

Beneficial land-use change in Europe: deployment scenarios for multifunctional riparian buffers and windbreaks

Oskar Englund (✉ oskar.englund@miun.se)

Mid Sweden University <https://orcid.org/0000-0002-1662-6951>

Pål Börjesson

Lund University

Blas Mola-Yudego

University of Eastern Finland <https://orcid.org/0000-0003-0286-0170>

Göran Berndes

Chalmers, Sweden

Ioannis Dimitriou

Swedish University of Agricultural Sciences

Christel Cederberg

Chalmers University of Technology <https://orcid.org/0000-0003-1362-6742>

Nicolae Scarlat

European Commission. Joint Research Centre

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1 Beneficial land-use change in Europe: deployment 2 scenarios for multifunctional riparian buffers and 3 windbreaks

4 Oskar Englund^{1,2,*}, Pål Börjesson³, Blas Mola-Yudego^{4,5}, Göran Berndes⁶, Ioannis Dimitriou⁵, Christel
5 Cederberg⁶, Nicolae Scarlat⁷

7 1 Dept. of Ecotechnology and Sustainable Building Engineering, Mid Sweden University, Östersund,
8 Sweden

9 2 Englund GeoLab AB, Östersund Sweden

10 3 Div. of Environmental and Energy Systems Studies, Dept. of Technology and Society, Lund University,
11 Lund, Sweden

12 4 School of Forest Sciences, University of Eastern Finland, Joensuu, Finland

13 5 Dept. of Crop Production Ecology, Swedish University of Agricultural Sciences, Uppsala, Sweden

14 6 Div. of Physical Resource Theory, Dept. Of Space, Earth and Environment, Chalmers University of
15 Technology, Göteborg, Sweden

16 7 European Commission. Joint Research Centre (JRC), Ispra, Italy

17

18 * Corresponding author: oskar.englund@miun.se

Abstract

19 The land sector needs to increase biomass production to meet multiple demands while reducing
20 negative land use impacts and transitioning from being a source to being a sink of carbon. The new
21 Common Agricultural Policy of the EU (CAP) steers towards a more needs-based, targeted approach to
22 addressing multiple environmental and climatic objectives, in coherence with other EU policies. In
23 relation to this, new schemes are developed to offer farmers direct payments to adapt practices
24 beneficial for climate, water, soil, air and biodiversity. Multifunctional biomass production systems
25 have potential to reduce environmental impacts from agriculture while maintaining or increasing
26 biomass production for the bioeconomy across Europe. Here, we present the first attempt to model the
27 deployment of two such systems, riparian buffers and windbreaks, across >81.000 landscapes in
28 Europe (EU27 + UK), aiming to quantify the resulting ecosystem services and environmental benefits,
29 considering three deployment scenarios with different incentives for implementation. We found that
30 these multifunctional biomass production systems can reduce N emissions to water and soil loss by
31 wind erosion, respectively, down to a “low” impact level all over Europe, while simultaneously
32 providing substantial environmental co-benefits, using less than 1% of the area under annual crops in
33 the EU. The GHG emissions savings of utilizing the biomass produced in these systems for replacing
34 fossil alternatives, combined with the increases in soil organic carbon, correspond to 1-1,4% of total
35 GHG emissions in EU28. The introduction of “eco-schemes” in the new CAP may resolve some of the
36 main barriers to implementation of large-scale multifunctional biomass production systems. Increasing
37 the knowledge of these opportunities among all EU member states, before designing and introducing
38 country-specific Eco-scheme options in the new CAP, is critical.

1 Introduction

1 Climate change, population growth and changes in per capita consumption will add further pressure on
2 managed as well as natural and semi-natural ecosystems (IPCC, 2019). At the same time, many global
3 scenarios that meet the targets set by the Paris Agreement include a rapid increase in the use of biomass
4 for bioenergy, which is often envisaged in conjunction with carbon capture and storage (IPCC, 2018).
5 Significant mitigation is also expected through changes in land use practices to reduce greenhouse gas
6 (GHG) emissions and provide carbon storage in soils and vegetation (IPCC, 2019). In addition, more
7 sustainable land-use strategies are anticipated regarding other environmental impacts, related to, e.g.,
8 water, soil and biodiversity, driven by various environmental policies (DeBoe, 2020). In short, the land
9 sector needs to increase biomass production to meet multiple demands while reducing negative land
10 use impacts and transitioning from being a source to being a sink of carbon.
11

12 Multiple policies are being developed in the EU to take on this double challenge. For example: (i) the
13 European Green Deal (EC, 2019) has a vision of achieving multiple sustainability and climate
14 neutrality goals by 2050. To decarbonize the energy system, the EU will, e.g., prioritize solutions based
15 on sustainable bioenergy, that needs to comply with strengthened sustainability criteria (EC, 2018a);
16 (ii) the Biodiversity Strategy for 2030 (EC, 2020a) includes general goals for the protection and
17 restoration of nature and biodiversity, requiring high-diversity landscape features on at least 10% of the
18 agricultural area; and (iii) the Farm to Fork Strategy (EC, 2020b) aims to promote the transition to
19 sustainable food production, to protect the environment and preserve biodiversity, and to tackle climate
20 change. Connected to all these policies is the new European Union (EU) Common Agricultural Policy
21 (CAP) for the period 2021-2027, that aims to drive the sustainability transition in agriculture, and
22 enable farmers to play a key role in tackling climate change, protecting the environment, and
23 preserving landscapes and biodiversity (EC, 2018b).
24

25 Three of the CAP's nine specific objectives will concern the climate and environment, namely (i)
26 contribute to climate change mitigation and adaptation, as well as sustainable energy, (ii) foster
27 sustainable development and efficient management of natural resources such as water, soil and air, and
28 (iii) contribute to the protection of biodiversity, enhance ecosystem services and preserve habitats and
29 landscapes (EU, 2019). The new CAP also introduces "Eco-schemes" to incentivize farmers to adopt
30 measures for contributing to the environmental and climate objectives. The schemes offer the
31 possibility to grant direct payments for implementing practices beneficial for climate, water, soil, air,
32 and biodiversity (EU, 2019). Member States will be free to define such schemes, but they are voluntary
33 for farmers.
34

35 Multifunctional biomass production systems are designed, located and managed to reduce
36 environmental impacts from agriculture while maintaining or increasing biomass production for the
37 bioeconomy (Christen and Dalgaard, 2013; Styles et al., 2016; Ferrarini et al, 2017a; Englund et al,
38 2020a; Englund et al, 2020b). Such systems could therefore contribute to the objectives of the
39 emerging EU policies and be eligible for compensation within the EU Eco-scheme framework.
40 Recently, an assessment of the potential for multifunctional biomass production systems in Europe
41 indicated a substantial potential for effective mitigation regarding soil loss by wind and water erosion,
42 nitrogen emission to water, losses of soil organic carbon (SOC), and recurring floods (Englund et al.
43 2020a). This assessment did not, however, provide any quantitative estimates concerning large-scale
44 deployment of specific systems, such as impact mitigation and biomass output.
45

1 Two examples of systems to explore further in this context are riparian buffers and windbreaks.
2 Riparian buffers can consist of woody and/or herbaceous crops, located along watercourses with the
3 primary purpose of retaining nutrients (Christen and Dalgaard, 2013; Ferrarini et al., 2017a; Styles et
4 al., 2016). Buffer strips can deliver additional multiple benefits associated with the characteristics of
5 the perennial crops, most notably flood mitigation and reduced streambank erosion. They are also
6 likely to enhance SOC, if established on land historically used for annual crop production, enhance
7 conditions for biodiversity by, e.g., improving landscape connectivity, and protect agricultural fields
8 from wind and water erosion (Englund et al., 2020a). Windbreaks are strips of woody crops, such as
9 poplar or willow, located within or between fields to protect agricultural land from wind erosion
10 (Osorio et al. 2019). Similar to riparian buffers, multifunctional windbreaks may lead to co-benefits
11 such as enhanced SOC and reduced nutrient leaching (Englund et al., 2020a). Both riparian buffers and
12 windbreaks can be designed using high-yielding species and harvested for biomass, thus increasing
13 land-use efficiency by maintaining agricultural productivity in the landscape while providing
14 environmental benefits. Buffer strips are also recognised as acceptable options by the EU to help
15 protect soil fertility and increase soil organic matter, reduce nutrient losses and soil erosion and
16 enhance carbon sequestration. Buffer strips also contribute to ensure connectivity among habitats, thus
17 avoiding habitat fragmentation through the implementation of the Birds and Habitats Directive
18 (European Commission, 1979; European Commission, 1992).

19
20 Here, we model the implementation of multifunctional riparian buffers and windbreaks in >81.000
21 landscapes in Europe (EU27 + UK), aiming to quantify the resulting ecosystem services and
22 environmental benefits, considering three deployment scenarios with different incentives for
23 implementation. We also estimate GHG emissions savings from utilizing the biomass produced in the
24 multifunctional systems to replace fossil materials, combined with increases in soil organic carbon.
25 Finally, we discuss implications associated with the land-use change, such as for current agricultural
26 production, and relevant land-use policies that may incentivize deployment.

2 Results

2.1 Riparian buffers

1 A total of 7574 landscapes were identified as suitable for riparian buffers in the "Biomass" scenario,
2 and 5705 landscapes in the "Low-impact" and "Food-first" scenarios. The difference is due to higher
3 requirements of N emissions to water to incentivize buffers in the latter two scenarios. These
4 landscapes are predominantly located in north-western Europe (Fig. 1). In most landscapes, SRC was
5 identified as the highest yielding buffer option, with willow as the most suitable SRC species, in terms
6 of productivity. In some countries, however (most notably France, Belgium, and Italy) grass was
7 identified as the highest yielding buffer option.

8
9
10 The degree of N emissions to water in suitable landscapes, and the degree of impact mitigation using
11 different buffer designs, varies substantially, both within and between countries (Fig 1; see also
12 Englund et al. (2020a)). While the impact is already at a "low" level in 1870 of the 7574 landscapes in
13 the "Biomass" scenario, it cannot even be reduced to a "low" level in 1031 other landscapes using only
14 narrow buffers.

15

Share of maximum narrow buffer area needed to achieve "low" impact

■ No buffers necessary

■ 0-10%

■ 10-25%

■ 25-50%

■ 50-75%

■ 75-100%

■ Narrow buffers insufficient

Scenario 1: "Biomass"

■ double-wide SRC buffers with willow

■ double-wide SRC buffers with poplar

■ double-wide SRC buffers with other species

Scenario 2: "Low impact"

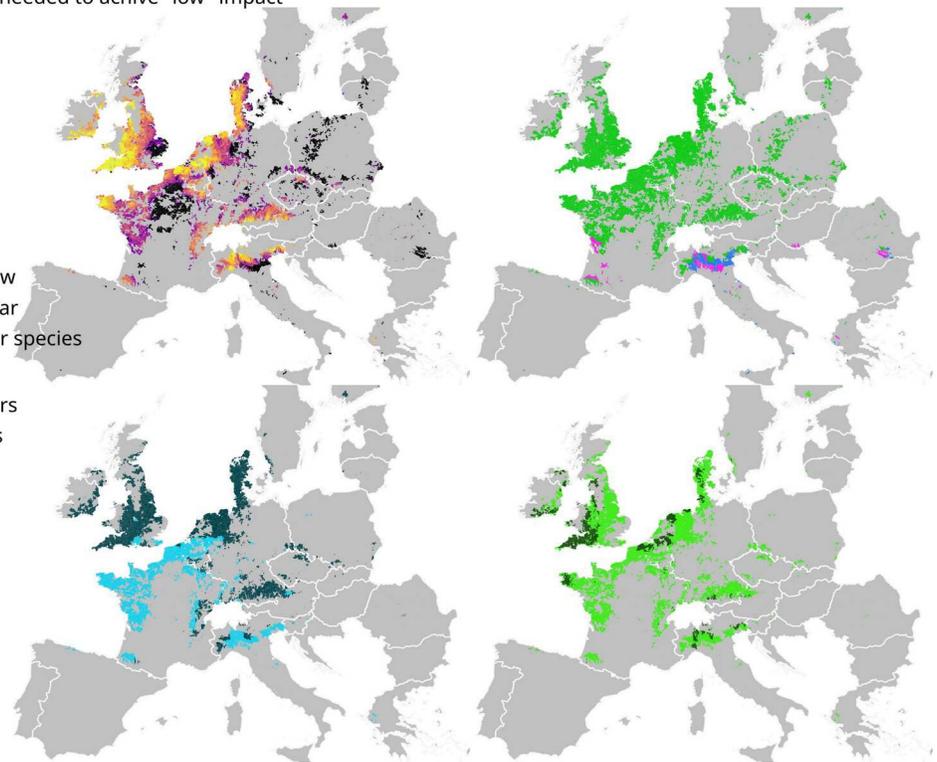
■ narrow to double-wide grass buffers

■ narrow to double-wide SRC buffers

Scenario 3: "Food first"

■ narrow buffers

■ narrow and wide buffers



16

17

18 **Figure 1:** Establishment of riparian buffers in the three deployment scenarios, and the share of maximum narrow buffer
19 area needed to achieve "low" N emissions to water in each landscape.

20

21

1 In the "Biomass" scenario, 1.4 million hectares (Mha) of double-wide SRC buffers are established,
 2 corresponding to 4.6% of the area under annual crops in the affected landscapes and 1.3% of the total
 3 area under annual crops in EU28. These buffers result in about 900 kt of avoided N emissions to water,
 4 while delivering over 16 Mt DM biomass annually. (Table 2; Table S1)
 5

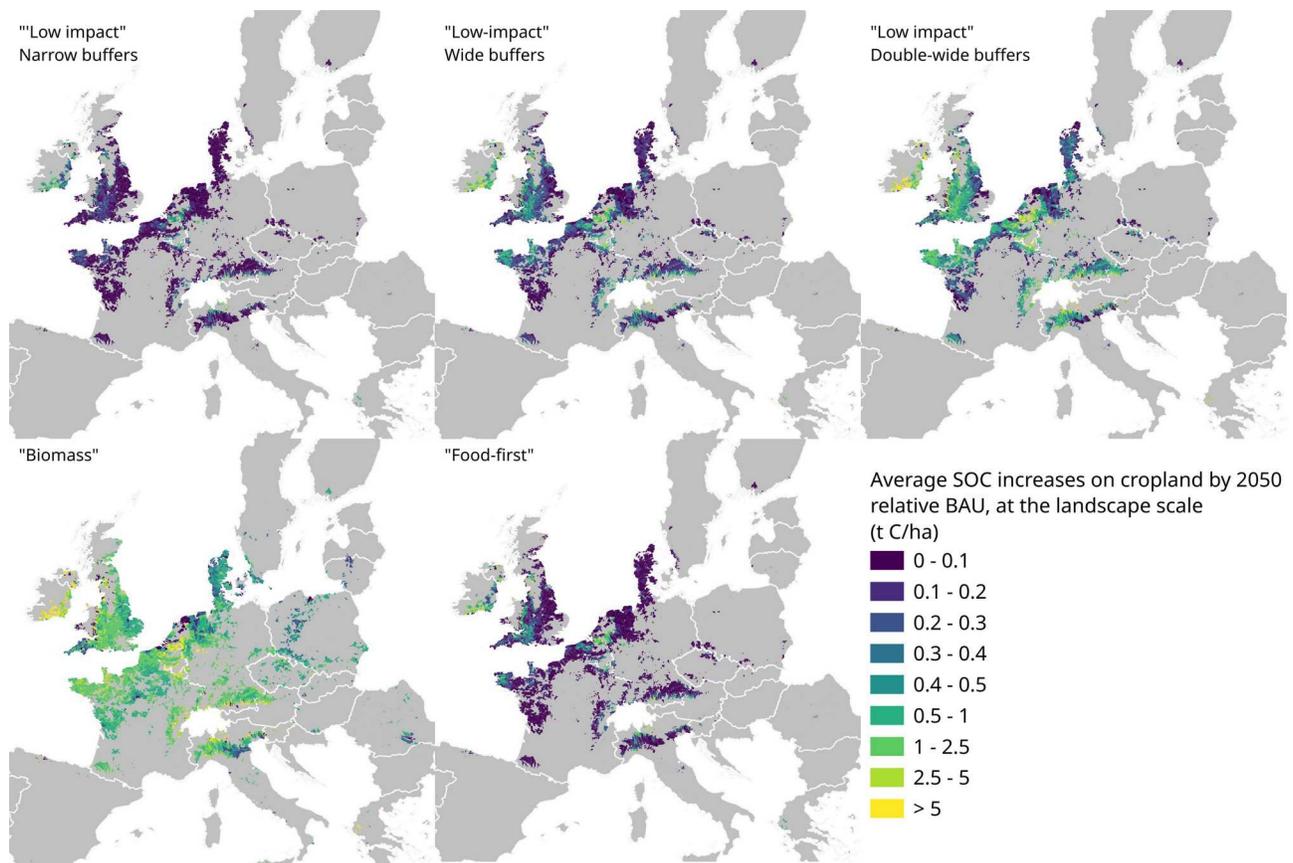
6 In the "Low-impact" scenario, there is a large spread in total buffer area, since farmers can freely
 7 decide which buffer option to implement. It ranges from about 69 kha (if only narrow buffers are
 8 implemented) to 431 kha (if only double-wide buffers are implemented), corresponding to 0.3-2.1% of
 9 the area under annual crops in the affected landscapes and 0.1-0.4% of the total area under annual crops
 10 in EU28. These buffers result in 371 kt of avoided N emissions to water, while delivering between 0.8-
 11 4.9 Mt DM of SRC biomass or 0.8-2.1 Mt DM of grass biomass. (Table 2; Table S1)
 12

13 In the "Food-first" scenario, a total of 101 kha of narrow (49 kha) and wide (52 kha) buffers are
 14 established, corresponding to 0.5% of the area under annual crops in the affected landscapes and 0.1%
 15 of the total area under annual crops in EU28. As in the "Low impact" scenario, these buffers result in
 16 371 kt of avoided N emissions to water, delivering about 1.2 Mt DM SRC or grass biomass annually.
 17 (Table 2; Table S1)
 18

Table 2: Area with riparian buffers, corresponding biomass production, share of buffer area relative areas currently under annual crops, and quantified environmental benefits, for the three scenarios where riparian buffers are implemented in EU28 on a large scale. All values aggregated to EU28.

Riparian buffers	Deployment scenario		
	Biomass	Low-impact	Food-first
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 EU28 (%)	1,3	0,1 - 0,4	0,1
Avoided N emissions to water (kt N)	908	371	371
SOC increase by 2050 (Mt C average kt C/y)	32,8 1094	1,1 - 6,3 35-211	2,2 74
Avoided soil erosion by water (Mt median % of mitigation necessary for achieving "low" impact)	3,3 26	0,2 - 1,2 1,9 - 11	0,3 2,2
Retained sediment (Mt)	49	12,7 - 16,5	15,6

19
 20



1
 2 **Figure 2:** Average increase in SOC on cropland by 2050, relative BAU, in each landscape, in different
 3 deployment scenarios and with different riparian buffer options.
 4

5 **2.1.1 Co-benefits**

6 **Enhanced SOC**

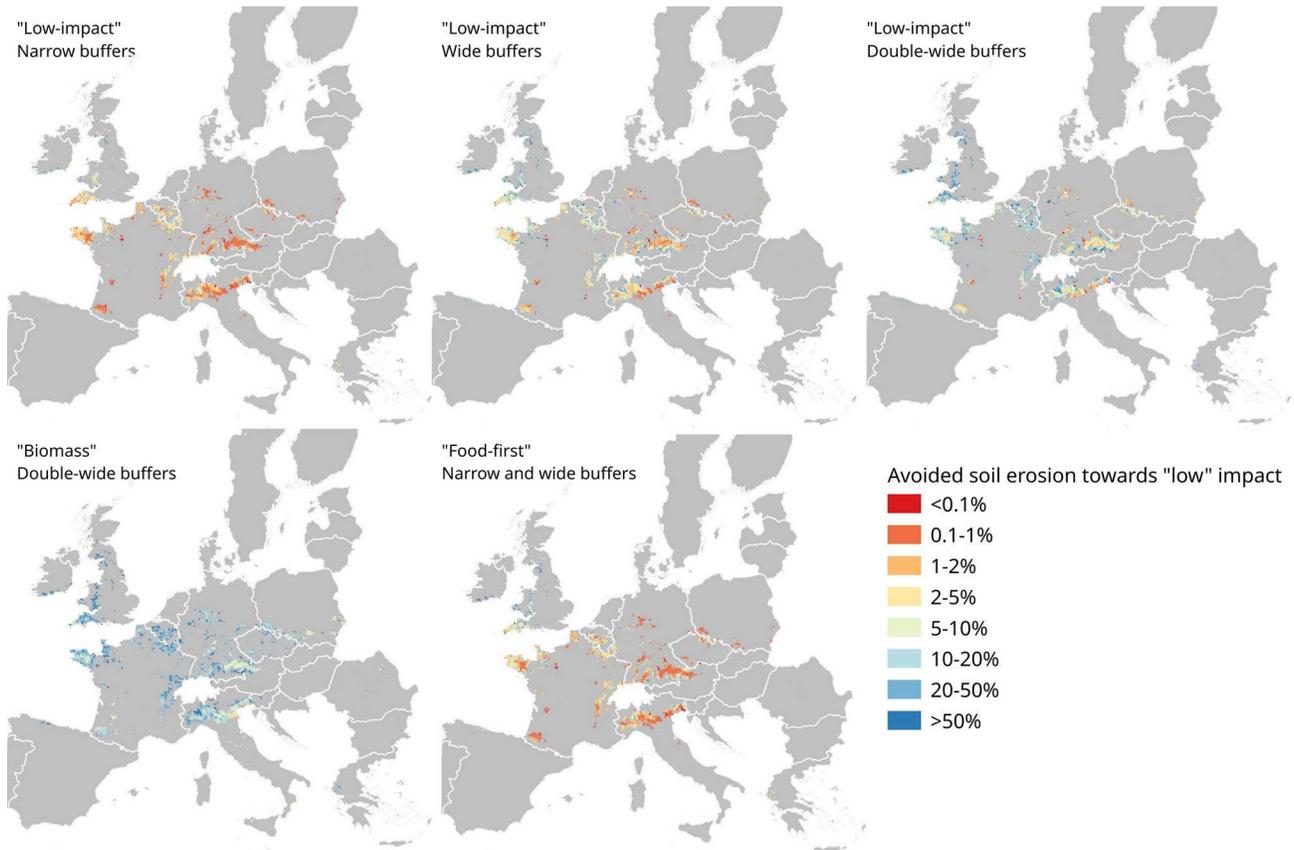
7 The potential of riparian buffers to enhance SOC in specific landscapes and in different scenarios
 8 depends on existing accumulated SOC losses and thus the potential to increase SOC by establishing
 9 perennials, combined with the total buffer area. Given the large variation of both factors, there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

11 In the "Biomass" scenario, given the large areas used for buffers, relative to the other scenarios, SOC
 12 increases are the greatest. By 2050, the SOC increase relative BAU amounts to almost 33 Mt C,
 13 corresponding to avoided GHG emissions of 4 Mt CO₂-eq annually. In the other scenarios the
 14 corresponding numbers are 1.1-6.3 Mt C and 0.1-0.8 kt Mt CO₂-eq/y for "Low impact" and 2.2 Mt C
 15 and 0.3 Mt CO₂-eq/y, until 2050. It should be noted that the annual GHG emissions savings presented
 16 here are average values over 30 years. In reality, SOC increases are greater during the first 10 years
 17 after establishment (Lugato et al. 2014), meaning higher short-term GHG emissions savings from
 18 increased SOC than what is indicated here.
 19

20 While these SOC increases can be considered substantial in absolute terms, riparian buffers are unlikely
 21 to play a significant role in restoring accumulated losses of SOC across Europe. Losses are widespread
 22 and substantial and riparian buffers only enhance SOC in the location where they are established,
 23 meaning that the majority of landscapes in Europe are unaffected, and also the majority of land within

1 the landscapes where buffers are established. To effectively restore SOC on a large scale, changes in
2 crop-rotation practices are necessary, e.g., using ley crops.

3



4

5 **Figure 3:** Degree to which establishment of riparian buffers contribute towards reducing soil loss by water
6 erosion down to a "low" level, in the three deployment scenarios for different buffers options

7

8 **Avoided soil loss by water erosion and sediment retention**

9 In the "Biomass" scenario, riparian buffers directly avoid about 3.3 Mt of soil loss by water erosion,
10 corresponding to 6.3% of soil loss by water erosion on cropland in landscapes where buffers are
11 established, and 1.2% of total soil loss by water erosion on cropland in EU28. The median landscape
12 contributes with 26% of the reductions in soil loss by water erosion necessary to achieve a "low"
13 impact, at the landscape scale. They can also retain an additional 49 Mt of soil eroded on cropland
14 outside the buffers. At EU28 level, 19% of all soil loss by water on cropland is retained in the
15 respective landscapes. (Table 2; Table S1)

16

17 In the "Low-impact" scenario, total avoided soil loss by water erosion ranges from 192 kt (only narrow
18 buffers) to 1150 kt (only double-wide buffers), corresponding to 0.5-3.1% of all soil loss by water
19 erosion on cropland in landscapes where buffers are established, and 0.1-0.4% of total soil loss by
20 water erosion on cropland in EU28. The median landscape contributes with 2-11% of the reductions in
21 soil loss by water erosion necessary to achieve a "low" impact, at the landscape scale. They also retain
22 an additional 13-16 Mt of soil eroded on cropland outside the buffers, totalling 38-50% direct and

1 indirect avoided soil loss by water erosion within the buffer landscapes At EU28 level, 5-6% of all soil
2 loss by water on cropland is retained in the respective landscapes. (Table 2; Table S1)

3
4 In the "Food-first" scenario, total avoided water erosion is 291 kt from narrow (126 kt) and wide (165
5 kt) buffers combined, corresponding to 0.8% of soil loss by water erosion on cropland in landscapes
6 where buffers are established, and 0.1% of total soil loss by water erosion on cropland in EU28. The
7 median landscape contributes with 2.2% of the reductions in soil loss by water erosion necessary to
8 achieve a "low" impact, at the landscape scale. They also retain an additional 16 Mt of soil eroded on
9 cropland outside the buffers, totalling 42.6% direct and indirect avoided soil loss by water erosion
10 within the buffer landscapes. At the EU28 level, 5.6% of all soil loss by water on cropland is retained in
11 the respective landscapes. (Table 2; Table S1)

12
13 Although there is a notable variation between different landscapes, countries, and regions (Fig. 3),
14 riparian buffers are considered as having limited potential for reducing soil loss by water erosion at the
15 European scale. However, this does not consider that the potential for avoiding streambank erosion,
16 which has not been modelled, could be substantial. The potential for retaining eroded soil in buffers
17 and thus avoiding sedimentation in watercourses appears substantial, especially within the buffer
18 landscapes but also at the EU28 level. It should, however, be noted that sediment retention does not
19 mitigate the negative effects of water erosion on eroded cropland.

20
21

2.2 Windbreaks

A total of 7483 landscapes are classified as having a "medium" or higher effectiveness concerning wind erosion mitigation. However, in 6315 landscapes, 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 a "low" impact, these landscapes are not subject to windbreak implementation in any of the deployment scenarios. Windbreaks are therefore implemented in 1168 landscapes, 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 (Fig 4; see also Englund et al. (2020a)). 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.



16
17
18 **Figure 4:** Top row: the implementation level used in the different scenarios. In the "Biomass scenario, it is always 100%. In
19 the "Low-impact" and "Food-first" scenarios, it is determined by the implementation necessary to reduce wind erosion to a
20 "low" level but not beyond. Bottom row: the different windbreak options that are implemented. In the Biomass and "Low

1 *impact” scenario, the highest yielding options are always used, in the "Food-first" scenario, the option is also affected by*
 2 *the ambition to minimize total windbreak area.*

3

4 In the "Biomass" scenario, total windbreak area ranges between about 1,7-2.3 Mha. This corresponds to
 5 1.6-2.1% of the current area under annual crops in EU28 and 30-33% of the current area under annual
 6 crops in the landscapes where windbreaks are established. Estimated wind erosion mitigation is about
 7 5-13 Mt avoided soil loss annually, corresponding to 9-23% of total soil loss by wind erosion in EU28.
 8 Biomass production from windbreaks sums up to 3-24 Mt DM/y. (Table 3; Table S2)

9

10 In the "Low-impact" scenario, the total windbreak area is significantly smaller, 185-555 kha,
 11 corresponding to 0.2-0.5% of the current area under annual crops in EU28, and 2.7-8.2% of the area
 12 under annual crops in the landscapes where they are established. Wind erosion mitigation is about 13
 13 Mt avoided soil loss, or 23% of total soil loss by wind erosion in EU28, regardless of how the
 14 windbreak options are combined. Total windbreak biomass production is about 2-6 Mt DM/y. (Table 3;
 15 Table S2)

16

17 In the "Food-first" scenario, the total windbreak area is 312 kha, of which 190 kha with SRC
 18 windbreaks and 212 kha with SRF windbreaks. This corresponds to 0.3% of the current area under
 19 annual crops in EU28, and 4.6% of the area under annual crops in the landscapes where windbreaks are
 20 established. As for the "Low-impact" scenario, wind erosion mitigation is about 13 Mt avoided soil
 21 loss, or 23% of total soil loss by wind erosion in EU28. Total windbreak biomass production is about 3
 22 Mt DM/y. (Table 3; Table S2)

23

Table 3: Area with windbreak, corresponding biomass production, utilized share of areas currently under annual crops, and avoided soil loss by wind erosion, for the three deployment scenarios. Aggregated to EU28.

	Scenario		
	Biomass	Low-impact	Food-first
Windbreak area (kha)	1685-2261	185-555	312
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 EU28 (%)	1.6-2.1	0.2-0.5	0.3
Avoided soil loss by wind erosion (kt % of total in EU28)	13094 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)	38 - 45 1253 - 1507	4 – 11 118-353	6 206
Avoided soil erosion by water (kt median % of mitigation necessary for achieving “low” impact)	1870-3175 44-95	213-639 4-12	289 10

24

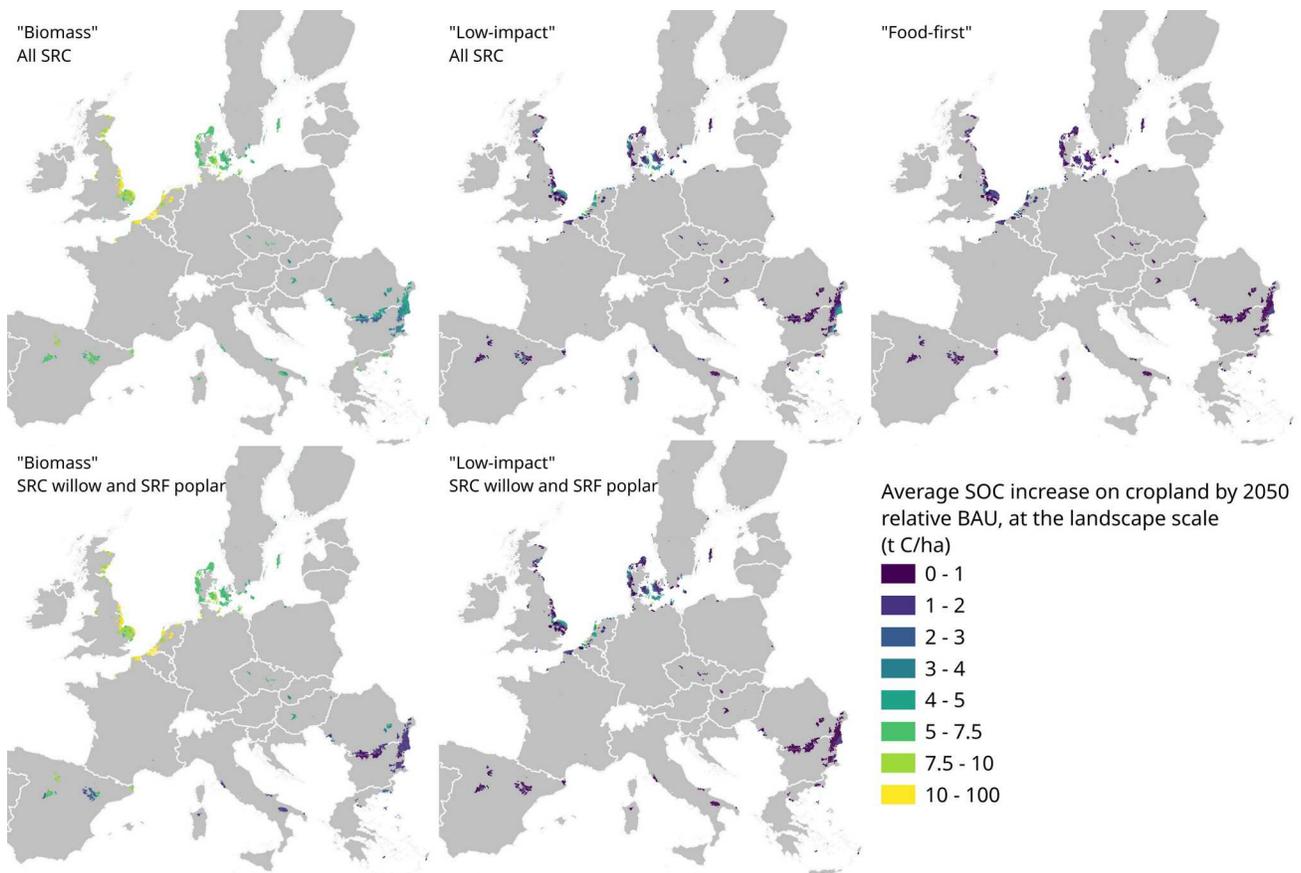
25

1
 2 As for riparian buffers, there is a notable difference between the "Biomass" scenario and the other two
 3 scenarios. However, in this case, the spatial deployment is the same in all scenarios. Here, the
 4 difference is instead solely explained by the difference in implementation level necessary to achieve the
 5 defined impact mitigation. In the "Biomass" scenario, buffers are implemented as defined in all
 6 landscapes, while in the other scenarios, windbreaks are only implemented to the extent where the
 7 impact is reduced to a "low" level at the landscape scale. In most landscapes, this means implementing
 8 windbreaks to a lesser extent than in the "Biomass" scenario, although in some landscapes to a
 9 considerably greater extent, as seen in Fig 4.
 10

11 2.2.1 Co-benefits

12 Enhanced SOC

13 As explained for riparian buffers, effects on SOC depend largely on the windbreak area. In the Biomass
 14 scenario, the total SOC increase is therefore the greatest, 38-45 Mt C by 2050, corresponding to 139-
 15 165 kt CO₂-eq of annual GHG emissions. In the other scenarios, total SOC increases are 4-11 Mt C for
 16 "Low-impact" and 6 Mt C for "Food-first". Corresponding annual GHG emission savings are 15-40
 17 and 22 kt CO₂-eq/y, respectively. (Table 3; Table S2)
 18



19
 20 **Figure 5:** Average increase in SOC on cropland by 2050, relative BAU, in each landscape, in different
 21 deployment scenarios and with different windbreak options.
 22

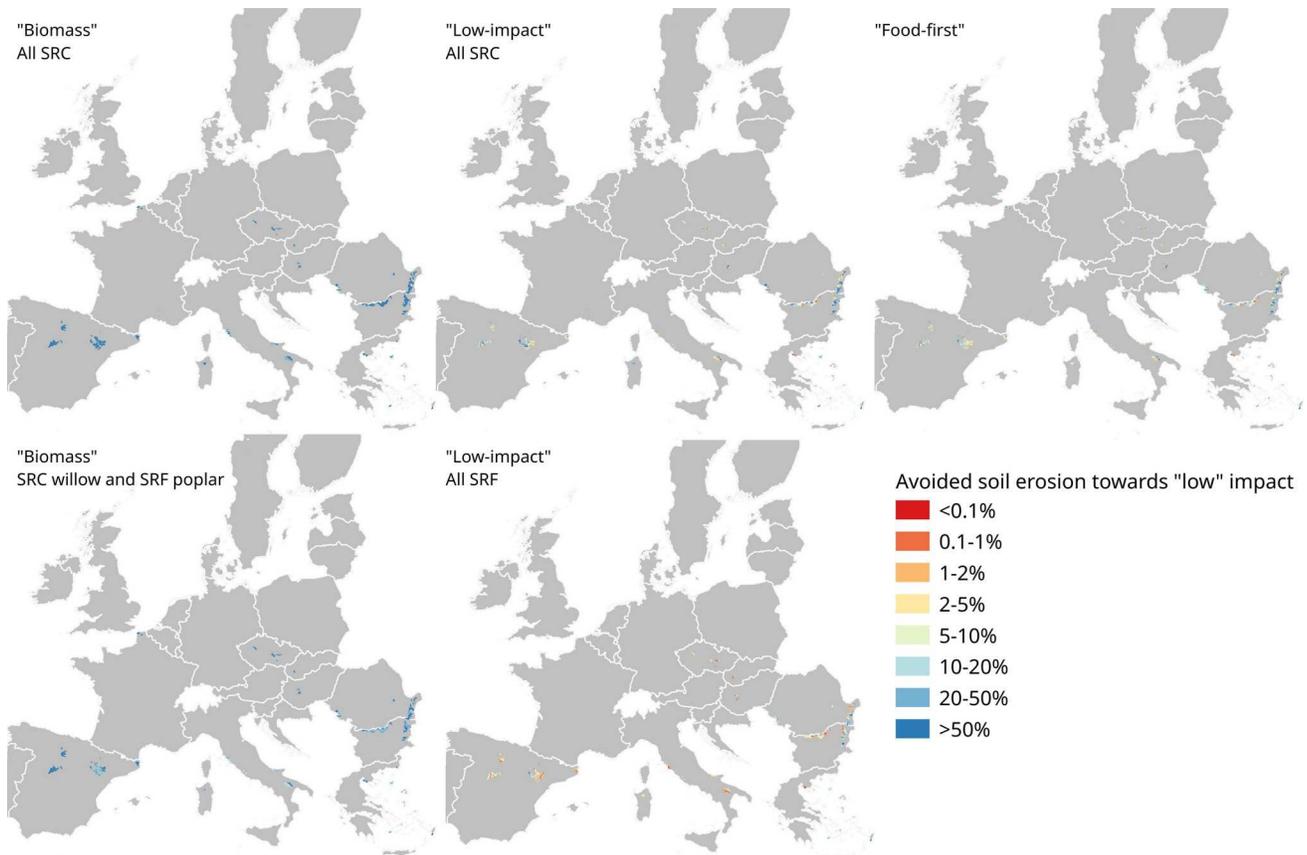
1 Unlike for most of the assessed co-benefits in this study, windbreaks could potentially play a significant
 2 role in restoring SOC in landscapes where they are established (Fig. 5). This is particularly the case in
 3 the “Biomass” scenario, where a substantial share of current cropland is used for windbreaks. In the
 4 other scenarios, where the implementation level is, in general, more limited, it can still play a
 5 significant role in restoring SOC where wind erosion is severe and the implementation level high. In
 6 other landscapes, it can contribute to varying degrees to restoring SOC, depending on the
 7 implementation level. The contribution to restoring SOC could be further increased if the location of
 8 the windbreaks is rotated during replanting, since the positive effects on SOC decrease over time. At
 9 the European level, however, the positive effect on SOC is small, given that most agricultural
 10 landscapes are not subject to windbreak implementation in these deployment scenarios.

11

12 **Avoided soil loss by water erosion**

13 In the "Biomass" scenario, windbreaks avoid between 1.9 Mt (if only SRF windbreaks) and 3.2 Mt (if
 14 only SRC windbreaks) soil loss by water erosion. This corresponds to about 1% of total water erosion
 15 in EU28 but a more significant 20-33% of total water erosion in the landscapes where windbreaks are
 16 established (Fig 6). The median contribution of windbreaks towards reducing water erosion down to a
 17 "low" level is 95-112%. (Table 3; Table S2)

18



19

20 **Figure 6:** Degree to which establishment of windbreaks contribute towards reducing soil loss by water erosion down to a
 21 “low” level, in the three deployment scenarios for different windbreak options

22

1 In the "Low-impact" scenario, windbreaks avoid between 0.2 Mt (only SRF) and 0,6 Mt (only SRC) of
2 soil loss by water erosion, corresponding to 0.1-0.2% of total water erosion in EU28 and 2-7% of total
3 water erosion in the landscapes where windbreaks are established. The median contribution towards
4 reducing water erosion to a "low" level is 4-12%. (Table 3; Table S2)
5

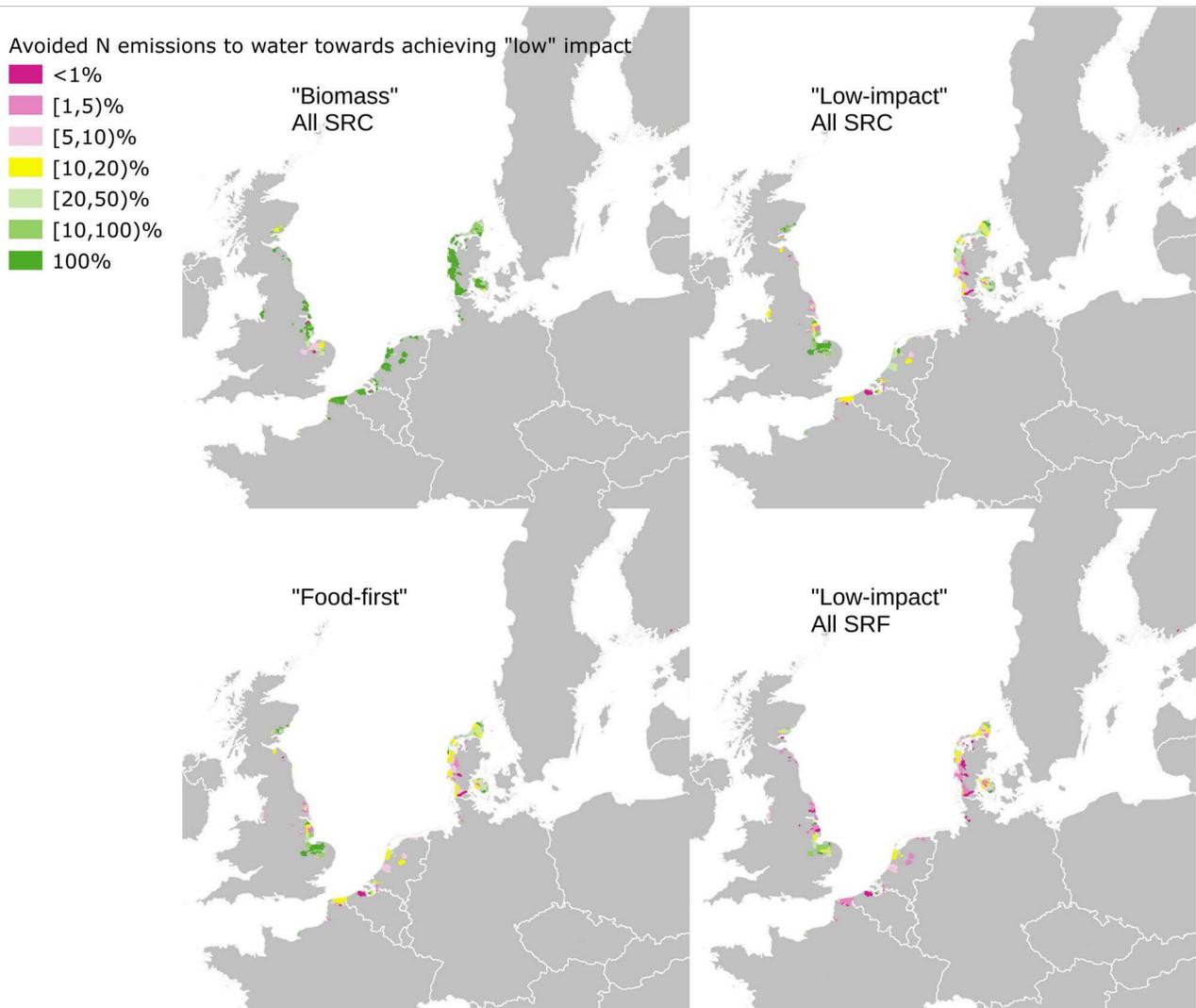
6 In the "Food-first" scenario, windbreaks avoid 0.3 Mt of soil loss by water erosion, corresponding to
7 0.1% of total water erosion in EU28 and 10% of total water erosion in the landscapes where
8 windbreaks are established. The median contribution towards reducing water erosion to a "low" level is
9 10%. (Table 3; Table S2)
10

11 This indicates that, in principle, no further measures to reduce water erosion are necessary in
12 landscapes with windbreaks, given the level of windbreak implementation in the "Biomass" scenario.
13 In the other scenarios, where the implementation level is generally lower, the role of windbreaks in
14 reducing water erosion is less, albeit still, significant (Fig. 6). It should be noted that some landscapes
15 have a greater reduction in water erosion in the "Low-impact" and "Food-first" scenarios, than in the
16 "Biomass" scenario, as these scenarios allow for an implementation level >100% (Fig. 4). As for the
17 other co-benefits, the contribution to reduced soil loss by water erosion is marginal on the European
18 scale.
19

20 To estimate windbreak sediment retention, it is necessary to know the orientation of windbreaks
21 relative slope, as this strongly influences the sediment trapping efficiency. While this is technically
22 possible, windbreak sediment retention has not been assessed here.
23

24 **Avoided N emissions to water**

25 In many landscapes where windbreaks are established, their effect on N emissions to water is
26 substantial (Fig. 7). This is particularly the case in the "Biomass" scenario, in which they suffice to
27 reduce the impact to a "low" level in most landscapes, totalling 20-22 kt avoided N emissions to water.
28 In the other scenarios, the variation is large. In some landscapes, i.e., where wind erosion is severe and
29 the implementation level high, N emissions are reduced to a "low" level or beyond, while in other
30 landscapes, the contribution is only marginal (Fig. 7). This is especially seen in the "Food-first"
31 scenario, where the windbreak area is optimized and thus the lowest. Total avoided N emission to water
32 in the "Low-impact" and "Food-first" scenarios are 1,6-4,8 and 2,9 kt, respectively. (Table 3, Table S2)



1
2 **Figure 7:** Degree to which establishment of windbreaks contribute towards reducing N emissions to water down to a “low”
3 level, in the three deployment scenarios for different windbreak options

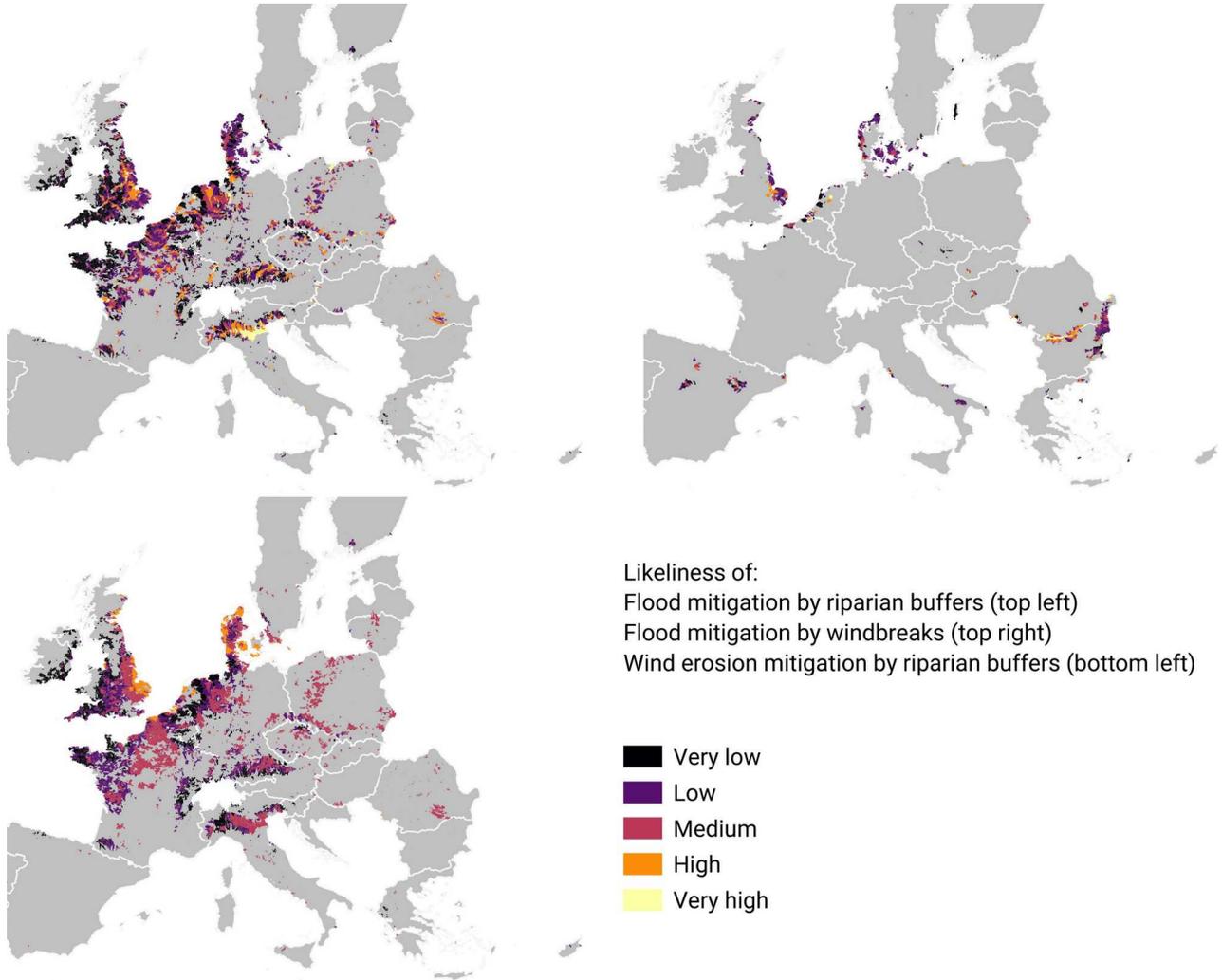
4
5 In many landscapes where windbreaks are implemented, N emissions to water is also high, indicating
6 that windbreaks can be equally effective as riparian buffers in this respect. This exemplifies how one
7 measure could suffice to simultaneously resolve two major environmental issues. This reduces the
8 cropland area needed for impact mitigation and thus increasing land-use efficiency. It also highlights
9 the need to focus on multiple objectives simultaneously and to adopt a landscape perspective.

10
11 **2.3 Potential additional co-benefits and trade-offs**

12 As discussed, several additional co-benefits of riparian buffers and windbreaks are possible, although
13 difficult to quantify without taking more landscape-specific characteristics into consideration. To
14 exemplify this, the likeliness of flood mitigation (by riparian buffers and windbreaks, respectively) and
15 wind erosion (by riparian buffers), is indicated in Fig. 8.

1 The likeliness of mitigating recurring floods is high or very high in 1/5-1/7 of all landscapes where
2 riparian buffers are established and in 1/6 of the landscapes where windbreaks are established. As wind
3 erosion is severe in much fewer landscapes than recurring floods, the likeliness of wind erosion
4 mitigation by riparian buffers is generally lower; being high or very high in only 2-4% of the affected
5 landscapes.

6



7

8 **Figure 8:** Likelihood of flood mitigation and wind erosion mitigation in riparian buffers and windbreaks.

9

10 These results illustrate that there may be several important additional co-benefits than what was
11 possible to quantify on this large scale. To provide a more comprehensive, and precise, understanding
12 of the benefits of strategic perennialization, it is therefore necessary to study a broad range of
13 environmental aspects on a smaller scale. This also applies for possible negative effects of the
14 otherwise “beneficial” LUC, as discussed below.

3 Discussion

1 Multifunctional biomass production systems in the form of energy crop cultivations, designed and
2 utilised as riparian buffers and windbreaks, can lead to significant environmental benefits with limited
3 negative effects on current agricultural production. These systems can reduce N emissions to water and
4 soil loss by wind erosion in Europe down to a “low” impact level, while simultaneously providing
5 substantial environmental co-benefits, utilizing less than 1% of the area under annual crops in the EU.
6 The biomass produced in these multifunctional systems can at the same time be used to displace fossil
7 materials and energy carriers in the emerging bioeconomy. The maximum total biomass production of
8 SRC in riparian buffers and windbreaks amount to some 300 PJ and 450 PJ per year, respectively, in
9 the Biomass scenario (see Tables 2, 3, S1, and S2), in this case utilizing 3.4% of the area under annual
10 crops in the EU. The GHG emissions savings obtained from this biomass depend on what biobased
11 product is produced (and how) and which other product is displaced. Assuming that the biomass is
12 converted to either (i) Fischer-Tropsch diesel, methanol, and dimethylether (DME) based on farmed
13 wood, displacing fossil diesel and gasoline, or (ii) electricity and heat, displacing coal and oil,
14 respectively, the corresponding GHG emissions savings are 29-44 Mt CO₂-eq/y (see SI for more
15 information). In the same scenario, an additional 9,5 Mt CO₂-eq/y is stored in soils until 2050 (annual
16 average, see Tables 2, 3, S1, and S2). The total GHG emissions savings of riparian buffers and
17 windbreaks, in this deployment scenario, consequently reach about 38,5-53.5 Mt CO₂-eq/y, or 1-1.4%
18 of total EU-28 GHG emissions in 2018 (Eurostat, 2020). However, it must be stressed that the results
19 vary substantially between the different deployment scenarios: when the implementation is limited to
20 achieve a certain mitigation level, but not beyond, the corresponding areas, biomass production,
21 environmental benefits, and GHG emissions savings are significantly lower.

22
23 While based on high-quality and high-resolution data, and assumptions founded in scientific literature,
24 the model is subject to several critical uncertainties and limitations, e.g., deployment scenario
25 assumptions, thresholds used for classifying environmental impacts and impact mitigation
26 effectiveness, and the assumption that co-benefits are linearly proportional to the share of annual crops
27 used for the different systems. The results presented here should therefore be interpreted as indicative
28 for large-scale deployment of riparian buffers and windbreaks, given the set of assumptions in the
29 different scenarios. For a thorough description of background and input data, and classification of
30 environmental impacts and mitigation effectiveness, see Englund et al. (2020a). Additional
31 uncertainties and limitations specific to this study are presented in the Supplementary Information.

32
33 The specific outcomes of large-scale deployment of riparian buffers and windbreaks are very difficult
34 to predict. However, our findings clearly demonstrate that it is possible to produce biomass feedstock
35 together with multiple and significant environmental benefits, using a limited amount of land. The
36 assessment and implications of these biomass plantation systems are, by no means, exhaustive. As the
37 establishment of perennial crop plantation stripes on agricultural land generate variations in the
38 landscape, they have direct benefits for biodiversity (Weih and Dimitriou 2012, Baum et al, 2012,
39 Vanbeveren and Ceulemans, 2019), and can play important roles concerning the preservation of
40 sensitive species such as semiaquatic amphibians (Ficetola et al, 2009). However, such effects must be
41 studied with caution, particularly if interfering with pre-existing unmanaged riparian zones.

1 Furthermore, as these perennial energy crop plantations modify the moisture regime, micro-climate,
2 vegetative structure, and productivity, depending on the management and location, they can act as
3 barriers against fire (Petit and Naimen, 2007). However, at the same time, these stripes can accumulate
4 dry biomass fuel and thereby become corridors for fire movement, which suggests additional
5 considerations concerning management and species selection in fire sensitive areas. The effects on
6 water availability in dry areas should also be considered, as fast-growing grass and SRC species have
7 high water demands (Fischer et al. 2018; Maleski et al. 2019). It is thus important to consider not only
8 benefits but also trade-offs in landscape-specific studies, to support well-informed decisions concerning
9 the deployment of different perennialization strategies.
10

11 Utilizing agricultural land for buffers and windbreaks implies that current agricultural production is
12 impacted. The consequences of this are difficult to quantify, as there are multiple landscape-specific
13 aspects that determine how the introduction of buffers or windbreaks affect current agricultural
14 production. For example, riparian buffers could be established entirely on cropland or to a varying
15 degree on existing, unmanaged, buffers, thus limiting the reduction in cropland area. In the former case,
16 agricultural production will initially decrease, but if yield levels increase on the cropland areas that
17 benefit from reduced erosion or flooding mitigation (Li et al., 2016; Osorio et al., 2019), this could
18 more or less outweigh the negative effect of reduced cropland area. For windbreaks, significant parts of
19 the agricultural landscape are converted from annual crops (1/3 for SRC windbreaks and 1/9 for SRF
20 windbreaks at 100% implementation) in the different scenarios. This can, however, fully or partly
21 (depending on the implementation level) be compensated for by yield increases on cropland sheltered
22 from wind erosion (Osorio et al. 2019). Finally, the different co-benefits of buffer and windbreaks (e.g.
23 SOC increase, see Lal, 2020) can also have positive long-term effects on yield levels.
24

25 In case yield improvements cannot fully compensate for losses in cropland area, the potential
26 connection between establishment of biomass production systems on cropland and indirect land use
27 changes, causing, e.g., biodiversity impacts and land carbon losses, remains an additional concern
28 (Sumfleth et al., 2020; Khanna et al., 2017; Takaes Santos, 2020; Berndes et al., 2012). The same
29 concern exists when lower-yielding alternative farming practices are introduced to reduce
30 environmental impacts, as exemplified by studies associating organic food with additional emissions
31 (Smith et al., 2019), or foregone carbon sequestration (Searchinger et al., 2018), due to the need for
32 more land to compensate for lower yields. Examples of such carbon leakage in other sectors include
33 those associated with electrification of vehicle fleets, which may result in significant up-front carbon
34 emissions due to large demand for batteries with significant embedded emissions, and low net
35 reduction on CO₂ emissions from displacing petrol and diesel use in ICE vehicles due to battery
36 charging with carbon-intensive electricity (Hill et al., 2019; Xiong et al., 2020). Indirect land use
37 change and carbon leakage need to be taken into account and addressed in appropriate ways. We argue
38 that decision-making in the context of societal sustainability transitions needs to reflect a holistic view
39 on both supply-side and demand-side mitigation, and be based on data and insights from many
40 scientific disciplines and complementary methodologies covering a multitude of sustainability
41 indicators. Taking the example of organic meat, consumers who are motivated to buy organic meat for
42 environmental and ethical reasons may also buy fewer animal-based products in the first place (Baudry
43 et al., 2017; Treu et al., 2017). Thus, the larger land demand associated with one individual food

1 product is balanced by a declining land demand associated with a broader dietary shift (van der Werf et
2 al., 2020).

3
4 An important barrier towards wider implementation of multifunctional systems has been described as
5 the lack of markets, or policies, compensating producers for enhanced ecosystem services and other
6 environmental benefits (Englund et al., 2020b). Realizing the deployment scenarios presented here thus
7 require significant policy efforts to generate sufficient incentives. Such efforts are now becoming
8 visible in the EU. One potential opening may be the introduction of Eco-schemes in the new CAP. Eco-
9 schemes will offer farmers the possibility to grant direct payments to adapt practices beneficial for
10 climate, water, soil, air and biodiversity (EU, 2019). As illustrated in this assessment, such practices
11 could include the establishment of multifunctional biomass production systems. This is a practical
12 example of how to combine climate and agriculture policy goals, by producing long-term sustainable
13 biomass feedstock which could replace fossil fuels and improve agricultural production in general. A
14 critical aspect is therefore to significantly increase the knowledge of the opportunities with
15 multifunctional biomass production systems among all EU member states before designing and
16 introducing country specific Eco-scheme options in the new CAP.

17
18 While this study provides novel insights into large-scale strategic perennialization for beneficial LUC,
19 it covers only two options, that are relevant only in parts of the EU. There are multiple additional
20 systems that could be implemented to address other primary impacts (Englund et al. 2020a; Englund et
21 al. 2020b). Such systems can be modelled similarly to what has been done here, to show a more
22 complete picture of the potential for beneficial LUC through widespread deployment of multifunctional
23 biomass production. Furthermore, intra-landscape modelling, considering a broad range of possible
24 benefits and trade-offs, is necessary to fully understand the effects of introducing these kinds of
25 systems at the landscape scale. Such information can also be valuable to support local or regional
26 spatial planning, where different goals and objectives, from different stakeholders, need to be
27 considered (Busch, 2017).

28

4 Material and 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 quantify the corresponding (i) areas; (ii) amounts of biomass produced and the corresponding energy content; (iii) primary benefit; and (iv) co-benefits.

All cases of strategic perennialization are modelled to achieve a primary objective, i.e., to mitigate a specific environmental impact, driven by specific incentives. The mitigation effect is designated "primary benefit". In many cases, additional co-benefits are likely, i.e., the perennialization aimed at the primary objective will have a beneficial influence on other objectives, thereby increasing the total benefits for the environment and society. Co-benefits are often subject to uncertainty and depend on local circumstances and implementation practices, among other factors (Smith et al., 2020; Jia et al., 2019). Here we differentiate between "co-benefits" that can be generally expected, although not being explicitly targeted, and "potential co-benefits" that may or may not occur, depending on landscape-specific characteristics.

Unless otherwise specified, the term *landscape* refers to polygons in a dataset with over 81.000 sub-watersheds across the EU27+UK; thus used synonymously to "sub-watershed" or "sub-catchment" (see Englund et al. 2020a for full justification and further details on the conceptual approach). The spatial analysis and operations, including all the database aggregation queries, were performed in GRASS GIS (GRASS Development Team, 2019) with projection EPSG:3035, whereas the cartography and some specific GIS operations were done in QGIS (QGIS.org, 2020).

4.1 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 by Englund et al. (2020a) 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".

Englund et al. (2020a) also estimated the effectiveness of strategic perennialization, for each impact and in each landscape, by combining the degree of impact with the density of annual crops. As for the impacts, the effectiveness for the different impacts is described on a five-step scale from "very low" to "very high". Further methodological details are available in Englund et al. (2020a).

4.2 Deployment scenarios for strategic perennialization

To illustrate different outcomes, three deployment scenarios were designed. 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 high demand for biomass produced in the multifunctional system within the bioeconomy.

The scenarios are conceptualized as follows, and further described under the respective multifunctional systems below:

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In scenario 1 (*Biomass*), there are incentives for implementing MBPSs in all landscapes where the effectiveness in reducing the impact of concern is classified as above "low" (defined below). The degree of the impact, and the corresponding impact mitigation potential, in individual landscapes are not considered. Incentives are such that farmers select the multifunctional systems that are expected to result in the highest mitigation, by default, while maximizing biomass output.

In scenario 2 (*Low impact*), incentives for mitigating impacts of concern are generally stronger than in scenario 1, but there are no incentives when impacts are below a defined "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 therefore seek to minimize the area used for the multifunctional system, while achieving mitigation where impacts are above the "low" level at the landscape scale.

4.3 Modelling of riparian buffers

The primary benefit of riparian buffers is considered to be reduced N emissions to water. In this case, this refers to diffuse N emissions that reach watercourses by runoff or shallow groundwater (Grizetti et al., 2012). Co-benefits include (i) enhanced SOC, (ii) avoided water erosion and (iii) retention of sediment. Potential co-benefits include (i) flood mitigation, and (ii) reduced wind erosion.

4.3.1 Design options and deployment scenarios

Five different riparian buffer systems have been defined (Table 1), based on three different widths. First, a 5 m "narrow" option represents mandatory requirements in Italy and is based on empirical experiments by Ferrarini et al. (2017a). Second, a 21 m "wide" option represents a buffer with 100% buffer strip efficiency (BSE), based on a regression analysis by Ferrarini et al. (2017a). Third, a 50 m "double-wide" option represents a system where agricultural practices and economic aspects are taken more into account (Styles et al., 2016). 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 Short Rotation Coppice (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 willow, as reported by Ferrarini et al. (2017a).

1 **Table 1:** Options for riparian buffer systems and corresponding buffer strip efficiency for reducing N emissions to water,
 2 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

3

4 **“Biomass” scenario**

5 Farmers are assumed only to implement double-wide SRC buffers, as this provides economical and
 6 practical advantages due to larger cropping sites, maximum biomass production from the SRC buffers,
 7 and maximum impact mitigation. In all landscapes, the highest yielding SRC species is used, to
 8 maximize land-use efficiency.

9

10 Spatial deployment: Buffers are established in landscapes where the effectiveness of strategic
 11 perennialization for mitigation N emissions to water has been classified as at least “medium”.

12

13 Buffer design options: Only double-wide buffers are implemented, as defined in Table 1.

14 **“Low-impact” scenario**

15 Farmers can implement any of the five defined buffer systems, depending on what is most favourable
 16 in their respective landscapes. The extent of the implementation in each landscape is, however, limited
 17 by the degree of impact mitigation necessary to reduce the impact down to a "low" level, at the
 18 landscape scale. In all landscapes, the highest yielding SRC and grass species, respectively, are used.

19

20 Spatial deployment: Landscapes suitable for implementation include those where both (i) N emissions
 21 to water and (ii) the effectiveness of mitigating N emissions to water, have been classified by Englund
 22 et al. (2020a) as at least "medium".

23

24 Buffer design options: All buffer options defined in Table 1 are possible.

25 **“Food-first” scenario**

26 Farmers establish narrow buffers to the greatest extent possible to minimize effects on food
 27 production. Where narrow buffers do not suffice to reduce the environmental impact down to a "low"
 28 level, at the landscape scale, wide buffers are used as a complement. Double-wide buffers are not
 29 implemented as they do not result in a higher primary impact mitigation than wide buffers. In all
 30 landscapes, the highest yielding SRC and grass species, respectively, is used, to ensure maximum land-
 31 use efficiency.

32

33 Spatial deployment: As for "low-impact".

34

1 Buffer design options: Narrow SRC or grass buffers where they suffice to reduce the impact down to a
2 "low" impact level. Wide SRC or grass buffers elsewhere.

3 **4.3.2 Primary impact mitigation potential**

4 The BSE:s for the respective buffer designs are defined in Table 1. The impact mitigation potential
5 depends on the current primary impact and the BSE of the different buffer designs. The following was
6 calculated for all buffers designs in the different deployment scenarios, for each landscape:
7

- 8 • *Maximum impact mitigation* (kg N/ha/y), estimated as the product of *current N emissions to*
9 *water* and the respective *BSE*.
- 10
- 11 • *Maximum amount of avoided N emissions per year*, estimated as the product of *maximum*
12 *impact mitigation* and *total landscape area*.
- 13
- 14 • *Necessary impact mitigation to achieve a "low" impact level*, estimated as the difference
15 between *current N emissions to water* and the *upper threshold for the impact class "low"*.
- 16
- 17 • *Share of impact mitigation necessary to achieve a "low" impact level*, estimated as the quotient
18 between *necessary impact mitigation to achieve a "low" impact level* and *maximum impact*
19 *mitigation*.

20 **4.3.3 Buffer areas**

21 For each buffer option in the three deployment scenarios, the buffer area in each individual landscape
22 was estimated as the product of *buffer width* (times two, assuming that it is established on both sides of
23 the watercourse) and the *total length of primary and secondary drains in each landscape*. The latter
24 was calculated based on a river dataset from the European Catchments and Rivers Network System
25 (ECRINS) project (European Environment Agency, 2012). This dataset was developed in parallel with
26 the sub-catchment dataset that is the basis for the landscape dataset used here. To calculate total river
27 length, all river polylines were first cut by the landscape polygons and the sum of the length of each
28 polyline in each landscape was then calculated and added as a new attribute to the landscape dataset
29 using the QGIS tool "sum line length".
30

31 The above approach resulted in the *maximum buffer area* for the three buffer designs, considering only
32 buffer widths and lengths of primary and secondary drains in each landscape. The maximum area was
33 thus used in the "Biomass" scenario, in which deployment is driven by incentives for maximized
34 multifunctional biomass production and maximum impact mitigation, not limited by a certain degree of
35 impact mitigation or implications for food production.
36

37 In the "Low-impact" and "Food-first" scenarios, however, deployment is driven by incentives to reduce
38 N emissions to water to a "low" level, but not beyond. This means that the buffer area in many cases
39 will be smaller than the maximum area, since the maximum area results in a greater impact mitigation
40 than what is necessary to fulfil the objective. To estimate the buffer area needed to achieve a "low"
41 impact in each landscape, it was assumed that BSE, at the landscape scale, is proportional to the share
42 of maximum buffer area. For example (cf. Table 1) if a BSE of 30% is necessary to reduce N emissions
43 down to a "low" impact level, 50% of the maximum area for narrow buffers (having a BSE of 60%) is
44 needed, and 30% of the maximum area for wide or double-wide buffers (having a BSE of 100%).

1 The buffer area for the different buffer design options in the "Low-impact" scenario was therefore
2 estimated as the product of *share of impact mitigation necessary to achieve a "low" impact level* (see
3 previous section) with *maximum buffer area*.
4

5 Finally, in the "Food-first" scenario, deployment is driven by incentives to reduce N emissions to water
6 to a "low" level, but not beyond, but also by incentives to minimize impacts on food production. Since
7 farmers would seek to optimize (in terms of buffer area) the impact mitigation, they utilize narrow
8 buffers to the extent that they suffice to reduce the impact down to a "low" impact level, at the
9 landscape scale, and wide buffers elsewhere. We therefore first assessed in which landscapes that
10 narrow buffers suffice, by comparing *impact mitigation necessary to achieve a "low" impact level* with
11 *maximum impact mitigation for narrow buffers* specifically. Where the former exceeds the latter, wide
12 buffers are implemented. In other landscapes, only narrow buffers are used. The corresponding buffer
13 areas were then calculated as for the "Low impact" scenario.

14 **4.3.4 Biomass from buffers**

15 Biomass production from riparian buffers was estimated for each suitable landscape and for each buffer
16 option in the three deployment scenarios, as the product of *buffer areas*, estimated as described above,
17 and the *yield of the highest yielding SRC and grass option*, respectively. The latter was identified using
18 pan-European yield simulations at NUTS3 level (Dees et al., 2017). Simulated yields for SRC willow,
19 SRC poplar, other SRC, miscanthus, switchgrass, and reed canary grass, using a "medium" yield-input
20 management level, were identified for each landscape by first spatially joining landscapes to NUTS-3
21 regions, and then joining the database tables. Yields are expressed as t DM ha/y. The energy output is
22 calculated as the product of *biomass production* and *energy content of the harvested biomass*; 18.7
23 MJ/kg DM, for both SRC (Nordborg et al., 2018a, 2018b) and grass (Baxter et al., 2014).

24 **4.3.5 Co-benefits**

25 **Enhanced SOC**

26 The effects on SOC from establishing riparian buffers were based on SOC simulations of permanent
27 grasslands in relation to a business-as-usual (BAU) SOC scenario (Lugato et al., 2014), available for
28 download at the Joint Research Centre European Soil Data Centre (ESDAC;
29 <https://esdac.jrc.ec.europa.eu/>).
30

31 The SOC simulations are spatially explicit and provide BAU SOC estimates (t C/ha) for 2010, 2020,
32 2050, 2080, and 2100, assuming a continued rotation with the four most dominant crops in each area.
33 They also provide SOC values in relation to these BAU values for multiple management options,
34 including a permanent grassland system, in which the BAU rotation is replaced by permanent
35 grassland. It is here assumed that SOC effects of establishing permanent grassland on cropland is
36 representative of SOC changes in riparian buffers, as these are permanent perennial systems with
37 documented positive effects on SOC (Ferrarini et al. 2017b).
38

39 SOC values relative BAU for permanent grassland were rasterized to 100 m and new SOC values were
40 added to the landscape dataset by identifying the median value within each landscape (GRASS:
41 `v.rast.stats`). BAU values are referred to below as "SOCbau_[year]" and SOC increases relative BAU
42 from implementation of permanent grassland are referred to as "SOCinc_[year]". SOCinc values in the
43 dataset are expressed in relation to 2010. They were therefore re-estimated with 2020 as base year, to
44 be able to represent SOC changes from current levels while maintaining 2050 and 2080 as points in

1 time for assessment. SOCbau did not require re-estimation as it represents a continuation of BAU land-
2 use. SOCbau_2020 was thus considered representative for current SOC.
3

4 To reflect that SOC tends to increase more rapidly early after the introduction of a new land-use system
5 (Lugato et al., 2014), SOCinc_2020 was assumed to represent the change in SOC during the first ten
6 years, i.e., between 2020 and 2030 ("SOCinc_first10"). SOC changes during the remaining period (i.e.,
7 20 and 50 years, for 2050 and 2080, respectively) was calculated by subtracting SOCinc_first10 from
8 SOCinc_2050/2080, representing SOC changes in 30/60 years following the first 10 years
9 ("SOCinc_last30/60"). Since we require SOC changes in 20/50 years, these values were downscaled by
10 20/30 and 50/60, respectively ("SOCinc_last20/50"). Finally, SOC increases by 2050/2080 relative
11 BAU could be calculated as the sum of SOCinc_first10 and SOCinc_last20/50.
12

13 At this point, SOC changes per hectare of riparian buffers by 2050/2080 relative BAU, with base year
14 2020, have been estimated. SOC changes per hectare of cropland were then calculated as the product of
15 *SOC changes per hectare of riparian buffers* and *share of area under annual crops used for riparian*
16 *buffers* in each deployment scenario, for all individual landscapes.

17 **Avoided water erosion**

18 Soil erosion within SRC systems can be considered marginal (Ferrarini et al. 2017a). Fully replacing
19 annual crop production with SRC is therefore assumed to reduce soil erosion nearly completely on that
20 specific land. Consequently, the share of land under annual crop production used for riparian buffers
21 indicates the share of reduced soil loss by water erosion, at the landscape scale.
22

23 First, avoided soil loss by water erosion per hectare and year was calculated in each landscape, for each
24 riparian buffer option, as the product of *share of area under annual crops used for riparian buffers* and
25 *current soil erosion by water on land used for annual crop production*. The total amount of avoided soil
26 loss by water erosion per year in each landscape was calculated as the product of *avoided water erosion*
27 *per hectare* and *total area under annual crop production*. The share of avoided water erosion relative
28 total water erosion was then calculated as the quotient of *amount of avoided soil loss* and *total soil loss*
29 in each landscape. Finally, the degree to which riparian buffers could contribute to reducing soil loss by
30 water erosion down to a "low" impact level, at the landscape scale, was estimated as the quotient of
31 *avoided soil loss by water erosion per hectare and year* and *soil loss by water erosion above the*
32 *threshold for "low" impact*.

33 **Sediment retention**

34 Sediment retention was quantified based on the assumption that all soil loss by water erosion on
35 cropland at the sub catchment scale is destined to end up in watercourses within the catchment. Total
36 sediment loads in each landscape are thus equivalent to soil loss by water erosion, as estimated by
37 Englund et al. (2020a), reduced by avoided water erosion as estimated above. Empirical studies have
38 shown that buffer widths of 3 m, 6 m, and 7 m, can have sediment trapping efficiencies (STE) of 66%,
39 77%, and 95%, respectively (Ferrarini et al., 2017b). Based on this, trapping efficiencies of 75% for the
40 narrow buffer and 100% for the wide and double-wide buffers, were assumed.
41

42 In the "Biomass" scenario, sediment retention at the landscape scale was estimated as the product of
43 *STE* and *total sediment load*, as estimated above. In the other scenarios, where buffers are only
44 implemented to the extent where N emissions to water is decreased to a "low" level, sediment retention
45 is calculated as the product of *sediment retention in the "Biomass" scenario* and the *share of total*

1 *buffer area that is needed in each landscape to achieve "low" N emissions to water, for each buffer*
2 *design.*
3

4 **4.4 Modelling of windbreaks**

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

7 **4.4.1 Design options and deployment scenarios**

8 Two design options for windbreaks have been defined. First, "SRC windbreaks" refer to the
9 establishment of SRC willow or poplar, with a rotation period of 3-4 years and a height of 5 m
10 (Tahvanainen, 1996). Second, "SRF windbreaks" refer to the establishment of SRF poplar, with a
11 rotation period of 15 years and a height of 20 m (Hjelm et al., 2015).
12

13 In both the SRC and the SRF design, a windbreak width of 50 m is assumed, for practical and
14 economic reasons, since larger cropping sites reduce management costs, following the same reasoning
15 as for double-wide riparian buffers. The distance between windbreaks is assumed to be 20H, i.e., 20
16 times the windbreak height (Osorio et al., 2019).
17

18 In both designs, half of the windbreak is harvested at a time, allowing for constant windbreak
19 functionality.
20

21 **"Biomass" scenario**

22 Farmers can implement either SRC willow/poplar or SRF poplar, depending on which is most
23 favourable in their respective landscapes. The design option is not affected by incentives to maximize
24 biomass production, as biomass production per hectare is the same in both options. The design option is
25 also unaffected by incentives to maximize mitigation of soil loss by wind erosion, as this is assumed to
26 be identical for both options.
27

28 Spatial deployment: Windbreaks are established where the effectiveness of strategic perennialization
29 for mitigating soil loss by wind erosion is classified as at least "medium". However, as it is assumed
30 that windbreaks can only achieve mitigation down to a "low" impact level (see below), landscapes also
31 need to have a current impact level of at least "medium" for soil loss by wind erosion.
32

33 Buffer design options: Where willow is higher yielding than poplar: SRC willow windbreaks. Where
34 poplar is higher yielding: either SRC or SRF poplar windbreaks.

35 **"Low-impact" scenario**

36 Farmers can implement either SRC willow/poplar or SRF poplar windbreaks, depending on what is
37 considered most favourable in their respective landscapes, but only to an extent where the
38 environmental impact is mitigated down to a "low" level, at the landscape scale.
39

40 Spatial deployment: As for "Biomass".
41

42 Buffer design options: SRC or SRF poplar windbreaks where poplar is higher yielding than willow.
43 Where willow is higher yielding, willow SRC is preferred but SRF poplar can also be established if it is

1 considered more favourable for other reasons. In all landscapes, implementation is limited to what is
2 necessary to achieve a "low" impact, at the landscape scale.

3 **"Food-first" scenario**

4 Since farmers are incentivized to minimize impacts on food production, they seek to limit the share of
5 cropland used for windbreaks to less than or equal to the expected resulting yield increases. Farmers
6 therefore seek to achieve impact mitigation down to a "low" level, in each landscape, while limiting the
7 area used for windbreaks to a maximum of 10% of the area under annual crops (Osorio et al. 2019).
8

9 Spatial deployment: As for "Biomass" and "Low-impact"
10

11 Buffer design options: Farmers implement SRC willow or poplar windbreaks, depending on what is
12 highest yielding, where the area needed for SRC windbreaks to reduce impact down to a "low" level
13 does not exceed 10% of the cropland area in the landscape. Where a larger share of the existing
14 cropland area is needed, SRF poplar is used.

15 **4.4.2 Primary impact mitigation potential**

16 Soil loss by wind erosion is classified as "low" (and rarely "very low") in a vast majority of agricultural
17 landscapes across Europe (Englund et al., 2020a). Windbreaks are therefore assumed to be able to
18 reduce soil loss by wind erosion to a "low" level, i.e., less than 5 t/ha/y (Englund et al., 2020a), but not
19 to a "very low" level. It is further assumed that a windbreak distance of 20H may not suffice to achieve
20 this level of impact mitigation (i.e., down to a "low" level) in all landscapes (Osorio et al., 2019;
21 Brandle et al. 2004). An assumption was therefore made that the defined windbreak options, if fully
22 implemented in all agricultural fields currently under annual crops, suffice to reduce wind erosion from
23 a "high" to a "low" impact level, at the landscape scale. Landscapes with a higher current impact than
24 "high" therefore need shorter windbreak distances to achieve the desired impact mitigation. It is further
25 assumed that landscapes with a current impact lower than "high", and thus in need of lesser impact
26 mitigation to achieve a "low" level of wind erosion, at the landscape scale, require lesser mitigation
27 efforts. In such cases, a greater distance between windbreaks, or windbreaks implemented only in
28 selected parts of the landscape, may suffice to achieve the desired impact mitigation.
29

30 Based on these assumptions, a windbreak implementation level was estimated for each landscape,
31 based on the need for impact mitigation to reach "low" soil loss by wind erosion. The implementation
32 level was assumed to decrease linearly from 100%, in landscapes with wind erosion of 10 t soil loss
33 /ha/y (the upper threshold for "high" impact), to 0% for landscapes already having a "low", or lower,
34 impact (≤ 5 t soil loss / ha / y). Landscapes exceeding the threshold for "very high" receive an
35 implementation level greater than 1 to reflect that the distance between windbreaks need to be shorter
36 (minimum 11H for the landscape having the highest wind erosion, 16.8). This implementation level
37 was calculated for all landscapes using Formula 1. Note that the implementation level in the "Biomass"
38 scenario is always 100%.
39

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

Where:

impact = current impact

impact_{low} = threshold for "low" impact

impact_{vhigh} = threshold for "very high" impact

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

1

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

3

4 *Necessary impact mitigation to achieve a "low" impact level (t soil loss/ha/y)* estimated as the
5 difference between the *upper threshold for the impact class "low"* and *current soil loss by wind erosion*.

6

7 *Maximum impact mitigation (t soil loss/ha/y)* for all windbreak options, estimated as equal to *necessary*
8 *impact mitigation to achieve a "low" impact level*. In the "Biomass" scenario, however, "simpler"
9 incentives are assumed, in which the landscape-specific potential for impact mitigation is not
10 considered. The implementation level in the "Biomass" scenario is therefore always 100%. In
11 landscapes where an implementation level greater than 100% is necessary to achieve this degree of
12 impact mitigation, necessary impact mitigation to achieve a "low" impact level will exceed maximum
13 impact mitigation. In the "Biomass" scenario, maximum impact mitigation was therefore set manually
14 to 8, i.e., the difference between the upper thresholds of "high" and "low" impact, in landscapes where
15 the implementation level exceeds 100%.

16

17 *Maximum amount of avoided wind erosion (t soil loss/y)* estimated as the product of *maximum impact*
18 *mitigation* and *total area under annual crops*.

19

20 *Share of impact mitigation necessary to achieve a "low" impact level*, estimated as the quotient of
21 *necessary impact mitigation to achieve a "low" impact level* and *maximum impact mitigation*.

22 **4.4.3 Windbreak deployment areas**

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

27

28 The *total share of agricultural land under annual crop production needed for establishing windbreaks,*
29 *at 100% implementation*, is calculated as the quotient of *windbreak width* and *windbreak distance*, i.e.,
30 1/3 for SRC windbreaks and 1/9 for SRF windbreaks.

31 **4.4.4 Biomass production in windbreaks**

32 Biomass production from windbreaks was estimated as for riparian buffers, but considering only SRC
33 willow and SRC poplar. The yield for SRF poplar was assumed to be identical to SRC poplar (Ayllot et
34 al., 2008; Dimitriou and Mola-Yudego, 2017). The energy content, 18.7 MJ/kg DM, was used for both
35 SRC willow and SRC/SRF poplar (Nordborg et al., 2018a, 2018b).

1 **4.4.5 Co-benefits**

2 **Avoided N emissions to water**

3 N emissions to water from SRC or SRF systems can be considered marginal (Dimitriou et al., 2012;
4 Dimitriou and Mola-Yudego, 2017; Ferrarini et al. 2017). Following the same assumptions as for water
5 erosion, *avoided N emissions to water (per hectare and year)* was estimated in each landscape as the
6 product of *share of area under annual crops used for windbreaks* in the two different windbreak
7 designs, and *current N emissions to water*. The *total amount of avoided N emission to water* in each
8 landscape was then calculated as the product of *avoided N emissions to water (per hectare and year)*
9 and *total area of the landscape*. Finally, the *degree to which riparian buffers could contribute to*
10 *reducing N emissions to water down to a "low" impact level*, at the landscape scale, was estimated as
11 the quotient of *avoided N emissions to water (per hectare and year)* and *current N emissions to water*
12 *above the threshold for "low" impact*.

13 **Enhanced SOC**

14 Effects on SOC estimated as for riparian buffers.

15 **Avoided water erosion**

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

17 **4.5 Potential additional co-benefits**

18 **4.5.1 Flood mitigation**

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

27
28 No attempts were therefore made to quantify this co-benefit. Instead, we attempt to indicate the
29 likeliness of mitigated or avoided flooding events as a result of the establishment of riparian buffers or
30 windbreaks. This was done by assuming that the likeliness is directly correlated with the effectiveness
31 of strategic perennialization in mitigating recurring floods (Englund et al., 2020a). An effectiveness of
32 medium corresponds here to a likeliness of medium, etc. The effectiveness of strategic perennialization
33 in mitigating recurring floods was therefore identified for each landscape where riparian buffers and
34 windbreaks are introduced, respectively, in the different deployment scenarios.

35 **4.5.2 Wind erosion mitigation**

36 Estimated in the same way as for "flood mitigation".

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Figures

Share of maximum narrow buffer area needed to achieve "low" impact

■ No buffers necessary

■ 0-10%

■ 10-25%

■ 25-50%

■ 50-75%

■ 75-100%

■ Narrow buffers insufficient

Scenario 1: "Biomass"

■ double-wide SRC buffers with willow

■ double-wide SRC buffers with poplar

■ double-wide SRC buffers with other species

Scenario 2: "Low impact"

■ narrow to double-wide grass buffers

■ narrow to double-wide SRC buffers

Scenario 3: "Food first"

■ narrow buffers

■ narrow and wide buffers

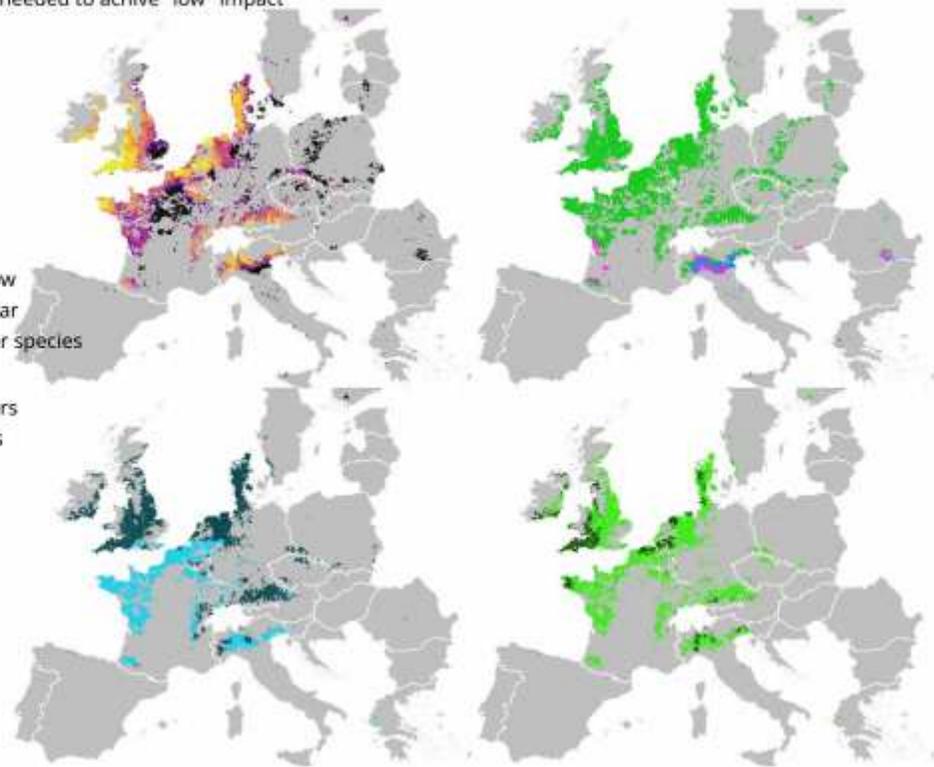


Figure 1

Establishment of riparian buffers in the three deployment scenarios, and the share of maximum narrow buffer area needed to achieve "low" N emissions to water in each landscape.

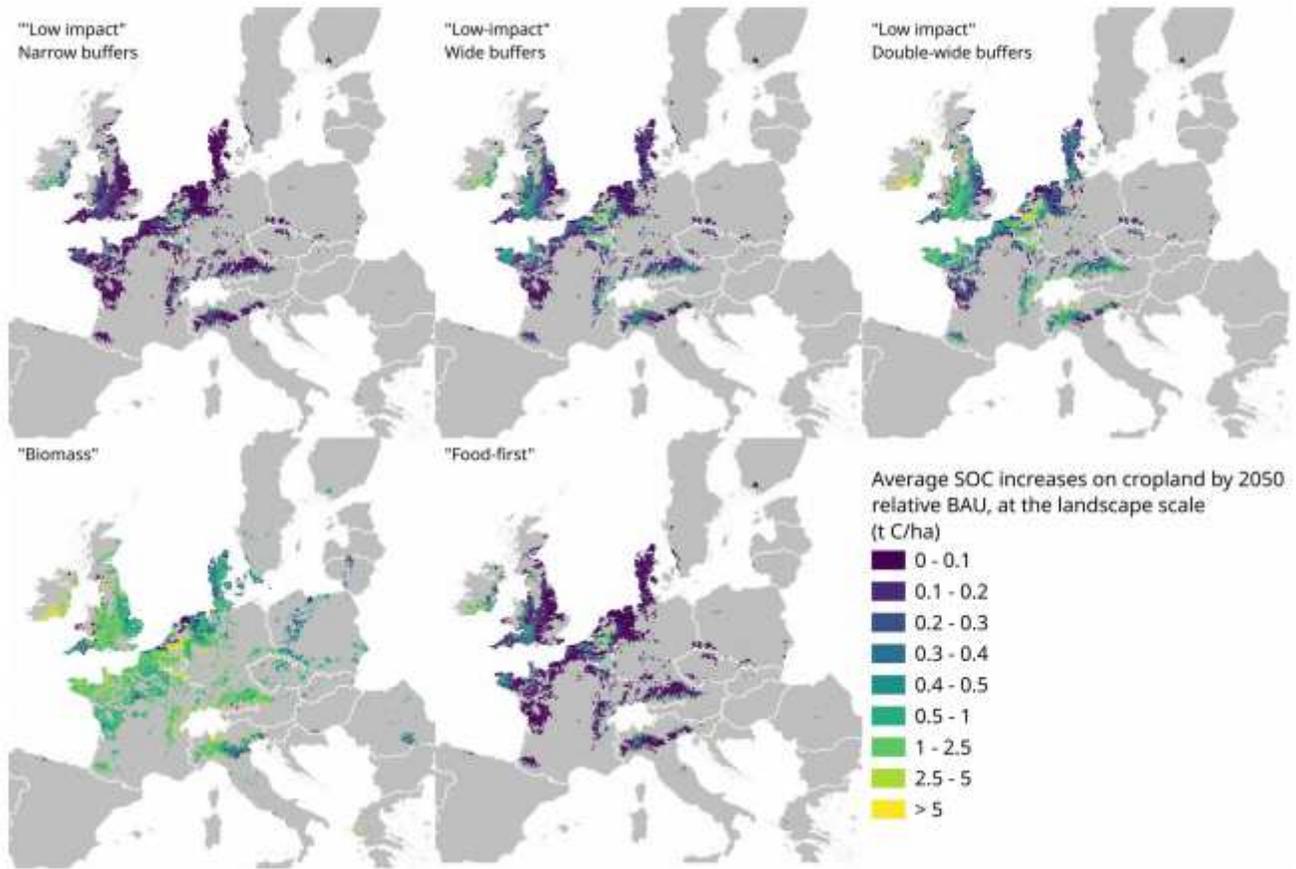


Figure 2

Average increase in SOC on cropland by 2050, relative BAU, in each landscape, in different deployment scenarios and with different riparian buffer options.

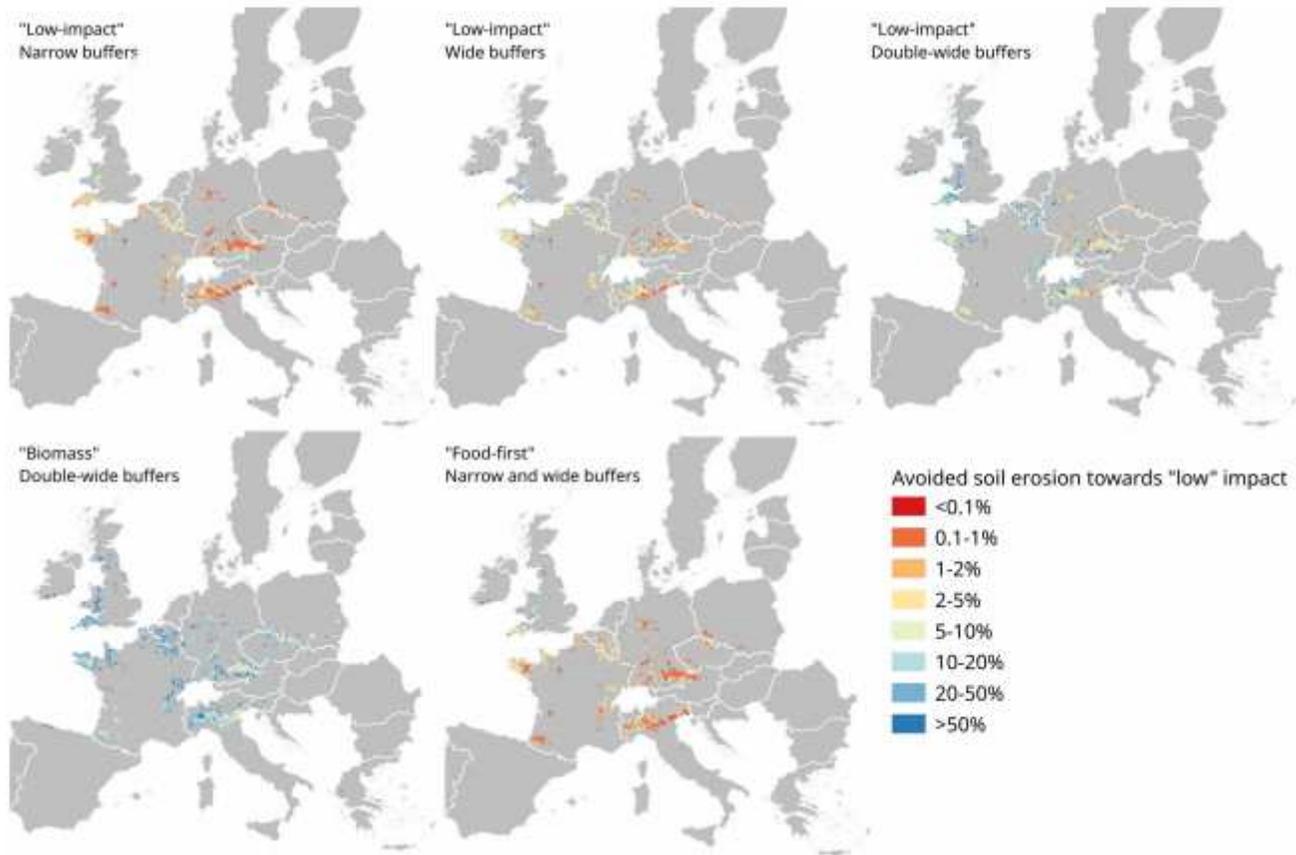


Figure 3

Degree to which establishment of riparian buffers contribute towards reducing soil loss by water erosion down to a "low" level, in the three deployment scenarios for different buffers options

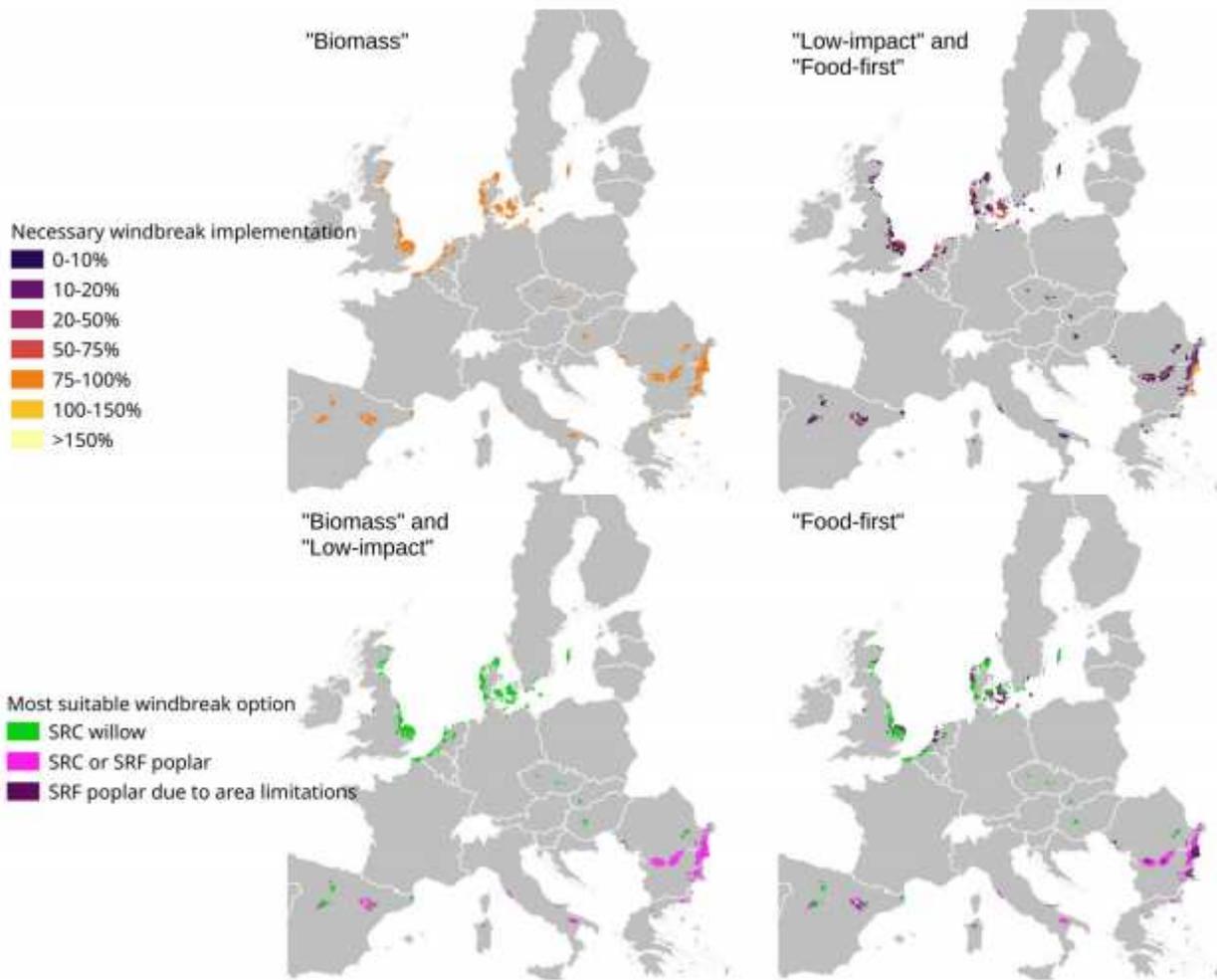


Figure 4

Top row: the implementation level used in the different scenarios. In the "Biomass scenario, it is always 100%. In the "Low-impact" and "Food-first" scenarios, it is determined by the implementation necessary to reduce wind erosion to a "low" level but not beyond. Bottom row: the different windbreak options that are implemented. In the Biomass and "Low impact" scenario, the highest yielding options are always used, in the "Food-first" scenario, the option is also affected by the ambition to minimize total windbreak area.

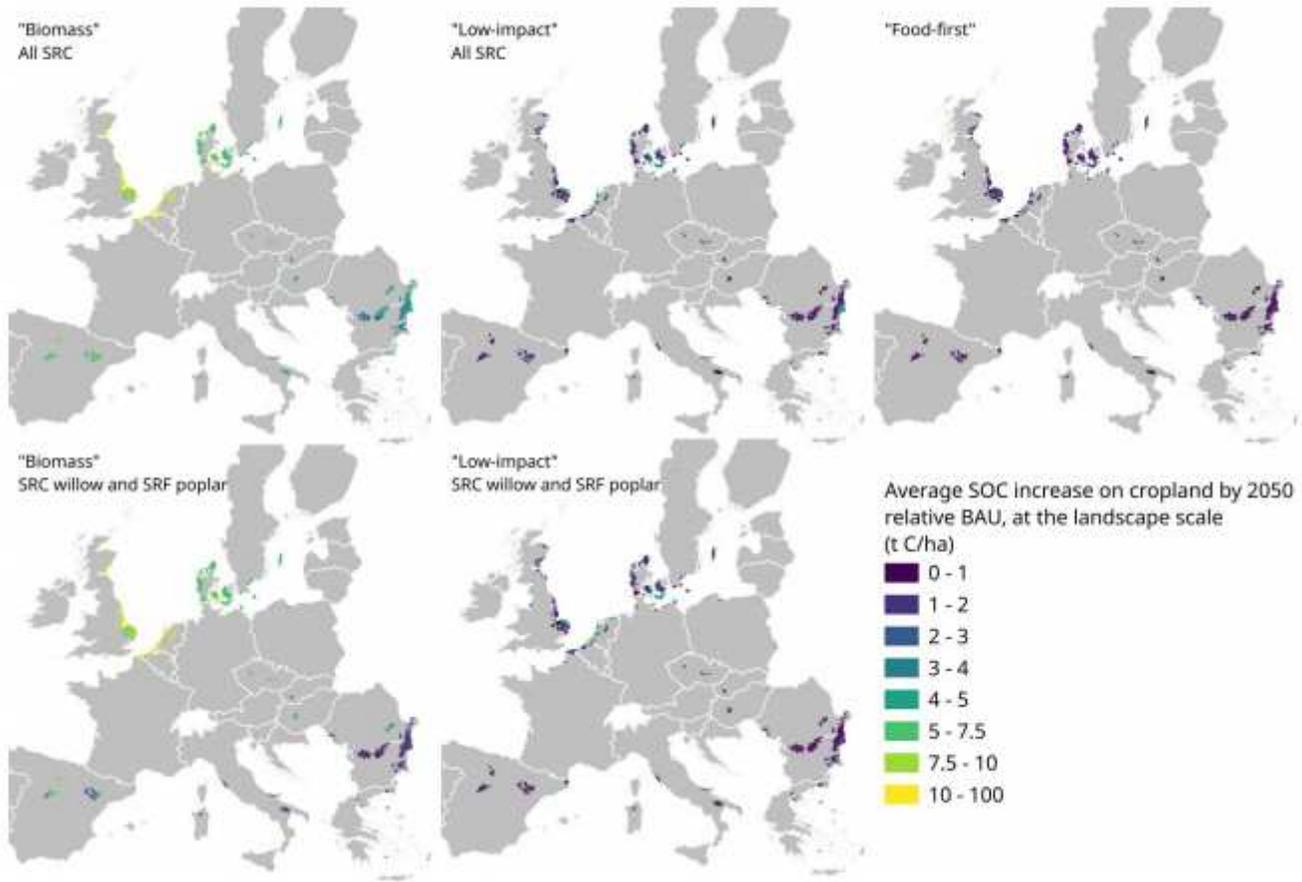


Figure 5

Average increase in SOC on cropland by 2050, relative BAU, in each landscape, in different deployment scenarios and with different windbreak options.

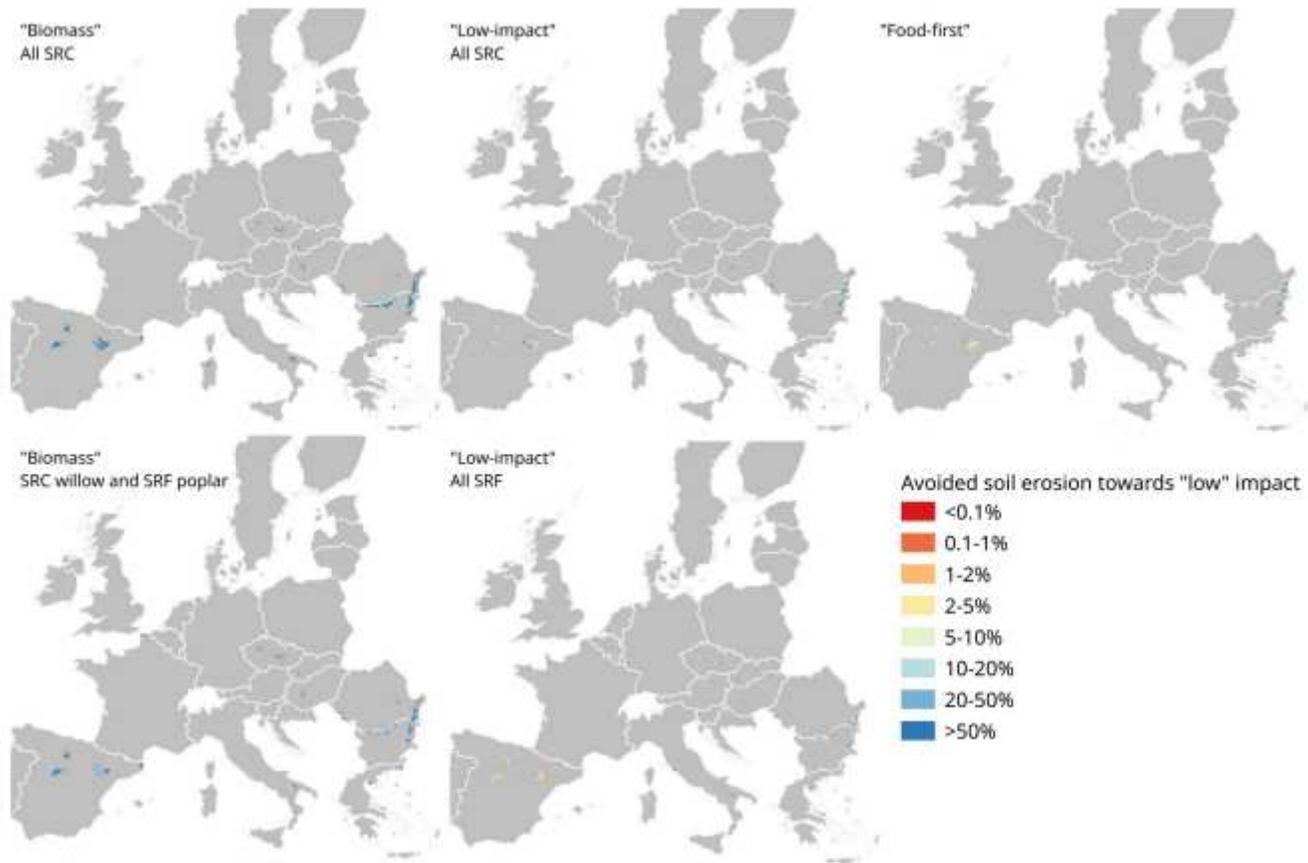


Figure 6

Degree to which establishment of windbreaks contribute towards reducing soil loss by water erosion down to a "low" level, in the three deployment scenarios for different windbreak options

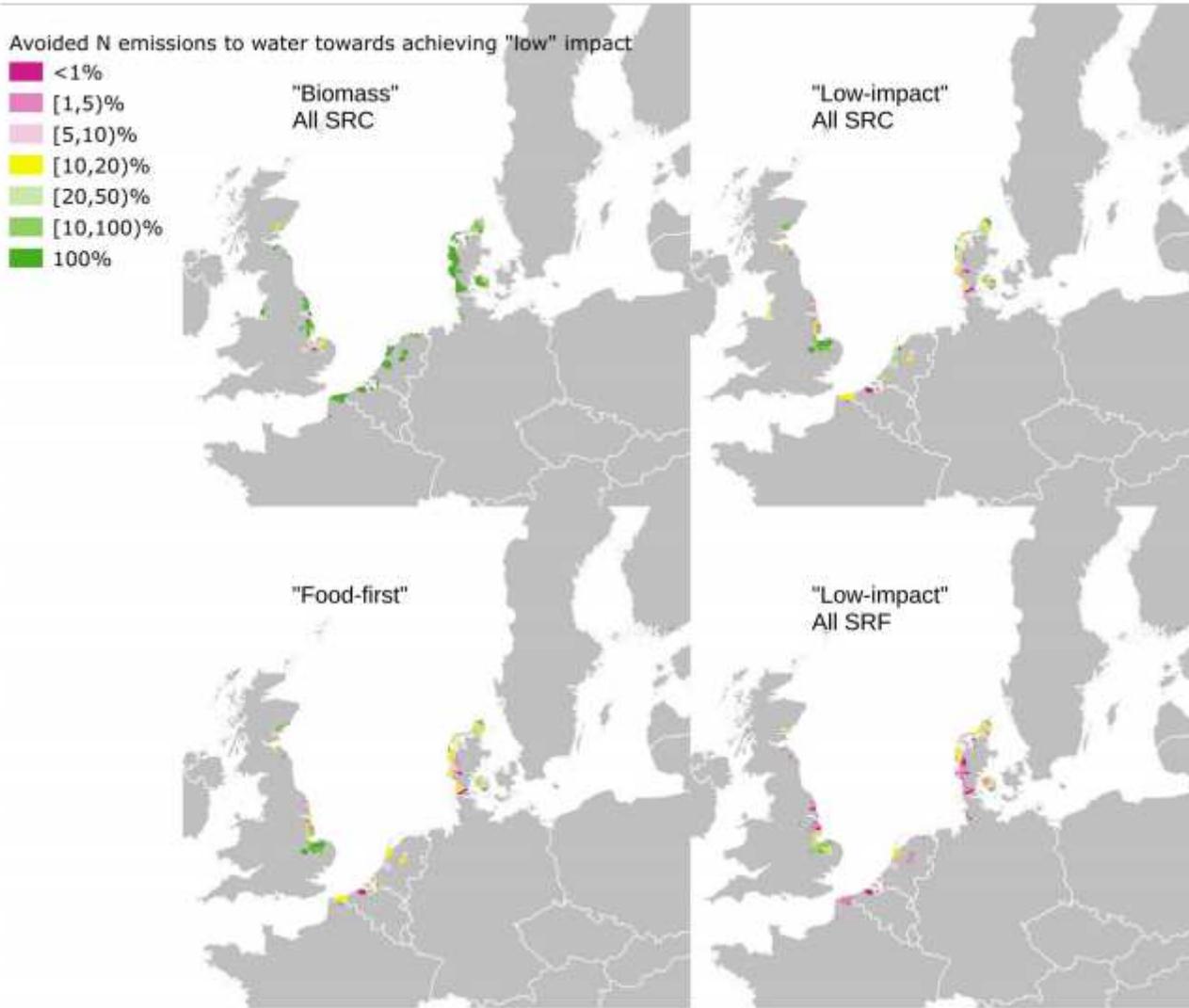


Figure 7

Degree to which establishment of windbreaks contribute towards reducing N emissions to water down to a "low" level, in the three deployment scenarios for different windbreak options

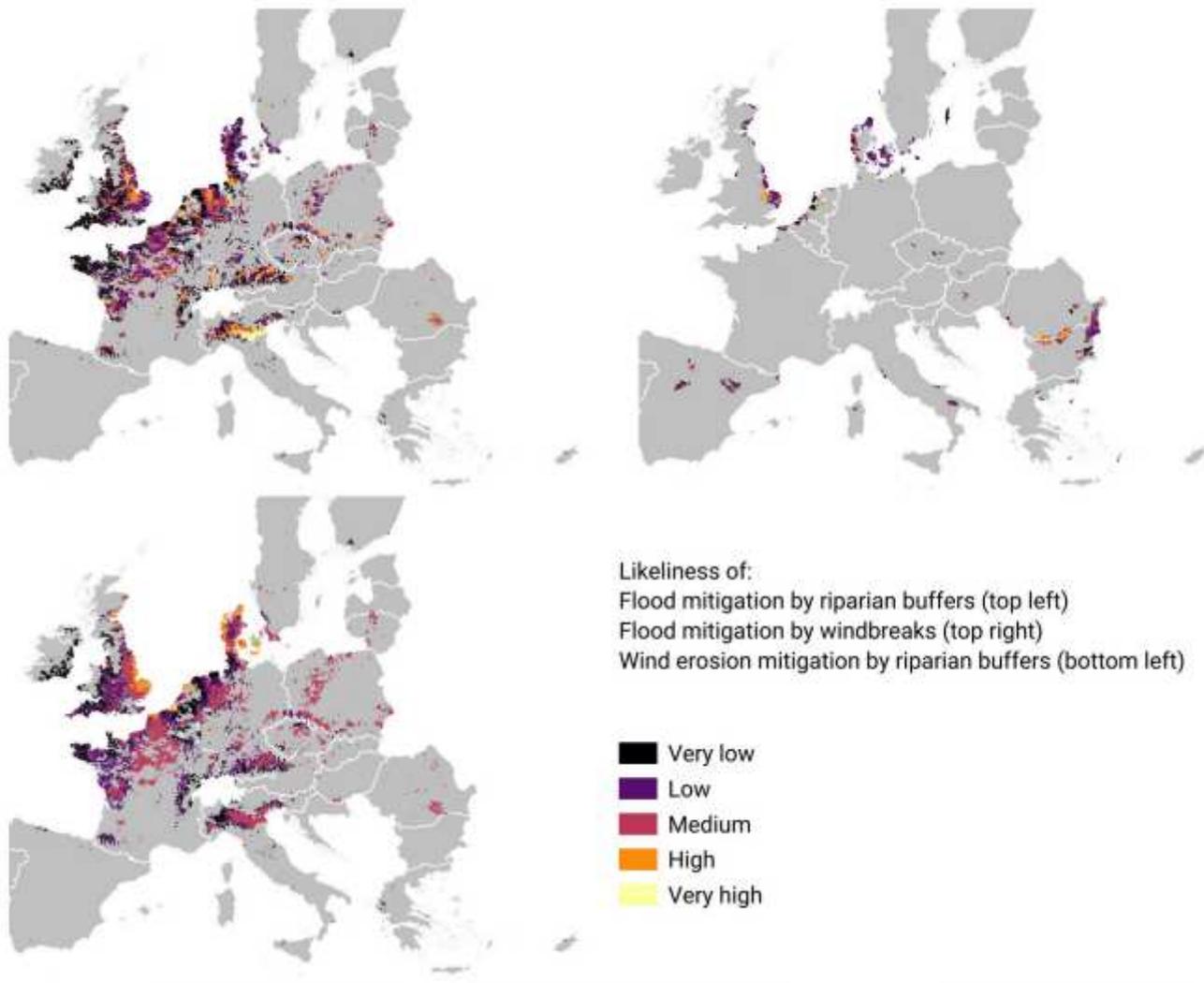


Figure 8

Likelihood of flood mitigation and wind erosion mitigation in riparian buffers and windbreaks.

Supplementary Files

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- [strategicperennializationSI.pdf](#)