 1).

Although there is a notable variation between different landscapes, countries, and regions (Fig. 3), riparian buffers are generally considered as having limited potential for reducing soil loss by water erosion at the European scale. However, the potential for avoiding streambank erosion, which has not been modelled, could be substantial². The potential for retaining eroded soil in buffers and thus avoiding sedimentation in watercourses appears substantial, especially within landscapes where buffers are established but also at the European level. It should, however, be noted that sediment retention in buffers does not mitigate negative effects of water erosion on eroded cropland, such as reduced soil fertility.

Large-scale deployment of windbreaks. The primary benefit of windbreaks is wind erosion mitigation. Co-benefits include enhanced SOC, avoided soil loss by water erosion, and avoided N emissions to water.

A total of 7483 landscapes, covering over 60 Mha, are classified as having a medium or higher effectiveness concerning wind erosion mitigation. However, in most of these landscapes ($n = 6315$), the impact is already at a low level. Given the assumptions for wind erosion mitigation potential, i.e., that windbreaks cannot reduce wind erosion beyond the threshold for the low-impact level (Table 1), these landscapes are not subject to windbreak implementation in any of the deployment scenarios.

Windbreaks are therefore implemented in 1168 landscapes, covering 10 Mha, in all deployment scenarios. The largest modelled windbreak area is in Denmark, followed by the UK, the Netherlands, and Spain. As noted for riparian buffers, willow is typically higher yielding in northern Europe, while poplar is typically higher yielding in southern Europe (Fig. 4).

As for riparian buffers, the degree of soil loss by wind erosion varies substantially, both within and between countries^{3,23}. The median implementation level required to achieve a low-impact level is about 16%, but with large variations; the implementation level is $<1\%$ and $>100\%$ in about 4% of all landscapes, respectively (Fig. 4b). The estimates of wind-erosion effects are consistent with previous assessments²¹, indicating low impacts in large areas of Central and Northern Europe. It is clear that despite high levels of wind-erodible fractions of soil estimated in some of these areas, the modelled land susceptibility to wind erosion is estimated to be low, due to land-use practices and general climatic and ecological conditions.

In the Biomass scenario, the total windbreak area ranges between about 1.7–2.3 Mha. This corresponds to 1.6–2.1% of the current area under annual crops in EU27 + UK and 30–33% of the current area under annual crops in landscapes with windbreaks. Wind erosion mitigation is about 13 Mt of avoided soil loss, annually, corresponding to 23% of total soil loss by wind erosion in EU27 + UK. Biomass production from these windbreaks sums up to 18–24 Mt DM y^{-1} . (Fig. 4c; Table 2; Supplementary Table 2).

In the Low-impact scenario, the total windbreak area is notably smaller, 185–555 kha, corresponding to 0.2–0.5% of the current area under annual crops in EU27 + UK, and 2.7–8.2% of the area under annual crops in the landscapes where they are established.

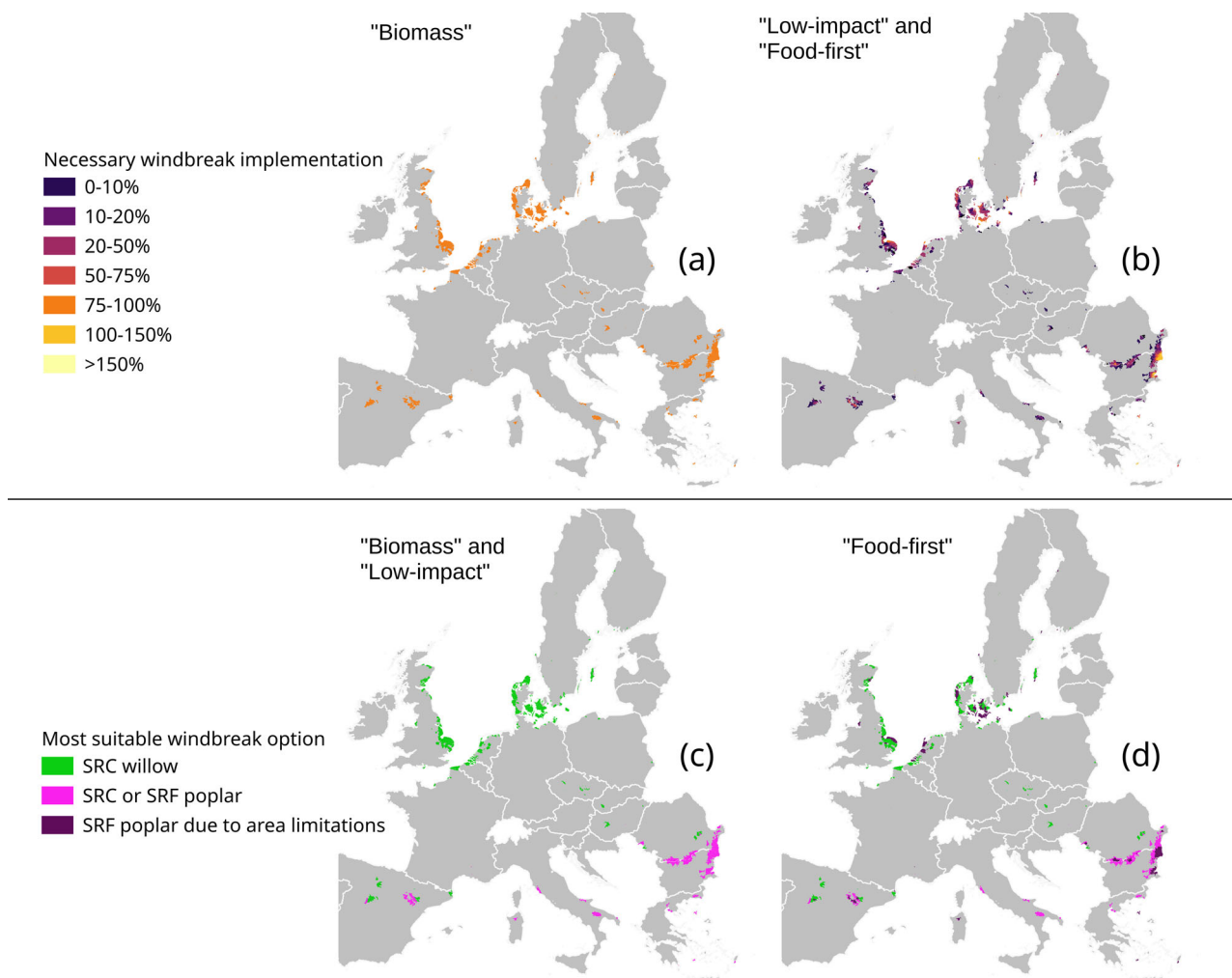


Fig. 4 Deployment of windbreaks. Implementation levels in the different scenarios and implemented windbreak options. In the Biomass scenario (a), the implementation level is always 100%. In the Low-impact and Food-first scenarios (b), it is determined by the implementation necessary to reduce wind erosion to a low-impact level but not beyond. In the Biomass and Low-impact scenarios (c), the highest yielding options are always used. In the Food-first scenario (d), the option is also affected by the ambition to minimize total windbreak area.

Wind erosion mitigation is about 13 Mt of avoided soil loss, annually, or 23% of total soil loss by wind erosion in EU27 + UK, regardless of how the windbreak options are combined. Total windbreak biomass production is about 2–6 Mt DM y^{-1} . (Fig. 4c; Table 2; Supplementary Table 2).

In the Food-first scenario, the total windbreak area is 312 kha, of which 190 kha SRC windbreaks and 212 kha SRF windbreaks. This corresponds to 0.3% of the current area under annual crops in EU27 + UK, and 4.6% of the area under annual crops in the landscapes where windbreaks are established. As for the other scenarios, wind erosion mitigation is about 13 Mt of avoided soil loss, annually, or 23% of total soil loss by wind erosion in EU27 + UK. Total windbreak biomass production is about 3 Mt DM y^{-1} . (Fig. 4d; Table 2; Supplementary Table 2).

As for riparian buffers, there is a notable difference between the Biomass scenario and the other two scenarios. However, in this case, the spatial deployment is identical across the scenarios. The difference is instead solely explained by differences in the implementation level. In the Biomass scenario, buffers are implemented at 100% in all landscapes (Fig. 4a), while in the other scenarios, windbreaks are only implemented to the extent where the impact is reduced to a low level at the landscape scale (Fig. 4b). In most landscapes, this means implementing windbreaks to a lesser extent than in the Biomass scenario, although in

some landscapes to a considerably greater extent. This also explains why wind erosion mitigation is similar in all scenarios, despite different windbreak areas.

Enhanced SOC as a co-benefit of windbreak deployment. As for riparian buffers, effects on SOC depend largely on the windbreak area. In the Biomass scenario (Fig. 5a, d), the total SOC increase is, therefore, the greatest, 38–45 Mt C by 2050, corresponding to 4.6–5.5 Mt CO₂-eq of annual GHG emissions savings. In the other scenarios, total SOC increases are 4–11 Mt C for Low-impact (Fig. 5b, e) and 6 Mt C for Food-first (Fig. 5c). Corresponding annual GHG emissions savings are 0.5–1.3 and 0.7 Mt CO₂-eq y^{-1} , respectively. (Table 2; Supplementary Table 2).

Unlike for most of the assessed co-benefits, windbreaks could potentially play an important role in restoring SOC in landscapes where they are established (Fig. 5). This is particularly the case in the Biomass scenario, where a substantial share of current cropland is used for windbreaks. In the other scenarios, where the implementation level is, in general, more limited, it can still play an important role in restoring SOC where wind erosion is severe and the implementation level high. In other landscapes, it can contribute to varying degrees to restoring SOC, depending on implementation level. The contribution to restoring SOC could be

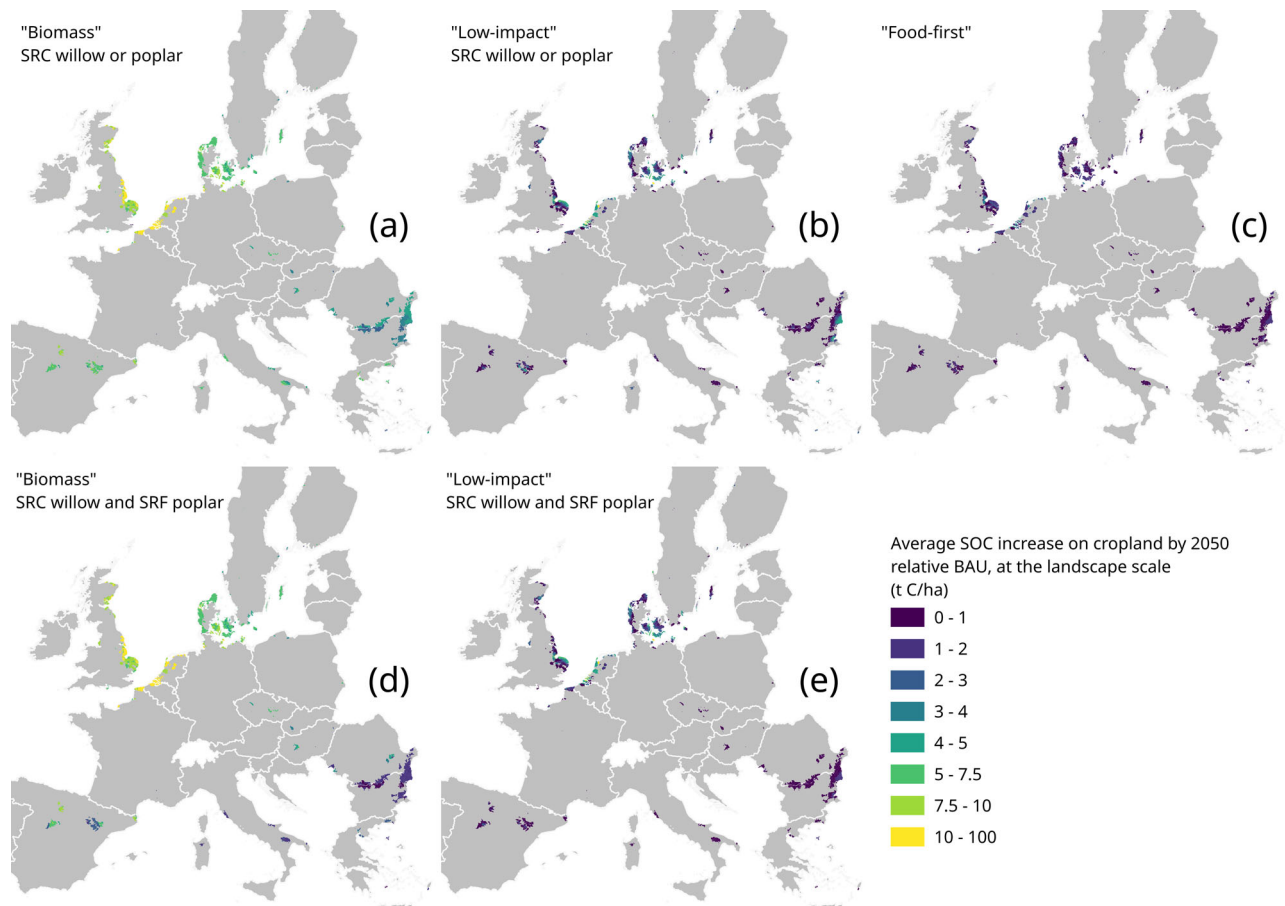


Fig. 5 Increase in soil organic carbon due to implementation of windbreaks. Average increase in SOC on cropland by 2050, relative a business-as-usual (BAU) scenario with continued existing land-use, in each landscape, for the different deployment scenarios (a–e), and different windbreak options for the Biomass (a, d) and Low-impact (b, e) scenarios.

further increased if the location of the windbreaks is shifted during replanting, since the positive effects on SOC decrease over time. At the European level, however, the positive effect on SOC is small, given that most agricultural landscapes are not subject to windbreak implementation in any of the deployment scenarios. This also means that the contribution to achieving climate neutrality in EU is marginal; in the biomass scenario, the annual emissions savings potential relative total GHG emissions (all sectors) in EU-27 + UK in 2018 is 0.14%.

Avoided soil loss by water erosion as a co-benefit of windbreak deployment. In the Biomass scenario, reduced soil loss due to water erosion ranges from 1.9 Mt y^{-1} (if only SRF windbreaks) to 3.2 Mt y^{-1} (if only SRC windbreaks). This corresponds to about 1% of total water erosion in EU27 + UK, although a more substantial 10–33% of total water erosion in the landscapes where windbreaks are established. The median contribution of windbreaks towards reducing water erosion down to a low-impact level is 95–112% (Fig. 6a, d; Table 2; Supplementary Table 2).

In the Low-impact scenario, avoided soil loss by water erosion ranges between 0.2 Mt y^{-1} (only SRF) and 0.6 Mt y^{-1} (only SRC), corresponding to 0.1–0.2% of total water erosion in EU27 + UK and 2–7% of total water erosion in the landscapes where windbreaks are established. The median contribution towards reducing water erosion to a low-impact level is 4–12%. (Fig. 6b, e; Table 2; Supplementary Table 2).

In the Food-first scenario, windbreaks avoid 0.3 Mt of soil loss by water erosion, annually, corresponding to 0.1% of total water

erosion in EU27 + UK and 10% of total water erosion in the landscapes where windbreaks are established. The median contribution towards reducing water erosion to a low-impact level is 10% (Fig. 6c; Table 2; Supplementary Table 2).

This indicates that, in principle, no further measures to reduce water erosion are necessary in landscapes with windbreaks, given the level of windbreak implementation in the Biomass scenario. In the other scenarios, where the implementation level is generally lower, the role of windbreaks in reducing water erosion is less, albeit still, substantial (Fig. 6b, c, e). It should be noted that some landscapes have a greater reduction in water erosion in the Low-impact and Food-first scenarios, than in the Biomass scenario, as these scenarios allow for an implementation level >100% (Fig. 4b). As for the other co-benefits, the contribution to reduced soil loss by water erosion is marginal at the European scale.

To estimate sediment retention, it is necessary to know the orientation of windbreaks relative slope, as this strongly influences the sediment trapping efficiency. While this is technically possible, sediment retention in windbreaks has not been assessed here.

Avoided nitrogen emissions to water as a co-benefit of windbreak deployment. In many landscapes where windbreaks are established, their effect on N emissions to water is substantial. This is particularly the case in the Biomass scenario (Fig. 7c), in which windbreaks suffice to reduce the impact to a low level in most landscapes, totalling 20–22 kt of avoided N emissions to water, annually. In the

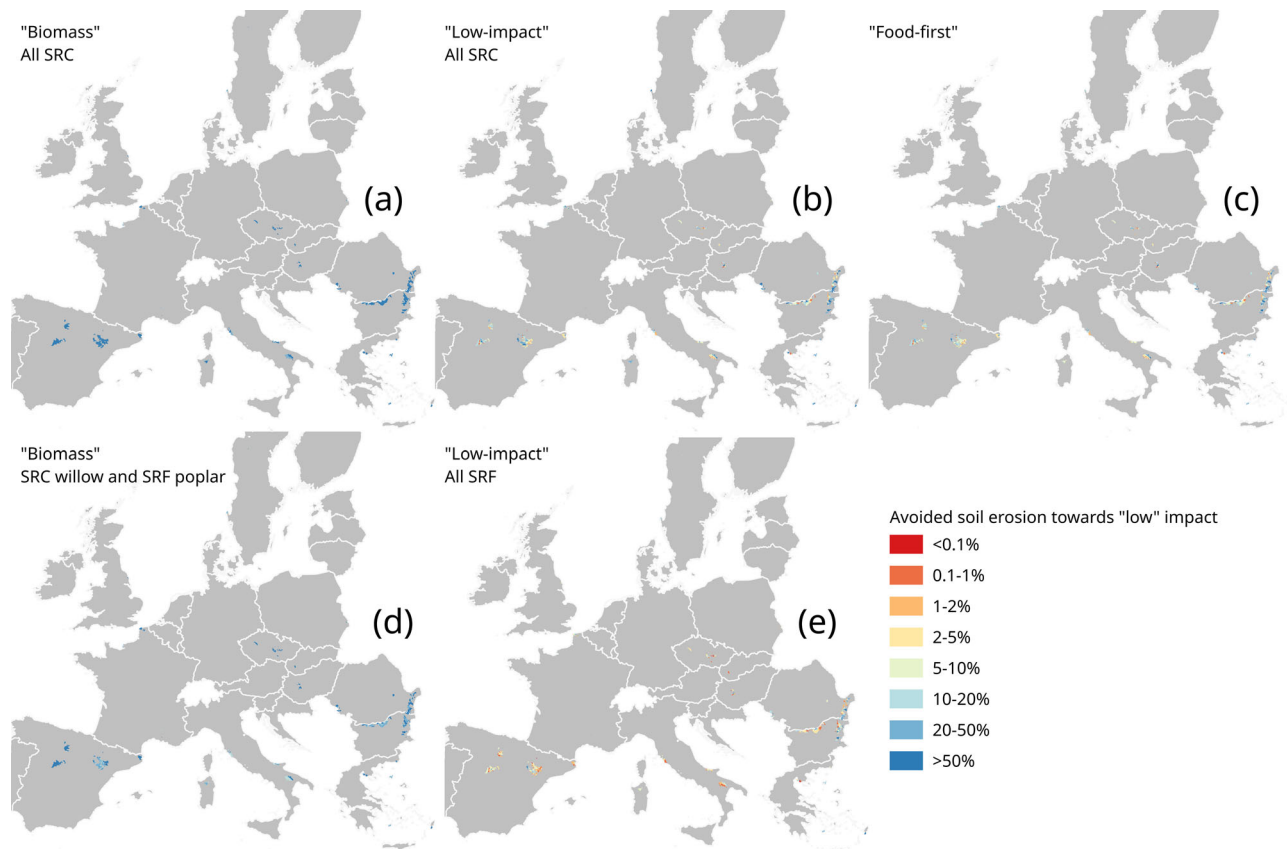


Fig. 6 Avoided soil erosion due to implementation of windbreaks. Degree to which establishment of windbreaks contribute towards reducing soil loss by water erosion down to a low-impact level, for the different deployment scenarios (a–e), and different windbreak options for the Biomass (a, d) and Low-impact (b, e) scenarios.

other scenarios, the variation is large. In some landscapes, i.e., where wind erosion is severe and the implementation level high, N emissions are reduced to a low level or beyond, while in other landscapes, the contribution is only marginal (Fig. 7a, b, d). This is especially seen in the Food-first scenario (Fig. 7d), where the windbreak area is optimized and thus the lowest. Total avoided N emissions to water in the Low-impact and Food-first scenarios are 1.6–4.8 and 2.9 kt, respectively (Table 2, Supplementary Table 2).

In many landscapes where windbreaks are implemented, N emissions to water are also high, indicating that windbreaks can be as effective as riparian buffers in this respect. Note, however, that windbreaks have a marginal effect on N emissions to water at the European scale, compared with riparian buffers (up to 22 kt N, compared with about 900 kt). This is because most areas subject to N emissions to water are not subject to windbreak implementation. Nevertheless, this exemplifies how one measure could suffice to simultaneously resolve multiple environmental impacts, thus reducing the cropland area needed for impact mitigation and increasing overall land-use efficiency. It also highlights the need to focus on multiple objectives simultaneously and to adopt a landscape perspective.

Additional co-benefits from riparian buffer and windbreak deployment. As discussed, several additional co-benefits of establishing riparian buffers and windbreaks are possible. Some are, however, difficult to quantify without taking more landscape-specific characteristics into consideration. One such example is recurring floods, which is likely to be effectively mitigated by both riparian buffers and windbreaks. To quantify this benefit in

biophysical units, hydrological modelling, based on the scenario maps generated here, is required. Similarly, riparian buffers may mitigate wind erosion, effectively functioning as windbreaks. Quantifying this effect requires considering the orientation of buffers relative to the dominating wind direction. To quantify these co-benefits in biophysical units was considered to be outside the scope of this study, but in order to explore and indicate the potential, we estimated the likelihood of flood mitigation from buffer and windbreak establishment, respectively, as well as the likelihood of wind erosion mitigation from riparian buffers. We found that the likelihood of flood mitigation is high or very high in 1/7–1/5 of all landscapes where riparian buffers are established (Fig. 8a, b) and in 1/6 of the landscapes where windbreaks are established (Fig. 8c). As wind erosion is severe on a small area compared with recurring floods, the likelihood of wind erosion mitigation by riparian buffers is generally lower; high or very high in only 2–4% of the affected landscapes.

As the establishment of perennial crop plantation stripes on agricultural land generate variations in the landscape, they can have direct benefits for biodiversity^{24,25}, and can play important roles concerning the preservation of sensitive species such as semiaquatic amphibians²⁶. However, the outcome depends on local conditions and effects may be negative if the establishment of plantation stripes interfere with pre-existing unmanaged riparian zones. Furthermore, as these perennial energy crop plantations modify the moisture regime, micro-climate, vegetative structure, and productivity, depending on the management and location, they can act as barriers against fire²⁷. At the same time, these stripes can accumulate dry biomass fuel and thereby become corridors for fire movement, which suggests additional



Fig. 7 Reduced N emissions to water due to implementation of windbreaks. Degree to which establishment of windbreaks contribute towards reducing N emissions to water down to a low-impact level, for the different deployment scenarios (a–d), and different windbreak options for the Low-Impact scenario (a, b).

considerations concerning management and species selection in fire-sensitive areas. While fast-growing grass and SRC species can be effective for flood mitigation, the effects on water availability in dry areas should also be considered, given their high water demands^{28,29}. Thus, to provide a more comprehensive, and precise, understanding of the benefits and trade-offs of strategic perennialization, it is necessary to study a broad range of environmental aspects on a smaller scale with higher resolution. This also applies for possible negative effects of the otherwise beneficial LUC, as discussed below.

Impacts on agricultural production. Utilizing agricultural land for buffers and windbreaks implies that current agricultural production is impacted. Such consequences are, however, complicated to quantify. For example, riparian buffers could be established entirely on cropland or to a varying degree on existing, unmanaged, buffers, thus limiting the need to convert cropland. In the former case, agricultural production will initially decrease, but if yield levels increase on the cropland areas that benefit from reduced erosion or flood mitigation^{16,30}, this could potentially outweigh the negative effect of reduced cropland area. For windbreaks, substantial parts of the agricultural landscape are converted from annual crops (1/3 for SRC windbreaks and 1/9 for SRF windbreaks at 100% implementation) in the different

scenarios. This can, however, be compensated for by yield increases on cropland that is sheltered from wind erosion¹⁶. Finally, the different co-benefits of buffer and windbreaks (e.g., SOC increases³¹) can also have positive long-term effects on yield levels.

GHG emissions savings. The maximum total biomass production of SRC in riparian buffers and windbreaks amount to about 16 kt y⁻¹ (300 PJ) and 24 kt y⁻¹ (450 PJ), respectively, in the Biomass scenario (see Table 2, Supplementary Table 1, and Supplementary Table 2), utilizing a total of 3.4% of the area under annual crops in the EU. The GHG emissions savings obtained from this biomass depend on what biobased products are produced (and how) and which other products are displaced. To illustrate, if biomass is converted to either (i) Fischer-Tropsch diesel, methanol, and dimethylether (DME), displacing fossil diesel and gasoline, or (ii) electricity and heat, displacing coal and oil, respectively, the estimated corresponding GHG emissions savings are in the range of 29–44 Mt CO₂-eq y⁻¹. In the same scenario, an additional 9.5 Mt CO₂-eq y⁻¹ is stored in soils until 2050 (annual average, see Table 2, Supplementary Table 1, and Supplementary Table 2). The total GHG emissions savings of riparian buffers and windbreaks would in this deployment scenario reach about 38.5–53.5 Mt CO₂-eq y⁻¹, corresponding to

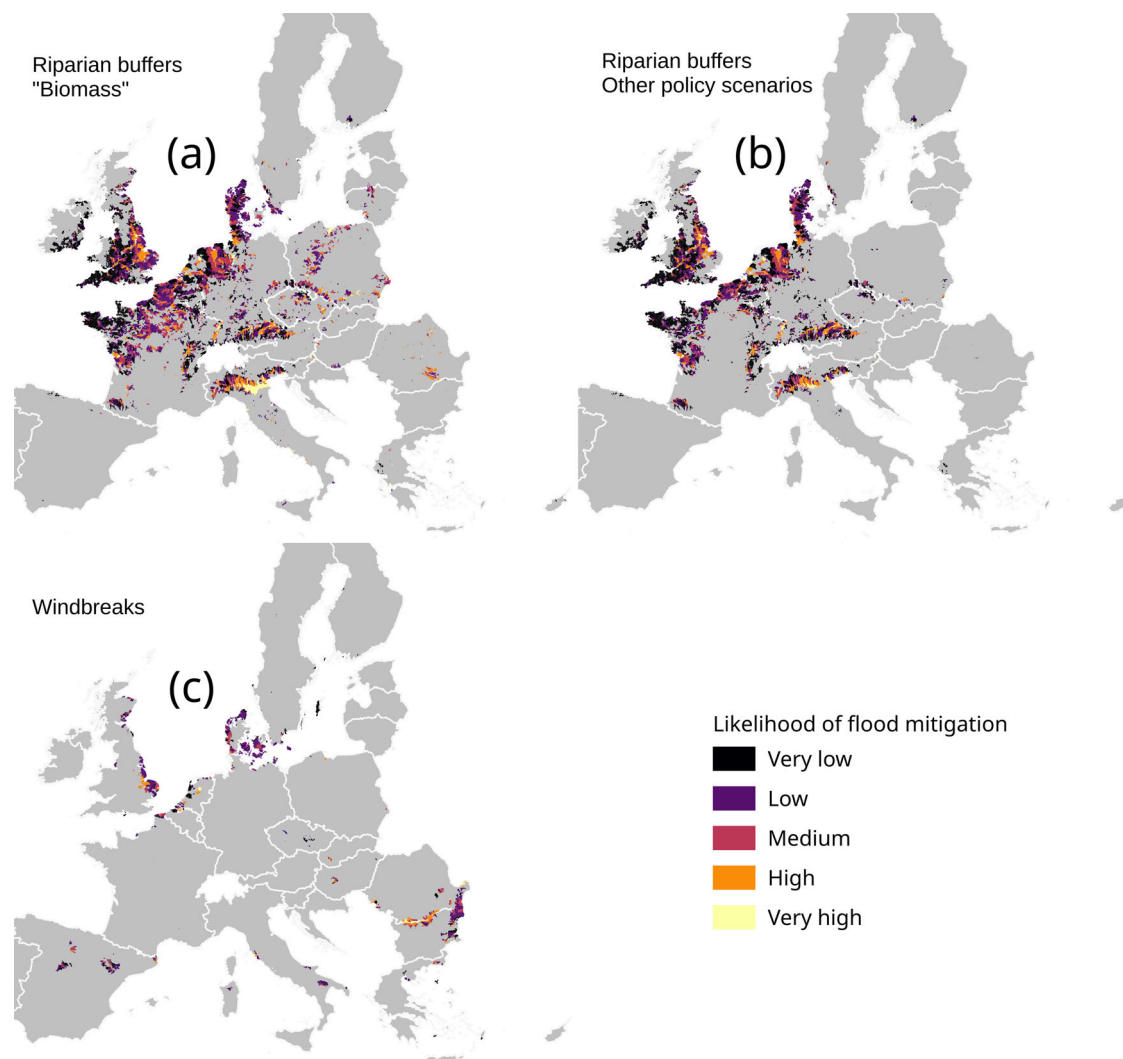


Fig. 8 Flood mitigation by implementation of riparian buffers and windbreaks. Likelihood of mitigated flooding events due to implementation of riparian buffers (a, b) and windbreaks (c).

1–1.4% of total EU-28 GHG emissions (all sectors) in 2018³². However, the results vary substantially between the different deployment scenarios. The GHG emission savings associated with biomass use can be expected to change over time, because both product substitution patterns and GHG intensity of biobased as well as substituted products will change as consumption and production systems develop towards lower GHG intensity. It is likely, however, that fossil fuels will continue to be used, and thus displaced on the margin by biomass-based alternatives, for a considerable time³³. Further, in the longer term, biomass may be increasingly used in applications where a combination with carbon capture and storage (CCS) enables removal and long-term storage of atmospheric CO₂ in geological reservoirs¹. Such biomass applications can have high mitigation effects also in a scenario where fossil fuels have been phased out.

Methodological comments. While the results for the different deployment scenarios show relatively coherent spatial patterns, spatial extents and absolute numbers vary substantially. This illustrates that large-scale deployment of strategic perennialization can have highly different outcomes, because different types of incentives may exist and farmers may react differently on them. For example, in the Biomass scenario for riparian buffers, farmers are assumed to establish a pre-defined buffer system

wherever the effectiveness of establishing buffers in mitigating N emissions to water has been estimated as medium or higher. This includes 1870 landscapes, out of 81,000 in total, where the impact is already at a low level. In the other scenarios, where farmers are assumed to only implement buffers where N emissions to water is above the low-impact level, these 1870 landscapes are not subject to implementation. Furthermore, as buffers in these scenarios are only implemented to an extent where the predefined impact mitigation is achieved (on average 67% for narrow buffers and 41% for wide or double-wide buffers, as compared with 100% in the Biomass scenario), the total buffer area is further decreased compared with the Biomass scenario. Finally, in the Food-first scenario, where farmers are assumed to achieve the mitigation objective using a minimal area of riparian buffers, the total buffer area is, naturally, decreased even further. The results presented here should therefore be interpreted as indicative for large-scale deployment of riparian buffers and windbreaks, given the set of assumptions in the different scenarios.

Besides uncertainties arising from scenario assumptions, the model is subject to several uncertainties and limitations. For example, the thresholds used for classifying environmental impacts and impact mitigation effectiveness directly influence where implementation takes place in the different scenarios. Furthermore, while biomass productivity is based on a well-

known pan-European yield model, such a model cannot take specific varying local conditions into account, meaning that local yield variations are not identified. It is also uncertain to which extent the production system assumptions in the yield model can be directly transferred to riparian buffers and windbreaks. This is, however, considered a lesser issue. Finally, assuming that some of the co-benefits are proportional to the share of annual crops is logical, but the relationship is most likely not linear. To assess co-benefits with greater certainty, new simulations for erosion and N emissions would be necessary, based on the land-use resulting from the different deployment scenarios.

Policy implications. Multifunctional riparian buffers and windbreaks can provide substantial environmental benefits with limited negative effects on current agricultural production. However, it must be taken into account that at local and regional levels, buffer and (especially) windbreak establishment can represent a substantial amount of agricultural land, which can influence the local economy and the general characteristics of the landscape.

At the same time, the local concentration of dedicated land to the proposed plantation systems may create an advantage for its implementation, by generating a critical mass of land that can assure a proper market development for the resulting biomass³⁴. In fact, an important barrier towards wider implementation of multifunctional systems has been described as the lack of markets, or policies, compensating producers for enhanced ecosystem services and other environmental benefits^{3,15}. Realizing the deployment scenarios presented here thus require substantial policy efforts to generate sufficient incentives. Such efforts are now becoming visible in the EU. One potential opening may be the introduction of Eco-schemes in the new CAP. Eco-schemes will offer farmers the possibility to grant direct payments to adapt practices beneficial for climate, water, soil, air and biodiversity¹¹. As illustrated in this assessment, such practices could include the establishment of multifunctional biomass production systems. This is a practical example of how to combine climate and agriculture policy goals, by producing long-term sustainable biomass feedstock which could replace fossil fuels and improve agricultural production in general. A critical aspect is therefore to increase the knowledge of opportunities with multifunctional biomass production systems among all EU member states before designing and introducing country specific Eco-scheme options in the new CAP.

Depending on the prioritization of specific environmental issues and ambitions regarding environmental targets in the various EU member states and regions, the different deployment scenarios presented here can act as strategic support. For example, if biomass production and high climate change mitigation are prioritized in a member state that is highly dependent on fossil energy, then the Biomass scenario can indicate the upper level of the amount of biomass that can be locally produced from these particular multifunctional production systems. Is, on the other hand, food production prioritized in a densely populated member state with a limited area of agricultural land per capita, then the Food-first scenario can indicate the deployment potential. Thus, the outcome of the different deployment scenarios could give valuable input to the development of target levels and the design of appropriate incentives.

In case yield improvements cannot fully compensate for losses in cropland area, the potential connection between the establishment of biomass production systems on cropland and indirect land use changes, causing, e.g., biodiversity impacts and ecosystem carbon losses, remains an additional concern^{35–38}. The same concern exists when lower-yielding alternative farming

practices are introduced to reduce environmental impacts, as exemplified by studies associating organic food with additional emissions³⁹, or foregone carbon sequestration⁴⁰, due to the need for more land to compensate for lower yields. Examples of such carbon leakage in other sectors include those associated with the electrification of vehicle fleets, which may result in substantial up-front carbon emissions due to large demand for batteries with high embedded emissions, and low net reduction of CO₂ emissions from displacing petrol and diesel use in ICE vehicles due to battery charging with carbon-intensive electricity^{41–43}. Indirect land use change and carbon leakage need to be taken into account and addressed in appropriate ways. We argue that decision-making in the context of societal sustainability transitions needs to reflect a holistic view on both supply-side and demand-side mitigation, and be based on data and insights from many scientific disciplines and complementary methodologies covering a multitude of sustainability indicators. Taking the example of organic meat, consumers who are motivated to buy organic meat for environmental and ethical reasons may also buy fewer animal-based products in the first place^{44,45}. Thus, the larger land demand associated with one individual food product is balanced by a declining land demand associated with a broader dietary shift⁴⁶.

Outlook. While this study provides new insights concerning strategic perennialization for achieving beneficial LUC, it is limited to two options that are relevant only in parts of the EU. There are additional options for strategic perennialization, addressing other negative impacts of current and historic land use^{3,15}. Such systems can be studied in a similar manner to provide complementary insights in the potential for beneficial LUC through widespread deployment of multifunctional biomass production systems. Furthermore, intra-landscape modelling, considering a broad range of possible benefits and trade-offs, is necessary to fully understand the effects of introducing these kinds of systems at the landscape scale. Such information can also be valuable to support local or regional spatial planning, where different goals and objectives, from different stakeholders, need to be considered⁴⁷. Finally, the model results could be compared to requirements in national implementations of the water framework directive (WFD), to identify the degree to which multifunctional production systems could contribute to fulfilling legal requirements, but also to support how such requirements could potentially be revised to effectively result in good ecological conditions.

Methods

Two main types of multifunctional biomass production systems were modelled: riparian buffers and windbreaks. For each system, we modelled the implementation in individual landscapes under different deployment scenarios where strategic perennialization is incentivized and quantified the corresponding (i) areas; (ii) amounts of biomass produced and the corresponding energy content; (iii) primary environmental benefit; and (iv) environmental co-benefits.

The analysis and aggregation unit is equivalent to (modified³) functional elementary catchments from the ECRINS database⁴⁸, and is thus identical to sub-catchment or sub-watershed. This unit was selected because of the need to model nitrogen emissions at this scale, but also because it was considered appropriate for analysing multiple other impacts, such as water erosion and flooding. This unit is here consistently referred to as landscape. While the term landscape can have different meanings and be used in different ways in different contexts, fields, and traditions, it is here considered an intermediate integration level between the field and the physiographic region⁴⁹. The extent of a landscape should also depend on the spatial range of the biophysical and anthropogenic processes driving the processes under study⁴⁹. In this case, we argue that 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 flows³. Sub-watersheds can thus, according to this definition and in this particular context, be considered equivalent to landscapes. An additional motivation for using the term landscape here, is the increasing focus on implementing a landscape perspective for addressing environmental impacts, acknowledging that

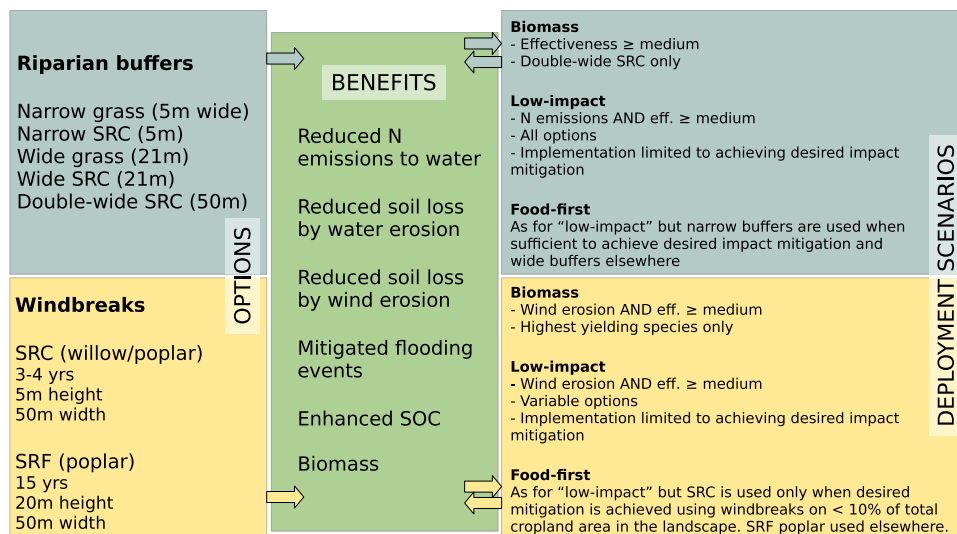


Fig. 9 Simplified illustration of options, benefits, and scenarios included in the model. Riparian buffers have five design options and aim primarily at reducing N emissions to water. Windbreaks have two design options and aim primarily at reducing soil loss by wind erosion. The model quantifies buffer/windbreak areas, corresponding biomass output, and respective primary environmental benefit. Simultaneous mitigation of multiple other negative environmental impacts (co-benefits) are also quantified.

mitigation depends on measures taken by multiple stakeholders, at a greater scale than the individual field⁴⁹.

The landscape dataset contains over 81,000 sub-watersheds across the EU27 + UK. The spatial analysis and operations, including all the database aggregation queries, were performed in GRASS GIS⁵⁰ with projection EPSG:3035, whereas the cartography and some specific GIS operations were done in QGIS⁵¹.

Degree of environmental impact and effectiveness of strategic perennialization.

Current N emissions to water, soil loss by water erosion, soil loss by wind erosion, recurring floods, and accumulated losses of SOC were estimated in a previous study³ for the same landscape dataset as used for the modelling presented here. The impacts are described both in absolute terms, based on spatial indicators, and in relative terms on a five-step scale from very low to very high (Table 1). The effectiveness of strategic perennialization, for each impact and in each landscape, was also estimated by combining the degree of impact with the density of annual crops⁵. As for the impacts, the effectiveness for the different impacts is described on a five-step scale from very low to very high. See the original article³ for further methodological details concerning impact and impact mitigation estimates.

Conceptual scenarios of widespread deployment. To illustrate different outcomes of widespread implementation of riparian buffers and windbreaks, three deployment scenarios were designed (Fig. 9). In all scenarios, it is assumed that certain environmental impacts are addressed at the EU-level via incentives for strategic introduction of perennials into intensively managed agricultural landscapes, to mitigate specific impacts of concern. It is also assumed that there is a demand for biomass produced in the multifunctional system within the biobased sectors, which are expected to grow in response to national and EU-level bioeconomy strategies⁵². It should be noted that there may be spatial mismatches between deployment potentials for perennial systems and biomass demand growth associated with existing or new biomass conversion plants⁵³. Such mismatches have not been considered here. The specific implementation under each scenario is assumed to be made by farmers (here generically referring to any relevant stakeholder in land use management) under different incentive schemes. The model does not aim to identify which specific option is implemented by a specific farmer or group of farmers, nor to the specific incentives needed, but rather identifies the outcomes when all farmers make the same decisions, based on an incentive scheme under the assumptions of each scenario. The scenarios are conceptualized as follows, and further described, including how they translate to specific modelling assumptions, under the respective multifunctional systems below:

In scenario 1 (Biomass), there are incentives for implementing multifunctional biomass production systems in all landscapes where the effectiveness in mitigating the corresponding primary impact has been classified as above low (Table 1). The degree of the impact, and the corresponding impact mitigation potential, in individual landscapes are generally not considered. Incentives are such that farmers are assumed to select the default option that is expected to result in the highest mitigation, while maximizing biomass output from the multifunctional biomass production system.

In scenario 2 (Low impact), incentives for mitigating the primary impact are generally stronger than in scenario 1, but there are no incentives when the primary impact is below a low level at the landscape scale. Local and regional circumstances will determine whether farmers will prefer to favour biomass production in the multifunctional system or to minimize effects on current agricultural production. Different options for strategic perennialization may therefore be implemented in different landscapes.

In scenario 3 (Food first), incentives are the same as in scenario 2, with the addition that impacts on food production are disincentivized. Farmers are therefore assumed to minimize the area used for the multifunctional system, while still achieving mitigation down to a low-impact level (Table 1) at the landscape scale.

Deployment scenarios and design options for riparian buffers. Reduced N emissions to water is considered to be the primary benefit of riparian buffers. This refers to diffuse N emissions that reach watercourses by runoff or shallow groundwater⁵⁴. Co-benefits include (i) enhanced SOC, (ii) avoided water erosion, and (iii) retention of sediment. We also explore the potential co-benefits (i) flood mitigation and (ii) reduced wind erosion.

Five different riparian buffer systems have been defined (Table 3), based on three different widths. First, a 5 m narrow option represents mandatory requirements in, e.g., Italy and is based on empirical experiments¹⁴. Second, a 21 m wide option represents a buffer with 100% buffer strip efficiency (BSE), based on a regression analysis¹⁴. Third, a 50 m double-wide option represents a system where agricultural practices and economic aspects are taken more into account¹³. In this system, only half of the buffer area is harvested each season, thus reducing temporal variations as a result of temporarily decreased BSE after harvest when all biomass is removed at once. The first two systems were modelled with either SRC, i.e., fast-growing tree species cultivated as coppice, with multiple shoots from the stump, or with grass. The third was modelled only with SRC. BSE for SRC and grass was determined based on “buffer width necessary to obtain a given value of BSE” for “bioenergy crops”, i.e., miscanthus and willow¹⁴.

In the Biomass scenario, farmers are assumed only to implement double-wide SRC buffers (Table 3), as this provides economical and practical advantages due to larger cropping sites, maximum biomass production from the SRC buffers, and maximum impact mitigation. In all landscapes, the highest yielding SRC species is used, to maximize land-use efficiency. Spatial deployment is constituted by landscapes where the effectiveness of strategic perennialization for mitigation N emissions to water has been classified as at least medium.

In the Low-impact scenario, farmers can implement any of the five defined buffer systems (Table 3), depending on what is most favourable in their respective landscapes. This means that the highest yielding SRC or grass species is used in all landscapes. Since the model assumes that all farmers make the same decision, this scenario results in three different alternatives, based on the three buffer types. The extent of the implementation in each landscape is, however, limited by the degree of impact mitigation necessary to reduce the impact down to a low level, at the landscape scale. Note that Table 2 shows the highest and lowest values while Supplementary Table 1 shows results for all alternatives. Spatial deployment is constituted by landscapes where both (i) N emissions to water and (ii) the

Table 3 Options for riparian buffer systems and corresponding buffer strip efficiency for reducing N emissions to water, and sediment trapping efficiency.

Name	Description	Buffer strip efficiency (%)	Sediment trapping efficiency (%)
Narrow grass	5 m buffer with grass	60	75
Narrow SRC	5 m buffer with SRC	60	75
Wide grass	21 m buffer with grass	100	100
Wide SRC	21 m buffer with SRC	100	100
Double-wide SRC	50 m buffer with SRC. Half of the buffer harvested each time	100	100

effectiveness of mitigating N emissions to water by strategic perennialization, have been classified as at least medium.

In the Food-first scenario, farmers establish narrow buffers (Table 3) to the greatest extent possible to minimize effects on food production. In landscapes where narrow buffers do not suffice to reduce the environmental impact down to a low level at the landscape scale, wide buffers (Table 3) are used as a complement. Double-wide buffers (Table 3) are not implemented as they do not result in a higher primary impact mitigation than wide buffers. In all landscapes, the highest yielding SRC and grass species, respectively, is used, to ensure maximum land-use efficiency. Spatial deployment is the same as in the Low-impact scenario.

Primary impact mitigation potential of riparian buffers. The impact mitigation potential depends on the current primary impact and the BSE of the different buffer designs (Table 3). The following was calculated for all buffers designs in the different deployment scenarios, for each landscape:

- *Maximum impact mitigation* ($\text{kg N ha}^{-1} \text{y}^{-1}$), estimated as the product of *current N emissions to water* and the respective *BSE*.
- *Maximum amount of avoided N emissions per year*, estimated as the product of *maximum impact mitigation* and *total landscape area*.
- *Necessary impact mitigation to achieve a low-impact level*, estimated as the difference between *current N emissions to water* and the *upper threshold for the impact class low*.
- *Share of impact mitigation necessary to achieve a low-impact level*, estimated as the quotient between *necessary impact mitigation to achieve a low-impact level* and *maximum impact mitigation*.

Riparian buffer deployment areas. For each buffer option in the three deployment scenarios, the buffer area in each individual landscape was estimated as the product of buffer width (times two, assuming that it is established on both sides of the watercourse) and the total length of primary and secondary drains in each landscape. The latter was calculated based on a river dataset from the European Catchments and Rivers Network System (ECRINS) project⁴⁸. This dataset was developed in parallel with the sub-catchment dataset that is the basis for the landscape dataset used here. To calculate total river length, all river polylines were first cut by the landscape polygons and the sum of the length of all polylines in each landscape was then calculated and added as a new attribute to the landscape dataset using the QGIS tool Sum line length.

The above approach resulted in the maximum buffer area for the three buffer designs, considering only buffer widths and lengths of primary and secondary drains in each landscape. The maximum area was thus used in the Biomass scenario, in which deployment is driven by incentives for maximized multifunctional biomass production and maximum impact mitigation, not limited by a certain degree of impact mitigation or implications for food production.

In the Low-impact and Food-first scenarios, however, deployment is driven by incentives to reduce N emissions to water to, but not beyond, a low level. This means that the buffer area in many cases will be smaller than the maximum area, since the maximum area results in a greater impact mitigation than what is necessary to fulfil the objective. To estimate the buffer area needed to achieve a low impact in each landscape, it was assumed that BSE, at the landscape scale, is proportional to the share of the maximum buffer area. For example (cf. Table 3) if a BSE of 30% is necessary to reduce N emissions down to a low-impact level, 50% of the maximum area for narrow buffers (having a BSE of 60%) is needed, and 30% of the maximum area for wide or double-wide buffers (having a BSE of 100%).

The buffer area for the different buffer design options in the Low-impact scenario was therefore estimated as the product of *share of impact mitigation necessary to achieve a low-impact level* (see the previous section) and *maximum buffer area*.

Finally, in the Food-first scenario, deployment is driven by incentives to reduce N emissions to water to, but not beyond, a low level, but also by incentives to minimize impacts on food production. Since farmers would seek to optimize (in terms of buffer area) the impact mitigation, they utilize narrow buffers to the extent that they suffice to reduce the impact down to a low-impact level, at the landscape scale, and wide buffers elsewhere. We therefore first assessed in which landscapes that narrow buffers suffice, by comparing impact mitigation necessary to achieve a low-impact level with maximum impact mitigation for narrow buffers specifically.

Where the former exceeds the latter, wide buffers are implemented. In other landscapes, only narrow buffers are used. The corresponding buffer areas were then calculated as for the Low-impact scenario.

Enhanced SOC as a co-benefit of riparian buffers. The effects on SOC from establishing riparian buffers were based on SOC simulations of permanent grasslands in relation to a BAU SOC scenario²², available at the Joint Research Centre European Soil Data Centre (ESDAC; <https://esdac.jrc.ec.europa.eu/>).

The SOC simulations are spatially explicit and provide BAU SOC estimates (t C ha^{-1}) for 2010, 2020, 2050, 2080, and 2100, assuming a continued rotation with the four most dominant crops in each area. They also provide SOC values in relation to these BAU values for multiple management options, including a permanent grassland system, in which the BAU rotation is replaced by permanent grassland. It is here assumed that SOC effects of establishing permanent grassland on cropland is representative of SOC changes in riparian buffers, as these are permanent perennial systems with documented positive effects on SOC¹⁴.

SOC values relative BAU for permanent grassland were rasterized to 100 m and new SOC values were added to the landscape dataset by identifying the median value within each landscape (GRASS: v.rast.stats). BAU values are referred to below as SOCbau_[year] and SOC increases relative BAU from implementation of permanent grassland are referred to as SOCinc_[year]. SOCinc values in the dataset 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 and 2080 as points in time for assessment. SOCbau did not require re-estimation as it represents a continuation of BAU land-use. SOCbau_2020 was thus considered representative for current SOC.

To reflect that SOC tends to increase more rapidly early after the introduction of a new land-use system²², SOCinc_2020 was assumed to represent the change in SOC during the first ten years, i.e., between 2020 and 2030 (SOCinc_first10). SOC changes during the remaining period (i.e., 20 and 50 years, for 2050 and 2080, respectively) was calculated by subtracting SOCinc_first10 from SOCinc_2050/2080, representing SOC changes in 30/60 years following the first 10 years (SOCinc_last30/60). Since we require SOC changes in 20/50 years, these values were downscaled by 20/30 and 50/60, respectively (SOCinc_last20/50). Finally, SOC increases by 2050/2080 relative BAU could be calculated as the sum of SOCinc_first10 and SOCinc_last20/50.

At this point, SOC changes per hectare of riparian buffers by 2050/2080 relative BAU, with base year 2020, have been estimated. SOC changes per hectare of cropland were then calculated as the product of SOC changes per hectare of riparian buffers and share of area under annual crops used for riparian buffers in each deployment scenario, for all individual landscapes.

Avoided water erosion as a co-benefit of riparian buffers. Soil erosion within SRC systems can be considered marginal^{14,55}. Fully replacing annual crop production with SRC is therefore assumed to reduce soil erosion nearly completely on that specific land. Consequently, the share of land under annual crop production used for riparian buffers indicates the share of reduced soil loss by water erosion, at the landscape scale.

First, avoided soil loss by water erosion per hectare and year was calculated in each landscape, for each riparian buffer option, as the product of *share of area under annual crops used for riparian buffers* and *current soil erosion by water on land used for annual crop production*. The total amount of avoided soil loss by water erosion per year in each landscape was calculated as the product of *avoided water erosion per hectare* and *total area under annual crop production*. The share of avoided water erosion relative total water erosion was then calculated as the quotient of *amount of avoided soil loss* and *total soil loss* in each landscape. Finally, the degree to which riparian buffers could contribute to reducing soil loss by water erosion down to a low-impact level, at the landscape scale, was estimated as the quotient of *avoided soil loss by water erosion per hectare and year* and *soil loss by water erosion above the threshold for low impact* (Table 1).

Sediment retention as a co-benefit of riparian buffers. Sediment retention was quantified based on the assumption that all soil loss by water erosion on cropland at the sub catchment scale is destined to end up in watercourses within the catchment. Total sediment loads in each landscape are thus equivalent to soil loss by water erosion³, reduced by avoided water erosion as estimated above. Empirical

studies have shown that buffer widths of 3, 6, and 7 m, can have sediment trapping efficiencies (STE) of 66%, 77%, and 95%, respectively⁵⁵. Based on this, trapping efficiencies of 75% for the narrow buffer and 100% for the wide and double-wide buffers, were assumed.

In the Biomass scenario, sediment retention at the landscape scale was estimated as the product of STE and total sediment load, as estimated above. In the other scenarios, where buffers are only implemented to the extent where N emissions to water is decreased to a low level, sediment retention is calculated as the product of sediment retention in the Biomass scenario and the share of total buffer area that is needed in each landscape to achieve low N emissions to water, for each buffer design.

Deployment scenarios and design options for windbreaks. The primary benefit of windbreaks is mitigation of soil loss by wind erosion. Co-benefits include enhanced SOC and reduced N emissions to water. Potential co-benefits include flood mitigation.

Two design options for windbreaks have been defined. First, SRC windbreaks refer to the establishment of SRC willow or poplar, with a rotation period of 3–4 years and a height of 5 m. Second, SRF windbreaks refer to the establishment of SRF poplar, with a rotation period of 15 years and a height of 20 m⁵⁶.

In both the SRC and the SRF design, a windbreak width of 50 m is assumed, for practical and economic reasons, since larger cropping sites reduce management costs, following the same reasoning as for double-wide riparian buffers. The distance between windbreaks is assumed to be 20H, i.e., 20 times the windbreak height¹⁶. In both designs, half of the windbreak is harvested at a time, allowing for constant windbreak functionality.

In the Biomass scenario, farmers can implement either SRC willow/poplar or SRF poplar, depending on which is most favourable in their respective landscapes. The design option is not affected by incentives to maximize biomass production, as biomass production per hectare is the same in both options. The design option is also unaffected by incentives to maximize mitigation of soil loss by wind erosion, as this is assumed to be identical for both options. Spatial deployment is constituted by landscapes where the effectiveness of strategic perennialization for mitigating soil loss by wind erosion is classified as at least medium (Table 1). However, as it is assumed that windbreaks can only achieve mitigation down to a low-impact level (see below), landscapes also need to have a current impact level of at least medium for soil loss by wind erosion. Where willow is higher yielding than poplar: SRC willow windbreaks are established. Where poplar is higher yielding: either SRC or SRF poplar windbreaks are established. Since the model assumes that all farmers make the same decision, this scenario results in two alternatives; one with SRC poplar and one with SRF poplar.

In the Low-impact scenario, farmers can implement either SRC willow/poplar or SRF poplar windbreaks, depending on what is considered most favourable in their respective landscapes, but only to an extent where the environmental impact is mitigated down to a low level, at the landscape scale. Spatial deployment is identical as in the Biomass scenario. SRC or SRF poplar windbreaks are established where poplar is higher yielding than willow. Where willow is higher yielding, willow SRC is preferred but SRF poplar can also be established if it is considered more favourable for other reasons. Since the model assumes that all farmers make the same decision, this scenario results in multiple alternatives: (i) only SRC, (ii) only SRF, (iii) SRC willow and SRF poplar, and (iv) SRC poplar and SRF poplar. In all landscapes, implementation is limited to what is necessary to achieve a low impact, at the landscape scale. Note that Table 2 shows the values for alternatives i and ii, while Supplementary Table 2 shows results for all alternatives.

In the food-first scenario, where farmers are incentivized to minimize impacts on food production, the share of cropland used for windbreaks is limited to less than or equal to the expected resulting yield increases on sheltered cropland. Farmers, therefore, seek to achieve impact mitigation down to a low level, in each landscape, while limiting the area used for windbreaks to a maximum of 10% of the area under annual crops¹⁶, as detailed below. Spatial deployment is identical as in the other scenarios. SRC willow or poplar windbreaks are implemented, depending on what is highest yielding, where the area needed for SRC windbreaks to reduce impact down to a low level does not exceed 10% of the cropland area in the landscape. Where a larger share of the existing cropland area is needed, SRF poplar is used.

Primary impact mitigation potential of windbreaks. Soil loss by wind erosion is classified as low (and rarely very low) in a vast majority of agricultural landscapes across Europe³. Windbreaks are therefore assumed to be able to reduce soil loss by wind erosion to a low level, i.e., $5 \text{ t ha}^{-1} \text{ y}^{-1}$ (Table 1), but not further. It is also assumed that a windbreak distance of 20H may not suffice to achieve this level of impact mitigation (i.e., down to a low level) in all landscapes^{16,57}. An assumption was therefore made that the defined windbreak options, if fully implemented in all agricultural fields currently under annual crops, suffice to reduce wind erosion from a high to a low-impact level, at the landscape scale. Landscapes with a higher current impact than high therefore need shorter windbreak distances to achieve the desired impact mitigation. It is further assumed that landscapes with a current impact lower than high, and thus in need of lesser impact mitigation to achieve a low level of wind erosion, at the landscape scale, require lesser mitigation efforts. In such cases, a

greater distance between windbreaks, or windbreaks implemented only in selected parts of the landscape, may suffice to achieve the desired impact mitigation.

Based on these assumptions, a windbreak implementation level was estimated for each landscape, based on the need for impact mitigation to reach a low level of soil loss by wind erosion. The implementation level was assumed to decrease linearly from 100%, in landscapes with wind erosion of $10 \text{ t soil loss ha}^{-1} \text{ y}^{-1}$ (the upper threshold for high impact), to 0% for landscapes already having a low, or lower, impact ($\leq 5 \text{ t soil loss ha}^{-1} \text{ y}^{-1}$), cf. Table 1. Landscapes exceeding the threshold for very high receive an implementation level >1 to reflect that the distance between windbreaks needs to be shorter (minimum 11H for the landscape having the highest wind erosion, 16.8). This implementation level was calculated for all landscapes using Formula 1. Note that the implementation level in the Biomass scenario is always 100%.

$$\text{implementation}_{\%} = (\text{impact} - \text{impact}_{\text{low}}) / (\text{impact}_{\text{high}} - \text{impact}_{\text{low}})$$

where impact = current impact; $\text{impact}_{\text{low}}$ = threshold for low impact; $\text{impact}_{\text{high}}$ = threshold for very high impact.

Formula 1: Estimation of the share of maximum implementation needed to achieve a low level of wind erosion at the landscape scale. Negative values = zero.

Having established the implementation level in each landscape, the following can be calculated:

- *Necessary impact mitigation to achieve a low-impact level ($t \text{ soil loss ha}^{-1} \text{ y}^{-1}$)* estimated as the difference between the upper threshold for the impact class low and current soil loss by wind erosion.
- *Maximum impact mitigation ($t \text{ soil loss ha}^{-1} \text{ y}^{-1}$)* for all windbreak options, estimated as equal to *necessary impact mitigation to achieve a low-impact level*. In the Biomass scenario, however, simpler incentives are assumed, in which the landscape-specific potential for impact mitigation is not considered. The implementation level in the Biomass scenario is therefore always 100%. In landscapes where an implementation level $>100\%$ is necessary to achieve this degree of impact mitigation, necessary impact mitigation to achieve a low-impact level will exceed maximum impact mitigation. In the Biomass scenario, maximum impact mitigation was therefore set manually to 8, i.e., the difference between the upper thresholds of high and low impact, in landscapes where the implementation level exceeds 100%.
- *Maximum amount of avoided wind erosion ($t \text{ soil loss y}^{-1}$)* estimated as the product of maximum impact mitigation and total area under annual crops.
- *Share of impact mitigation necessary to achieve a low-impact level, estimated as the quotient of necessary impact mitigation to achieve a low-impact level and maximum impact mitigation.*

Windbreak deployment areas. For each landscape, and for the two windbreak designs, the total windbreak area needed to reduce wind erosion to a low level was calculated as the product of (i) implementation level, as calculated above, (ii) the share of land under annual crops needed for establishing windbreaks at 100% implementation, and (iii) the total area under annual crops.

The total share of agricultural land under annual crop production needed for establishing windbreaks, at 100% implementation, is calculated as the quotient of windbreak width and windbreak distance, i.e., 1/3 for SRC windbreaks and 1/9 for SRF windbreaks.

Co-benefits of windbreaks. N emissions to water from SRC or SRF systems can be considered marginal^{55,58,59}. Following the same assumptions as for water erosion, avoided N emissions to water (per hectare and year) was estimated in each landscape as the product of *share of area under annual crops used for windbreaks* in the two different windbreak designs, and *current N emissions to water*. The total amount of avoided N emission to water in each landscape was then calculated as the product of *avoided N emissions to water* (per hectare and year) and *total area of the landscape*. Finally, the degree to which riparian buffers could contribute to reducing N emissions to water down to a low-impact level, at the landscape scale, was estimated as the quotient of *avoided N emissions to water* and *current N emissions to water above the threshold for low impact*.

Effects on SOC estimated as for riparian buffers.

Avoided soil loss by water erosion estimated as for riparian buffers.

Estimation of biomass production from riparian buffers and windbreaks.

Biomass production from riparian buffers was estimated for each suitable landscape and for each buffer option in the three deployment scenarios, as the product of buffer areas, estimated as described above, and the yield of the highest yielding SRC and grass option, respectively. The latter was identified using pan-European yield simulations at NUTS3 level⁶⁰. Simulated yields for SRC willow, SRC poplar, other SRC, miscanthus, switchgrass, and reed canary grass, using a medium yield-input management level, were identified for each landscape by first spatially joining landscapes to NUTS-3 regions, and then joining the database tables. Yields are expressed as $\text{t DM ha}^{-1} \text{ y}^{-1}$. The energy output is calculated as the product of

biomass production and energy content of the harvested biomass; 18.7 MJ/kg DM, for both SRC^{61,62} and grass⁶³.

Biomass production from windbreaks was estimated as for riparian buffers, but considering only SRC willow and SRC poplar. The yield for SRC poplar was assumed to be identical to SRC poplar^{64,65}. The energy content, 18.7 MJ kg⁻¹ DM, was used for both SRC willow and SRC/SRF poplar^{61,62}.

Additional co-benefits. As detailed above, riparian buffers and windbreaks are likely to have positive effects in reducing flooding events. However, no empirical data for quantifying such effects have been found. The extent to which this benefit may occur is therefore considered to differ between different landscapes, depending on landscape-specific characteristics. For example, if the predominant wind direction is parallel to watercourses in a landscape, windbreaks will be established predominantly perpendicular to contour lines and thus have limited effect on regulating water flows. Furthermore, for riparian buffers, the cause of flooding in a landscape may be predominantly caused by the land-use upstream of the main catchment drain, i.e., in another landscape.

No attempts were therefore made to quantify this co-benefit in biophysical units. Instead, we attempt to indicate the likelihood of mitigated or avoided flooding events as a result of the establishment of riparian buffers or windbreaks. This was done by assuming that the likelihood is directly correlated with the effectiveness of strategic perennialization in mitigating recurring floods³. An effectiveness of medium corresponds here to a likelihood of medium, etc. The effectiveness of strategic perennialization in mitigating recurring floods was therefore identified for each landscape where riparian buffers and windbreaks are introduced, respectively, in the different deployment scenarios.

Wind erosion mitigation by riparian buffers was estimated in the same way as for flood mitigation.

Avoided GHG emissions. The EU Renewable Energy Directive presents GHG emissions default values for several different production pathways of liquid and gaseous biofuels as vehicle fuels in road transport, and solid biomass fuels for electricity, heating and cooling⁷. These default values do not include any net-carbon emissions from potential land-use change.

Regarding Fischer-Tropsch (FT) diesel, methanol, and dimethylether (DME) based on farmed wood, equivalent SRC, the GHG emissions savings are estimated to amount to ~82% when fossil diesel and gasoline are replaced. This is equivalent to 77 g CO₂-eq per MJ biofuel. Assuming an energy conversion efficiency from biomass feedstock to final biofuel of, on average, 50%, 60%, and 65% for FT-diesel, methanol and DME, respectively, the 300 PJ SRC biomass produced in riparian buffers can lead to an annual GHG emission saving of 11.5–15.0 Mt CO₂-equivalents, depending on the biofuel pathway. The corresponding GHG emissions savings of using 450 PJ SRC biomass produced in windbreaks are 17.5–22.5 Mt CO₂-equivalents per year.

If the SRC biomass is used for electricity and heat production, the default GHG emission savings are, according to EU RED, ~80 and 86%, respectively⁷. Compared with the fossil fuel comparator, and an estimated energy conversion efficiency of 40% and 85%, respectively, the GHG saving per MJ of SRC biomass is equivalent to some 58 g CO₂-equivalents for both electricity and heat production. Thus, utilising the 300 PJ SRC biomass from riparian buffers for electricity or heat production may lead to an annual GHG saving of 17.5 Mt CO₂-equivalents. The corresponding annual GHG emissions saving of using 450 PJ SRC biomass produced in windbreaks is 26.0 Mt CO₂-equivalents.

Data availability

Spatial data used in the modelling as described in the Methods section can be accessed by following the respective references. Data on environmental impacts and the mitigation effectiveness of strategic perennialization can be accessed from the Swedish National Data service research data portal: <https://doi.org/10.5878/7jw8-ka21>. Spatial data generated in the study and presented in the article can be accessed from the Swedish National Data service research data portal: <https://doi.org/10.5878/yz9j-q902>.

Code availability

No code is necessary to reproduce the study but information on specific GRASS GIS execution codes can be given by the corresponding author upon request.

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Conceptualization and study design: O.E., G.B., P.B., Model development: O.E. with contributions from G.B., P.B., B.M.Y., I.D., C.C. and N.S., Analysis: O.E., Investigation: all authors, Visualization: O.E., Manuscript: all authors.

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