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REDUCING NEGATIVE IMPACTS FROM BIOMASS PRODUCTION WHILE PRODUCING MORE BIOMASS

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PREFACE

This project has been carried out within the collaborative research program *Renewable transportation fuels and systems* (Förnybara drivmedel och system), Project no. 48364-1. The project has been financed by the Swedish Energy Agency and f3 – Swedish Knowledge Centre for Renewable Transportation Fuels.

The Swedish Energy Agency is a government agency subordinate to the Ministry of Infrastructure. The Swedish Energy Agency is leading the energy transition into a modern and sustainable, fossil free welfare society and supports research on renewable energy sources, the energy system, and future transportation fuels production and use.

f3 Swedish Knowledge Centre for Renewable Transportation Fuels is a networking organization which focuses on development of environmentally, economically and socially sustainable renewable fuels. The f3 centre is financed jointly by the centre partners and the region of Västra Götaland. Chalmers Industriteknik functions as the host of the f3 organization (seehttps://f3centre.se/en/about-f3/).

The project addresses the question how increased biomass demands for food, energy and materials can be met while improving the overall land use sustainability, i.e., how to achieve *beneficial land use change*. A GIS based analytical framework was developed and used in the project for mapping and analyzing existing environmental impacts in agriculture and the effectiveness for impact mitigation by strategic introduction of perennial crops into the landscape. This was done for more than >80 0000 individual sub-catchments in EU27+UK. The analytical framework was also applied at national scale for Sweden.

Complementary to the studies at EU27+UK and Swedish level, a case study was carried out exploring integrated bio-oil production in an existing combined heat and power (CHP) plant in Örtofta in southern Sweden utilizing lignocellulosic energy crops as feedstock. The case study investigated (i) the amount of arable land needed to produce biomass feedstock in form of willow, also including abandoned arable land for poplar plantations, to provide the biomass needed in a scenario where the Örtofta CHP plant is converted into a bio-refinery that also produce bio-oil; and (ii) the possibilities to locate, design and manage the biomass plantations to achieve additional environmental benefits. Specific benefits relating to water purification and soil carbon sequestration were quantified, together with the biomass feedstock produced in association with these benefits.

The project involved researchers from Chalmers University of Technology, Lund University, Mid-Sweden University, Campus Östersund, and Englund GeoLab AB. Part of the dissemination in the project was carried out within IEA Bioenergy Task 45 - Climate and sustainability effects of bioenergy within the broader bioeconomy.

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SUMMARY

The agriculture sector can play a key role in meeting climate targets by providing biomass for biofuels and other biobased products, while simultaneously sequestering atmospheric carbon in vegetation, soil, and root systems. Multiple new policies at EU level have the potential to provide incentives for more sustainable land use practices, including the establishment of multifunctional perennial production systems that provide both biomass and environmental benefits, e.g., soil carbon sequestration, reduced nitrogen emissions to water, reduced soil loss by wind and water erosion, mitigated flooding events, etc. This report includes assessments of multifunctional systems at EU, national (Sweden), and county (Scania in South Sweden) level. The assessments at EU level use spatial modelling across more than 81 000 landscapes in Europe (EU27+UK) to study effects of large-scale deployment of riparian buffers and windbreaks consisting of short-rotation coppice (willow and poplar plantations) and perennial grass in rotation with annual crops. The assessment on national level is based on a similar approach. The county-level assessment investigates the potential of multifunctional plantations in Scania to provide biomass for a combined heat and power plant that also produces bio-oil from pyrolysis.

The study of riparian buffers and windbreaks includes three scenarios for "widespread deployment". The *Biomass* scenario assumes that farmers select the design that is expected to result in the highest mitigation by default, while maximizing biomass output from the multifunctional system. The *Low-impact* scenario allows for greater flexibility in system design but assumes that there are no incentives to reduce the identified main environmental impact below a predefined, acceptable, level. The *Food-first* scenario resembles "Low impact" but with the addition that impacts on food production are disincentivized. The study of grass in crop rotations includes two scenarios for widespread deployment. The *Low estimate* deployment scenario assumes that two years of grass cultivation are added to a four-year rotation with the most common annual crops in the area, at 25-100% of the fields in the landscape, depending on the degree of accumulated soil carbon losses. The *High estimate* deployment scenario assumes a higher implementation of grass cultivation with two, three or four years of grass added to the rotation, depending on the degree of accumulated SOC losses. The county-level study in Scania includes two scenarios with *low* and *high* biomass demand, determined by the scale of pyrolysis oil production, where short-rotation coppice plantations are located in buffer strips and filter zones (willow) and on abandoned arable land (poplar).

The results show that a strategic introduction of biomass production systems as riparian buffers and windbreaks on arable land in EU27+UK can effectively reduce nitrogen emissions to water and soil loss by wind erosion, while simultaneously providing environmental co-benefits, using less than 1% of the area under annual crops in Europe. The net greenhouse gas (GHG) emissions savings from replacing fossil fuels with the produced biomass, combined with increases in soil organic carbon, correspond to 1-1.4% of total GHG emissions in Europe. The avoided nitrogen emissions to water in the riparian buffer Biomass scenario represent some 11% of the gross surplus of nitrogen on agricultural land, and 33% of total N emissions to water in EU27+UK. Corresponding avoided emissions in the low-impact and food-first scenario represent about 4% of total gross nitrogen surplus and 13% of total nitrogen emissions to water. The deployment of windbreak plantations reduced the total soil loss by wind erosion in EU27+UK by some 23%, regardless of how the windbreak options are combined.

Large-scale deployment of grass in rotation with annual crops can provide soil organic carbon sequestration on European cropland at levels possibly exceeding 10% of total annual GHG emissions from agriculture in EU27-UK. The increased grass cultivation in rotations would also provide other environmental co-benefits, including reduced wind and water erosion, reduced N emissions to water, and mitigated flooding events. The combined annual GHG savings from soil-carbon sequestration and the use of biogas from grass-based biorefineries are equivalent to 13-48% of the current GHG emissions from agriculture.

The results from the county-level assessment in Scania show that willow cultivations as buffer strips and filter zones, and poplar plantations on abandoned arable land, has the potential to provide biomass corresponding to some 85-135% of the biomass needed for integrated bio-oil production in the Örtofta combined heat and power plant, in Scania. Furthermore, the total nutrient load from arable land in Scania could be reduced by 5-6% through strategic establishment of willow cultivations. The increased soil carbon sequestration in the willow and poplar plantations may reduce Scania's annual GHG emissions by 0.4-0.6%.

A large part of the buffer strips and filter zones could be located on so called Ecological Focus Areas (EFAs), included in the EU Common Agriculture Policy (CAP). EFAs should represent some 5% of the arable land with the purpose of protecting the environment and supporting biodiversity in agriculture landscapes, and willow cultivations and biomass energy harvests qualify as EFAs. Besides incentives associated with policies, farmers' interest in multifunctional biomass production systems will increase if they see new demand for biomass, e.g., as feedstock for biofuels and protein concentrate.

SAMMANFATTNING

Jordbruket kan spela en viktig roll i klimatomställningen genom att producera biomassa för biobränslen och andra biobaserade produkter, och samtidigt binda in koldioxid i vegetation och mark. Nya styrmedel på EU-nivå kan ge ökade incitament för biomassaproduktion som ger olika miljövinster. Utöver kolbindning i vegetation och mark, så kan olika slags *multifunktionella biomassaodlingar* genom väl vald lokalisering och skötsel exempelvis minska markerosion och kväveläckage som orsakar övergödning, samtidigt som jordbrukslandskapet blir mer varierat och ger bättre förutsättningar för biologisk mångfald.

Denna rapport beskriver resultaten från ett samarbetsprojekt mellan Chalmers, Lunds universitet och Mittuniversitetet i Östersund, där vi undersöker potentialen för multifunktionell biomassaproduktion i EU, Sverige och Skåne. Bedömningarna på EU-nivå baseras på GIS-baserad modellering som omfattar mer än 81 000 vattenavrinningsområden i Europa (EU27+UK). Vi studerade här olika miljöeffekter som kan erhållas vid etablering av Salix- och poppelodlingar i form av lähägn och bufferzoner längs med vattendrag. Vi undersökte också vilka miljövinster som kan erhållas genom ett ökat inslag av vall i områden där ettåriga grödor dominerar växtföljderna. Bedömningen på Sverige-nivå baserades på en liknande metodansats som EU-bedömningarna. I fallstudien för Skåne så undersökte vi hur multifunktionella odlingar kan tillhandahålla biomassa till ett kraftvärmeverk som även producerar bioolja från pyrolys.

I studien av biomassaproduktion i lähägn och bufferzoner så utvecklade vi tre olika scenarier. *Biomassa* bygger på att jordbrukare väljer den utformning av odlingssystemen som förväntas maximera miljönyttan, samtidigt som biomassaproduktionen skall vara så hög som möjligt. *Låg påverkan* bygger på en större flexibilitet i utformningen av odlingssystemen men det finns inte några incitament att minska negativa miljöeffekter som ligger under en fördefinierad, acceptabel nivå. *Food first* liknar *Låg påverkan* men med tillägget att effekterna på livsmedelsproduktionen minimeras.

I studien av ökat inslag av vall i växtföljder ingick två scenarier för vallodlingens utbredning. Scenariot med mindre utbredning bygger på att två års vallodling läggs till en fyraårsrotation med de vanligaste ettåriga grödorna i området, på 25–100 % av fälten i landskapet, beroende på graden av ackumulerat markkol förluster. Scenariot med mer utbredning bygger på en vallodling under två, tre eller fyra år läggs till rotationen med ettåriga grödor, beroende på graden av ackumulerade markkolsförluster. Studien på länsnivå i Skåne omfattar två scenarier med produktion av biomassa för Örtofta kraftvärmeverk, där efterfrågan beror på hur mycket pyrolysolja som produceras tillsammans med el och värme. Salix odlas i buffertzoner längs vattendrag och som vegetationsfilter för behandling av kväverikt dräneringsvatten, medan poppel odlas på övergiven åkermark.

Resultaten visar att biomassaproduktion i buffertzoner och lähägn, på mindre än 1% av åkermarken med ettåriga grödor i EU27+UK, kan effektivt minska kväveutsläppen till vatten och markförluster genom vinderosion, och även ge andra miljövinster. Nettoreduktionen av växthusgaser, som erhålls från substitution av fossila bränslen med den producerade biomassan i kombination med kolinbindning i åkermarken, motsvarar 1–1,4 % av de totala växthusgasutsläppen i Europa. Minskningen av kväveläckaget till vattendrag i scenariot *Biomassa* motsvarar cirka en tredjedel av de totala kväveutsläppen till vatten i EU27+UK. Minskningarna i *Låg påverkan* och *Food first* motsvarar cirka

13 % av de totala kväveutsläppen till vatten i EU27+UK. Biomassaproduktion i lähägn minskade den totala markförlusten genom vinderosion i EU27+UK med knappt en fjärdedel

Vallodling i rotation med ettåriga grödor kan resultera i kolinbindning odlingsmarken motsvarande drygt 10 % av de totala årliga växthusgasutsläppen från jordbruket i EU27-UK. Ökad vallodling skulle också ge andra miljövinster, såsom minskad vind- och vattenerosion, minskat kväveläckage till vatten och mildare översvämningar. Nettoreduktionen av växthusgaser, som erhålls från kolinbindning i åkermarken och substitution av fossila bränslen med biogas från gräsbaserade bioraffinaderier motsvarar, 13–48 % av de nuvarande växthusgasutsläppen från jordbruket.

Studien av salix- och poppelodling i Skåne visade på en biomassapotential motsvarande cirka 85–135% av biomassabehovet i Örtofta kraftvärmeverk. Vidare skulle det totala näringsläckaget från åkermarken i Skåne kunna minskas med 5–6 % tack vare salixodlingarna. Den ökade kolbindningen i marken i salix- och poppelodlingarna kan minska Skånes årliga växthusgasutsläpp med 0,4–0,6 %.

En stor del av salixodlingarna skulle kunna kvalificera som ekologiska fokusområden (EFA), som ingår i EU:s gemensamma jordbrukspolitik. EFA-arealer bör etableras på cirka 5 % av åkermarken med syftet att skydda miljön och stödja biologisk mångfald i jordbrukslandskap. Utöver att det skapas incitament inom ramen för styrmedel kan en växande efterfrågan på biomassa, t ex. som råvara för biobränslen och proteinkoncentrat, öka intresset för multifunktionella biomassaodlingar bland jordbrukare.

CONTENTS

1 INTRODUCTION

There is strong evidence and agreement that climate change, population growth, and increases in per capita consumption of food, wood and biobased products will add further pressures on managed as well as natural and semi-natural ecosystems (IPCC 2018, 2019). At the same time, many climate change mitigation scenarios presented in IPCC assessment reports rely heavily on the deployment of land-based mitigation, including bioenergy and other biobased options. Thus, the global society faces the double challenge of increasing biomass production to meet multiple demands while reducing negative land use impacts, including greenhouse gas (GHG) emissions.

The growing bioeconomy offers both opportunities and challenges to mitigate and adapt to climate change and natural resource constraints. Yet, links between land use change (LUC) and the emerging bioeconomy are commonly a basis for questioning biobased options, due to a view that LUC is – by definition – "bad" and new biobased solutions should be constrained to using residues and waste as feedstock to minimize LUC. However, this view ignores the fact that many current land uses are unsustainable, so maintaining status quo is not a viable option. Further, there are many examples showing that strategic integration of new biomass production systems (commonly perennial plants) into agricultural landscapes can provide additional biomass along with co-benefits such as enhanced landscape diversity, habitat quality, retention of nutrients and sediment, erosion control, soil carbon sequestration, pollination, pest and disease control, and flood regulation (Asbjornsen et al. 2014; Englund et al. 2020; Cacho et al. 2018; Christen and Dalgaard 2013; Dauber and Miyake 2016; Holland et al. 2015; Milner et al. 2016; Ssegane et al. 2015; Zalesny et al. 2019; Ssegane and Negri 2016; Styles et al. 2016; Zumpf et al. 2017). Such approaches can help limit environmental impacts from intensive agriculture, while maintaining or increasing land productivity and biomass output at the landscape scale.

This report presents results from a project that identifies options for achieving *beneficial LUC* with new perennial biomass production systems that are integrated into intensively managed agricultural landscapes, mitigating impacts associated with current land use and improving the way we manage land, water, and other essential resources. As many of the Sustainable Development Goals, SDGs, are closely linked to land use, the identification and promotion of such beneficial LUC can support a growing use of bioenergy and other biobased products while contributing to SDG implementation, especially SDG2 "Zero hunger", SDG6 "Clean water and sanitation", SDG7 "Affordable and Clean Energy", SDG13 "Climate Action", and SDG15 "Life on Land".

Studies have so far either addressed specific localized situations or have addressed generic characteristics of specific biomass production systems on a more conceptual level. We attempted to take one additional step using an analytical approach to consistently investigate different land use options at several scales: EU27+UK Sweden, and a region in south Sweden. We believe that our analytical framework is one of the most comprehensive yet developed for analyzing options to mitigate land use impacts by integrating new biomass production systems into agricultural landscapes. While the geographical scope for the project was EU27+UK and Sweden, the analytical framework can be applied also in other regions and our general findings are of global relevance.

2 MODEL-BASED EXPLORATION OF BENEFICIAL LAND USE CHANGE IN AGRICULTURE LANDSCAPES

2.1 MODELLING FRAMEWORK

In this project, we finalized a model that could identify individual landscapes where strategic introduction of perennial crops in intensively managed agricultural landscapes could mitigate different environmental impacts. The model is a static GIS model based on 50-1000 m resolution data on current land-use and indicators for different environmental impacts. It covers >8 000 individual sub-catchments (”landscapes”) across EU27+UK and includes the following impacts (Figure 1):

- Soil loss by water erosion
- Soil loss by wind erosion
- Nitrogen emissions to water
- Soil organic carbon (SOC) losses
- Recurring floods

The spatial analysis is based on functional elementary catchments (FECs), equivalent to sub-watersheds, from the ECRINS database (European Environment Agency, 2012). This unit was selected based on the importance of hydrological processes, constrained by a watershed, in determining how the flow of nutrients, water, and other substances can be affected by changes in land use. It was also considered an appropriate size for assessing implementation options regarding perennial biomass production systems.

Each landscape (sub-catchment) was classified as having *very low*, *low*, *medium*, *high* or *very high* (i) nutrient emissions to water, (ii) soil loss by water erosion, (iii) soil loss by wind erosion, (iv) recurring flood, and (v) accumulated loss of SOC. This classification was made using geostatistical analyses of spatial indicators at the landscape scale The corresponding ecosystem services that facilitate impact mitigation was then expressed in quantitative units, such as kg N/ha/y (nutrient retention), ton soil loss/ha/y (mass flow regulation), etc. The assessment of mitigation effectiveness is based on the judgement that the introduction of perennial crops for mitigating environmental impacts is most effective in landscapes dominated by the production of annual crops, which has caused the environmental impacts by degrading the capacity for regulating ecosystem services. Therefore, as a basis for assessing the effectiveness of perennialization, the *annual crop dominance*, i.e., the share of land in each landscape used for the production of annual crops, compared with the total vegetated area, was therefore calculated for each landscape (see Figure 1). Finally, priority areas for strategic perennialization were identified by identifying landscapes where one impact could be mitigated with very high effectiveness or where multiple impacts could be mitigated with either high or very high effectiveness.

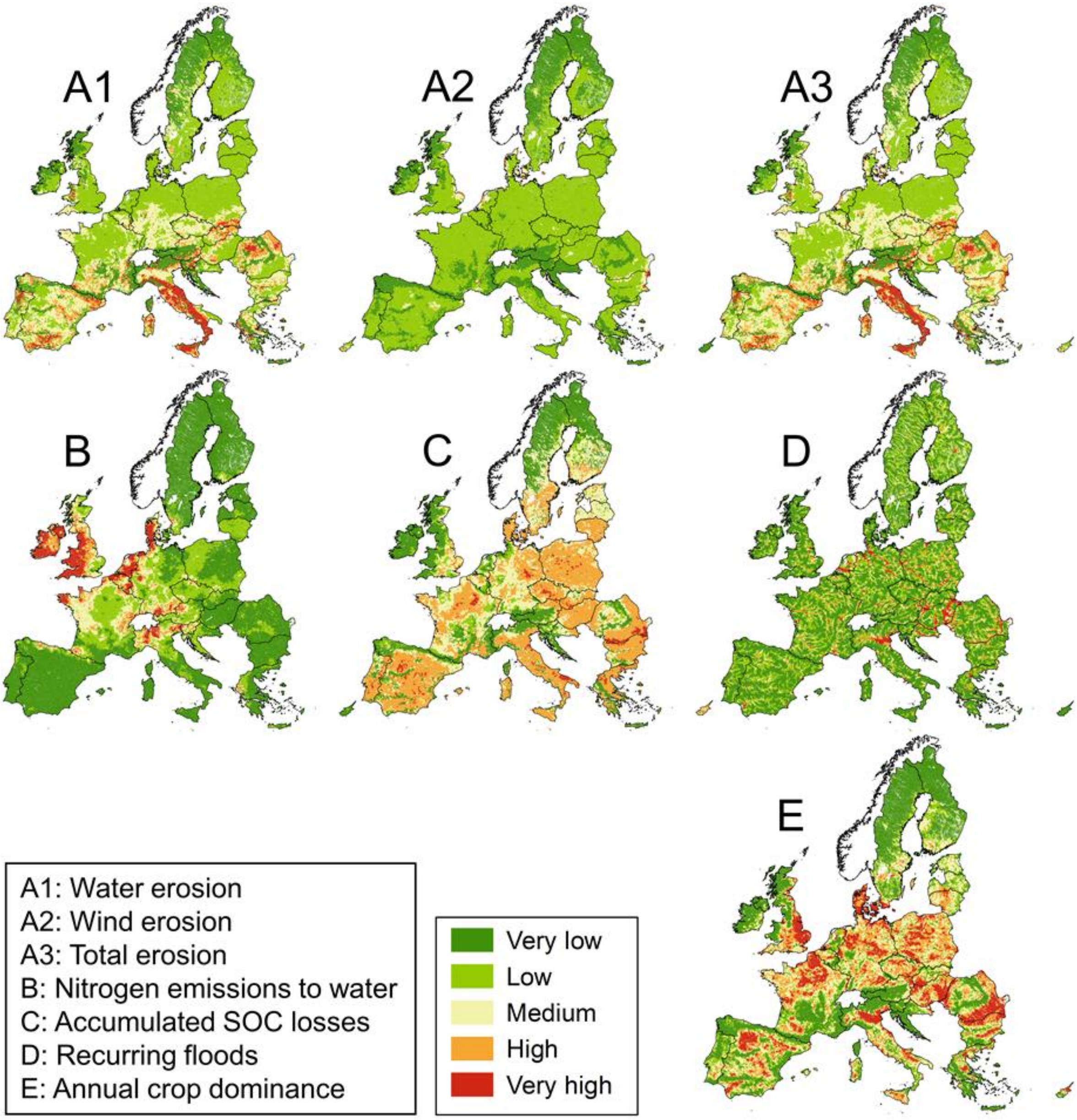

Figure 1. Environmental impacts at landscape scale across EU27+UK (Englund et al. 2020).

After completing this model (ref), we expanded it to include specific multifunctional biomass production systems and to produce quantitative results. The model basically identifies, in different scenarios, whether or not a specific multifunctional production system can be established in each landscape and to what extent. For each landscape, the area of the production system and the biomass output is then calculated, as well as corresponding environmental benefits. We have so far included three production systems in the model:

- Riparian buffers, with the primary purpose to reduce N emissions to water
- Windbreaks, with the primary purpose of reducing soil loss by wind erosion
- In-rotation grass cultivation, with the primary purpose to increase soil organic carbon.

The following three scenarios were included in the assessment of multifunctional riparian buffers and windbreaks: (i) *Biomass*, (ii) *Low-impact*, and (iii) *Food-first*. The *Biomass* scenario assumes that farmers select the design that is expected to result in the highest mitigation by default, while maximizing biomass output from the multifunctional system. The *Low-impact* scenario allows for greater flexibility in system design but assumes that there are no incentives to reduce the primary impact below a predefined, acceptable, level. The *Food-first* scenario resembles “Low impact” but with the addition that impacts on food production are disincentivized. Farmers are therefore assumed to minimize the area used for the multifunctional system while achieving the desired 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), is required to identify a landscape as “suitable”.

Multifunctional riparian buffers and windbreaks were modelled to achieve a primary objective, i.e., to mitigate a specific environmental impact (nitrogen emissions to water for buffers, soil loss by wind erosion for windbreaks, and SOC losses for grass in crop rotations), motivated by specific incentives. This mitigation effect is designated *primary benefit*. In many cases, additional co-benefits are likely, i.e., multifunctional systems will contribute positively also to other objectives, thereby increasing the total benefits for the environment and society (Bustamante 2014).

To illustrate the effects of different management alternatives regarding the introduction of grass in crop rotations, three rotation systems were modelled: two, three, and four years of grass, respectively, added to a 4-year rotation with the most dominant crops in the area. These systems are henceforth referred to as 2/6-grass, 3/7/7-grass, and 4/8/8-grass, or simply 2/6, 3/7, and 4/8. Two scenarios for widespread deployment were then constructed: In the (i) *Low estimate* scenario, a 2/6 system was implemented on 100% of all agricultural fields where the accumulated losses of SOC in the landscape is classified as "very high", on 50% of all fields where it is classified as "high", and on 25% of all fields where it is classified as "medium". In the (ii) *High estimate* deployment scenario, a 2/6 system was instead implemented on all land currently under annual crop production where the impact is classified as "medium", a 3/7 system where it is "high" and a 4/8 system where it is "very high". Based on this, areas, effects on SOC, biomass production and selected co-benefits were modelled for the three rotation systems and the two deployment scenarios, as follows.

In each scenario, the model identifies the total area under grass production in each landscape and the corresponding biomass production, in terms of dry matter (DM) and energy (J). In addition, the amount of extractable protein (tonnes of extractable crude- and true protein, respectively) and biogas output are also quantified, assuming that the grass biomass is used as feedstock in biorefineries that are currently under development (Njakou Djomo et al. 2020). Furthermore, the model estimates corresponding SOC increases by 2030, 2050, and 2080, both relative to 2020 and relative to a business-as-usual (BAU) scenario with a continuation of current land use. The effects on SOC from the introduction of the different production systems were based on SOC simulations of 2-year grass systems and permanent grassland, respectively. The simulation output is available for download at the Joint Research Centre European Soil Data Centre (ESDAC) (see Englund et al. 2021b). The model, as for buffers and windbreaks, also quantifies several co-benefits.

2.2 BENEFICIAL LAND USE CHANGE IN EU27+UK

The results indicate that there is a substantial potential for effective impact mitigation from multifunctional production systems in Europe. Depending on criteria selection (Table 1), 10–46% of the land used for annual crop production in EU27+UK is located in landscapes that could be considered priority areas for beneficial LUC. These areas are scattered all over Europe, but there are notable "hot-spots" where priority areas are concentrated, e.g., large parts of Denmark, western UK, The Po valley in Italy, and the Danube basin (Figure 2).

Table 1. The total number of landscapes and areas under annual crops where strategic perennialization can mitigate different numbers of environmental impacts, with a high and/or very high effectiveness. Numbers in the colored rows can be linked to the identically colored areas in Figure 2. (Englund et al. 2020).

Effectiveness of perennialization	Number of impacts	% of total number of landscapes	Area under annual crop production	
			Thousand hectares	% of total
High	0	78%	33 814	31%
	1	13%	41 217	38%
	2	7%	27 140	25%
	3	2%	6 661	6%
	4	0,1%	765	0,7%
Very high	0	98%	99 266	91%
	1	2%	10 070	9%
	2 [1)]	0,1%	262	0,2%
	3	-	-	-
	4	-	-	-
High or very high [2)]	0	78%	32 055	29%
	1	12%	37 326	34%
	2	8%	30 151	28%
	3	2%	8 757	8%
	4	0,2%	1 309	1%

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

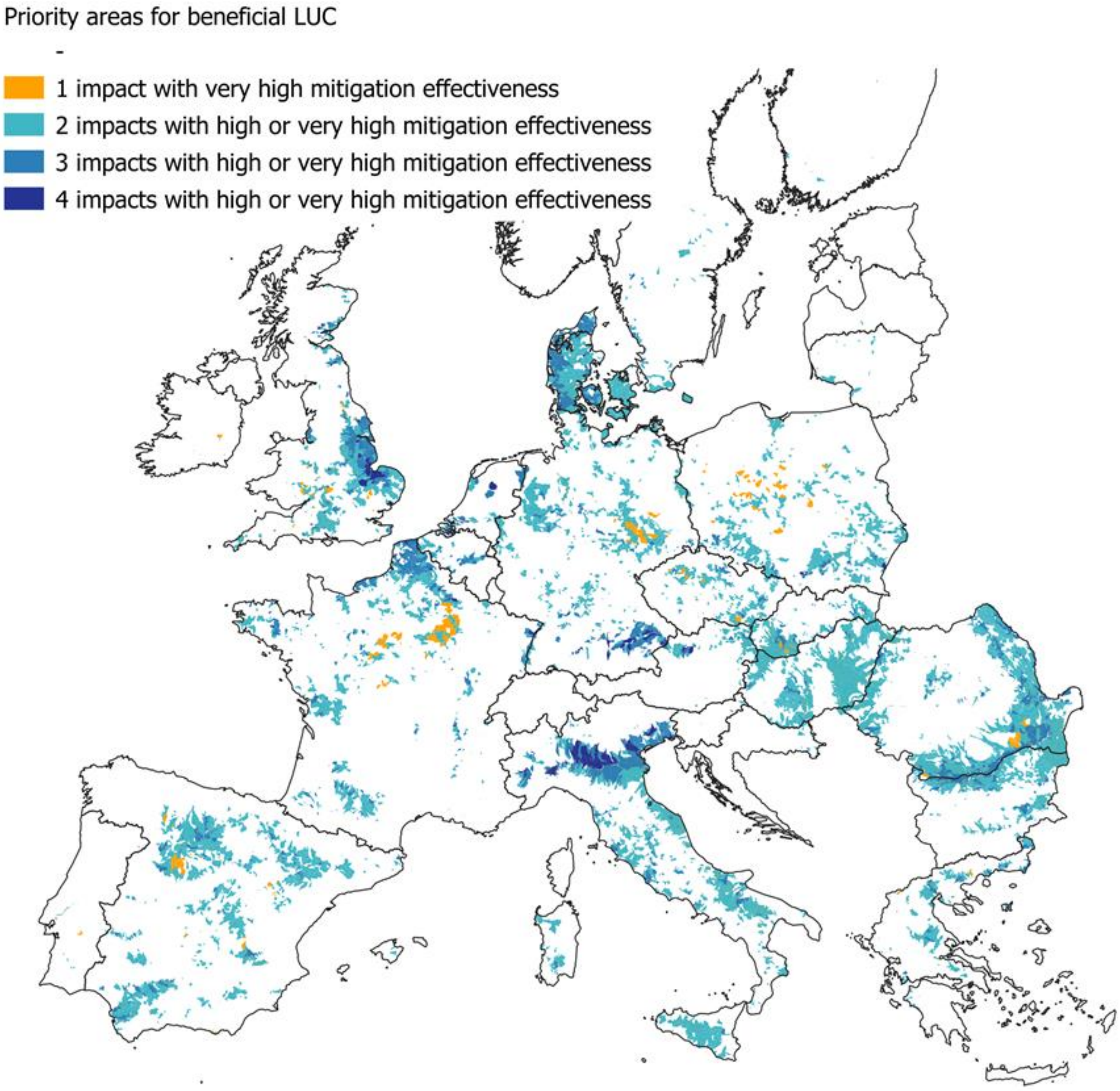

Figure 2. Priority areas for strategic establishment of multifunctional perennial production systems in intensively managed agricultural landscapes across EU27+UK (Englund et al. 2020).

2.2.1 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. All information and all numbers reported below are further explained in the original research article (Englund et al. 2021a). See also Table 2 for a summary of the model results.

Table 2. Model results for the three scenarios where riparian buffers are implemented in EU27+UK on a large scale. (Englund et al. 2020).

Riparian buffers	Deployment scenario		
	Biomass	Low-impact	Food-first
Buffer area (kha)	1 424	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 “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

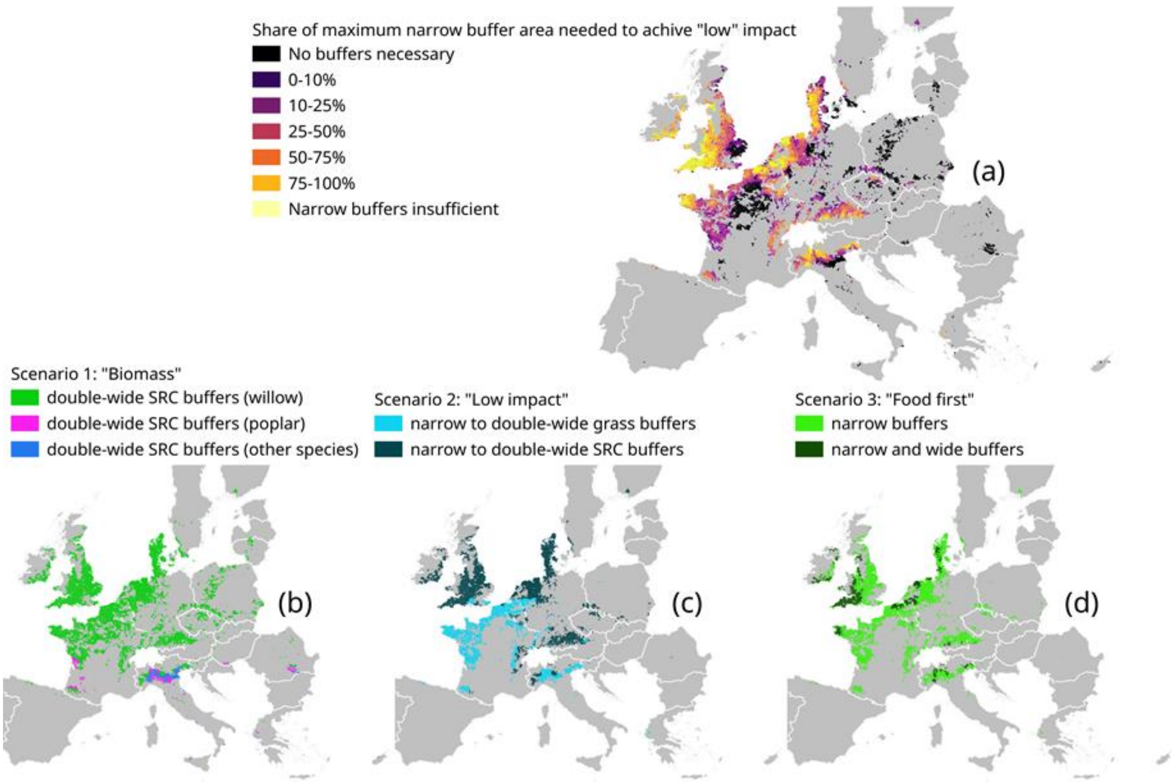

Figure 3. Strategic deployment of riparian buffers. Share of maximum narrow buffer area needed to achieve a low level of nitrogen emissions to water (a), and the type of riparian buffers established in the three deployment scenarios (b–d). (Englund et al. 2021a).

A total of 7 574 landscapes, covering a total of about 58 Mha, were identified as suitable for riparian buffers in the *Biomass* scenario (**Fel! Hittar inte referenskälla.**b). In the *Low-impact* (**Fel! Hittar inte referenskälla.**c) and *Food-first* (**Fel! Hittar inte referenskälla.**d) scenarios, fewer (n=5 705) 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 **Fel! Hittar inte referenskälla.**b-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 (**Fel! Hittar inte referenskälla.**c).

In the *Biomass* scenario, 1.4 million hectares (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.

In the *Low-impact* scenario, there is a large spread in 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 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} SRC biomass or 0.8-2.1 Mt DM y^{-1} of grass biomass.

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}.

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 2015 (Eurostat 2021). In total, this is equivalent to some 8 500 kt N, based on 173 million hectares of agricultural land in EU-27+UK (Eurostat 2018). Not this entire surplus of nitrogen will be leached to surface water; the degree depends on specific local and regional conditions (see **Fel! Hittar inte referenskälla.**). 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 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.

Co-benefits: Increased SOC

In the *Biomass* scenario, given the large buffer areas relative to the other scenarios, SOC increases are the greatest. By 2050, the SOC increase relative a BAU scenario with continued existing land-use, amounts to almost 33 Mt C, corresponding to avoided GHG emissions of 4 Mt CO_2-eq y^{-1}. In the other scenarios, the corresponding numbers are 1.1-6.3 Mt C and 0.1-0.8 kt Mt CO_2-eq y^{-1} for Low-impact and 2.2 Mt C and 0.3 Mt CO_2-eq $y^{-1}$for Food-first. 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 establishment (Lugato et al. 2014), meaning higher short-term GHG emissions savings from increased SOC than what is indicated here.

While improving GHG-balances of those biobased systems that use biomass from riparian buffers as feedstock, deployment of biomass production in riparian buffers will not play a critical role in restoring accumulated losses of SOC across the whole of Europe. SOC losses are widespread and substantial, and riparian buffers only enhance SOC in the location where they are established. Thus, the majority of landscapes in Europe will not be affected, and most land within the landscapes where buffers are established will also be unaffected. To effectively restore SOC on a large scale, changes in crop-rotation practices are necessary, e.g., using ley crops (Lugato et al. 2014).

Co-benefits: Avoided soil loss by water erosion and sediment retention

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.

In the *Low-impact* scenario, total avoided soil loss by water erosion ranges from 192 kt (only narrow buffers) to 1 150 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 13-16 Mt y^{-1}, thus totaling 38-50% direct and indirect avoided soil loss by water erosion within the buffer landscapes. At the Europan level, buffers retain 5-6% of all soil loss by water on cropland.

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 what is necessary to achieve a low impact level at the landscape scale. Additional sediment retention amounts to 16 Mt y^{-1}, totaling 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.

Although there is a notable variation between different landscapes, countries, and regions, riparian buffers are 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 substantial. 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.

2.2.2 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. All information and all numbers reported below are further explained in the original research article (Englund et al. 2021a). See also Table 3 for a summary of the model results.

Table 3. Model results for the three scenarios where windbreaks are implemented in EU27+UK on a large scale. (Englund et al. 2021a).

	Scenario		
	Biomass	**Low impact**	**Food-first**
Windbreak area (kha)	1 685-2 261	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 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 | 1 253-1 507	4–11 | 118-353	6 | 206
Avoided soil erosion by water (kt | median % of mitigation necessary for achieving "low" impact)	1 870-3 175 | 44-95	213-639 | 4-12	289 | 10

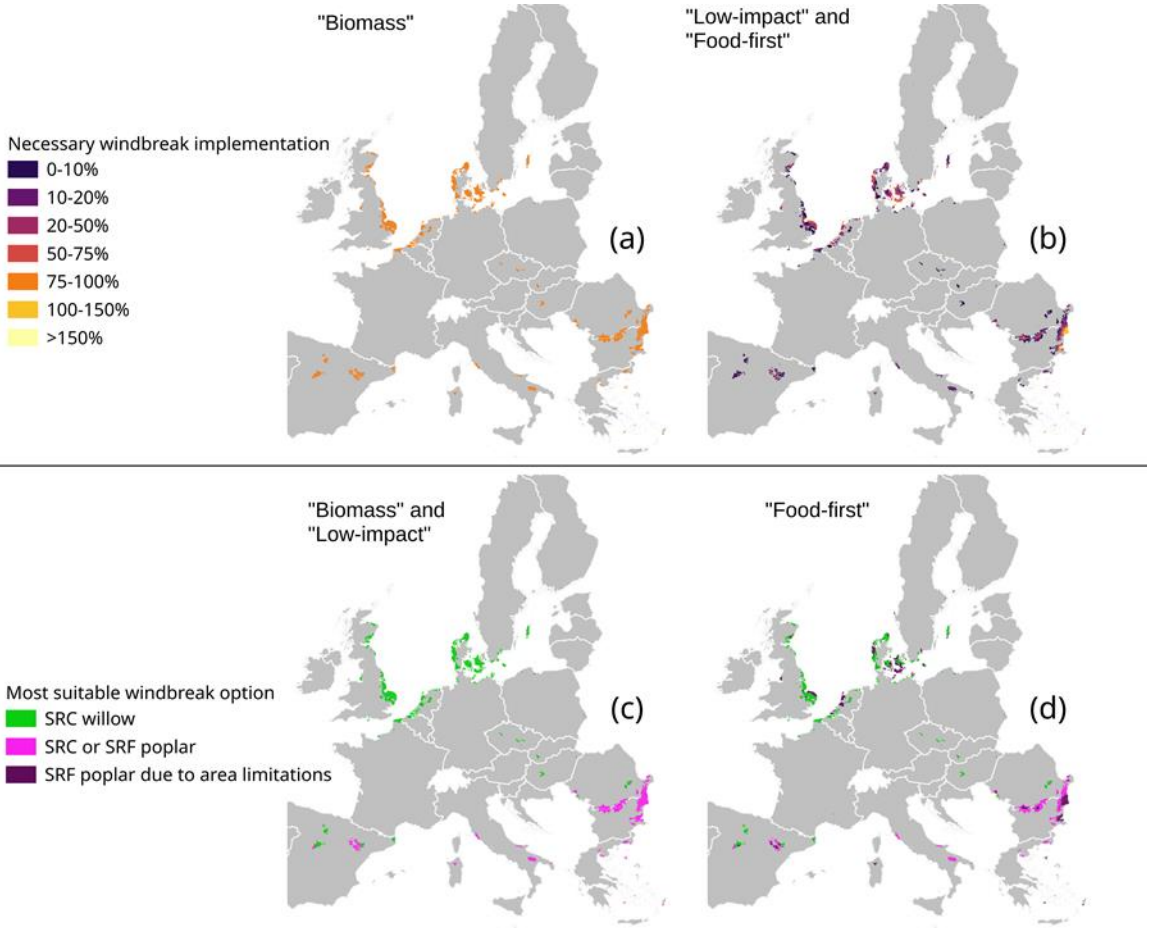

Figure 4. Strategic deployment of windbreaks. Implementation levels in the different scenarios and implemented windbreaks options. In the Biomass scenario (a), the implementation level is always 100%. In the Low-impact and Food-first scenarios (b), it is determined by the implementation necessary to 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. (Englund et al. 2021a).

A total of 7 483 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=6 315), 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, these landscapes are not subject to windbreak implementation in any of the deployment scenarios. Windbreaks are therefore implemented in 1 168 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 (Figure 4).

As for riparian buffers, the degree of soil loss by wind erosion varies substantially, both within and between countries (Englund et al. 2020; Borrelli et al. 2016). 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 (Figure 4b).

In the Biomass scenario, 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 ranges between 5-13 Mt of avoided soil loss, annually, corresponding to 9-23% of total soil loss by wind erosion in EU27+UK. Biomass production from these windbreaks sums up to 3-24 Mt DM y^{-1}. (Figure 4c)

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. Wind erosion mitigation is about 13 Mt y 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}. (Figure 4c)

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 Low-impact scenario, 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}. (Figure 4d)

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 (Figure 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 (Figure 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.

Co-benefits: Increased SOC

As for riparian buffers, effects on SOC depend largely on the windbreak area. In the Biomass scenario, the total SOC increase is therefore the greatest, 38-45 Mt C by 2050, corresponding to 4.6-5.5 Mt CO_2-eq of annual GHG emissions savings. In the other scenarios, total SOC increases are 4-11 Mt C for Low-impact and 6 Mt C for Food-first. Corresponding annual GHG emissions savings are 0.5-1.3 and 0.7 Mt CO_2-eq y^{-1}, respectively.

Unlike for most of the assessed co-benefits, windbreaks could potentially play an important role in restoring SOC in landscapes where they are established. 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 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 small; in the biomass scenario, the annual emissions savings potential relative total GHG emissions (all sectors) in EU-27 + UK in 2018 is 0.14%.

Co-benefits: Avoided soil loss by water erosion

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%.

In the Low-impact scenario, avoided soil loss by water erosion ranges between 0.2 Mt y^{-1} (only SRF) to 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%.

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%.

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. 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% (Figure 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.

Co-benefits: Avoided nitrogen emissions to water

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, in which windbreaks suffice to reduce the impact to a low level in most landscapes, totaling 20-22 kt of avoided N emissions to water, annually. In the 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. This is especially seen in the Food-first scenario, 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.

In many landscapes where windbreaks are implemented, N emissions to water is 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 nitrogen 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.

2.2.3 Additional co-benefits from riparian buffer and windbreak deployment

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, but quantifying this effect requires considering the orientation of buffers relative the dominating wind direction. While the quantification of these co-benefits in biophysical units was outside the scope of this study, we indicated the potential by estimating 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 (Figure 5a,b) and in 1/6 of the landscapes where windbreaks are established (Figure 5c). 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.

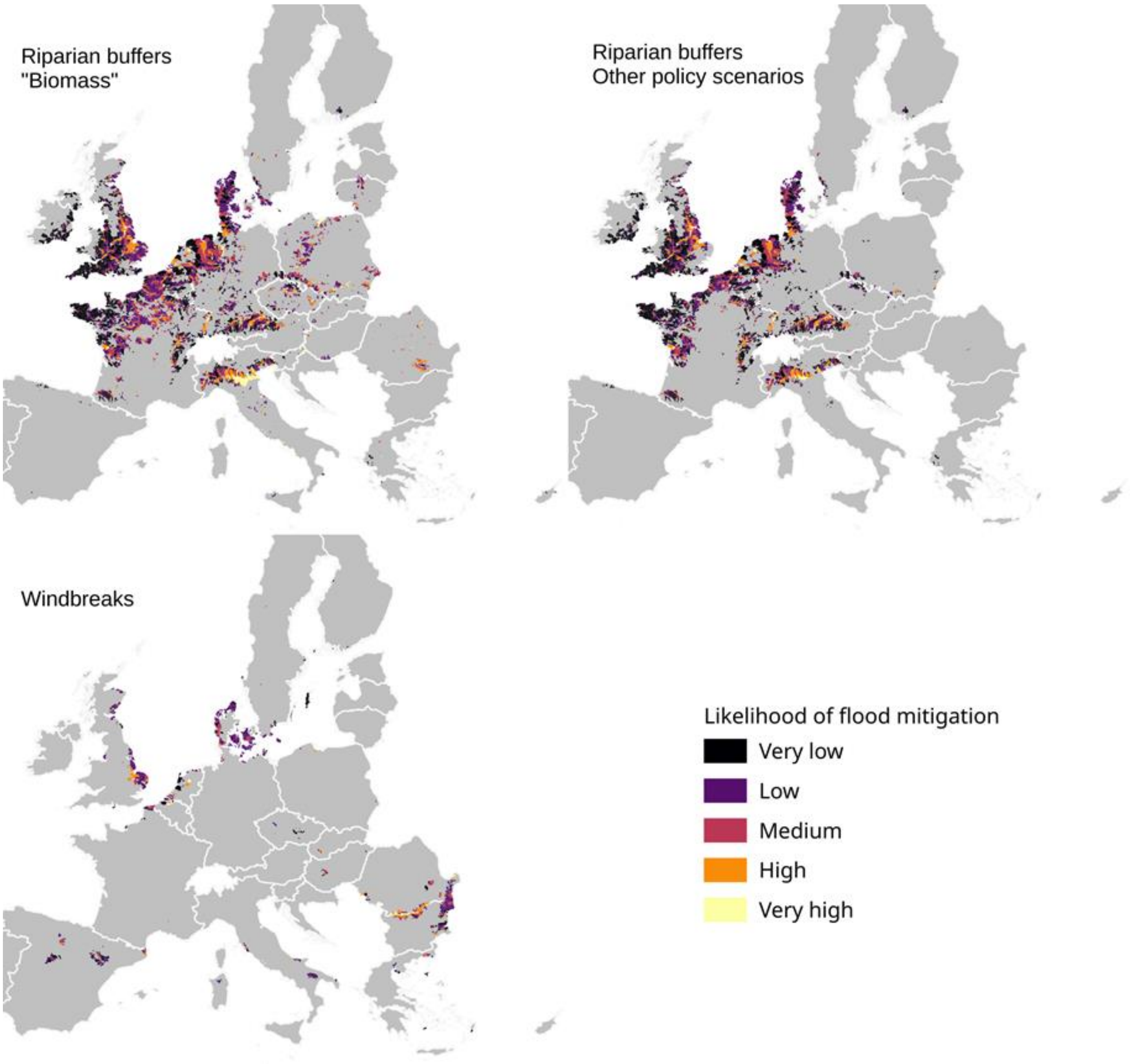

Figure 5. Likelihood of mitigated flooding events due to implementation of riparian buffers (a, b) and windbreaks (c). (Englund et al. 2021a).

As the establishment of perennial crop plantation stripes on agricultural land generate variations in the landscape, they can have direct benefits for biodiversity (Baum et al. 2012; Vanbeveren and Ceulemans 2019) and can play important roles concerning the preservation of sensitive species such as semiaquatic amphibians (Ficetola et al. 2009). However, the outcome depends on local conditions and effects may be negative if 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 fire (Pettit and Naiman 2007). At the same time, these stripes can accumulate dry biomass fuel and thereby become corridors for fire movement, which suggests additional 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 (Fischer et al. 2018; Maleski et al. 2019). 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.

2.2.4 Introduction of grass in crop rotations

The primary benefit of "in-rotation" grass cultivation is enhanced soil organic carbon. Co-benefits include avoided soil loss by wind- and water erosion, avoided N emissions to water, and mitigated flooding events. All information and all numbers reported below are further explained in the published preprint (Englund et al. 2021b). See also Table 4 for a summary of the model results.

Table 4. Model results for large-scale introduction of grass into crop rotations, aggregated at the European (EU27+UK) scale. BAU = Land use continues as per business as usual. Numbers are rounded. (Englund et al. 2021b).

		2/6 system	3/7-grass system	4/8-grass system	Low estimate scenario	High estimate scenario
Area on which grass is included in annual crop rotations (Mha)		91				
Average area under grass production (Mha)		30	39	46	15	38
Biomass output (Mt DM y^{-1}| PJ y^{-1})		209 | 3 908	298 | 5 573	365 | 6 826	102 | 1 907	286 | 5 348
Biogas production (PJ y^{-1})		1 932	2760	3 404	938	2 631
Extractable crude protein (Mt) | true protein (Mt)		43 | 27	62 | 38	76 | 47	21 | 13	59 | 37
Average SOC increase relative to BAU | relative to 2020 (tC ha^{-1} of total cropland area)	2050	3.2 | 3.5	4.1 | 4.4	4.8 | 5.1	1.5 | 1.9	4.1 | 4.3
	2080	4.4 | 4.9	5.7 | 6.2	6.6 | 7.2	2.1 | 2.6	5.5 | 6.0
Total SOC increase relative to BAU | relative to 2020 (Mt)	2050	294 | 335	378 | 419	442 | 483	141 | 181	363 | 404
	2080	402 | 476	517 | 591	603 | 677	193 | 266	497 | 570
Annual GHG emission savings from SOC sequestration until 2050 relative to BAU | relative to 2020 (as % of total current GHG emissions from agriculture)		8.3 | 9.5	10.7 | 11.9	12.5 | 13.6	4.0 | 5.1	10.3 | 11.4
Annual GHG savings when biogas substitutes for gasoline and diesel in cars (Mt C yr^{-1} | as % of total current GHG emissions from agriculture)		32 | 27	46 | 39	56 | 47	16 |14	44 | 37
Annual GHG savings when biogas substitutes for natural gas for electricity (Mt C yr^{-1} | as % of total current GHG emissions from agriculture)		20 | 17	29 | 25	35 | 30	10 | 8	27 | 23
Avoided soil loss by water erosion (Mt y^{-1})		76	97	114	37	95
Avoided soil loss by wind erosion (Mt y^{-1})		18	23	27	9	22
Avoided N emissions to water (kt y^{-1})		271	348	406	119	324

The model introduces perennial grass into crop-rotations on 115 million hectares (Mha) of arable land, in 24 363 landscapes, including about 80% of all arable land in Europe currently used for annual crop cultivation. Most of these landscapes (76%) are classified as subject to “high” accumulated SOC losses, while 17% and 7% are classified as subject to “medium” and “very high” accumulated SOC losses, respectively. Adding two years of grass cultivation to a four-year crop rotation (2/6 system) in all these landscapes results in 30 Mha of land being used for cultivation of grass instead of annual crops, on average over time. Adding one or two additional years of grass cultivation in the crop rotation (3/7 system and 4/8 system) increases the grass area to 39 Mha and 46 Mha, respectively. The corresponding grass production on these areas is about 210, 300, and 370 Mt DM y^{-1}, for the 2/6, 3/7, and 4/8 systems, respectively. The estimated energy content in this biomass is about 4-7 EJ and the corresponding biogas output is about 2-3.4 EJ. Extractable crude- and true protein amounts to about 40-80 Mt and 30-50 Mt, respectively. The SOC increase corresponds to 290, 380, and 440 Mt C by 2050, and about 300, 510, and 600 Mt C by 2080, respectively. The SOC simulations showed no further SOC increases at European scale between 2080 and 2100.

In a “low estimate” deployment scenario – in which the 2/6 system is implemented on all agricultural land where the accumulated SOC loss is classified as "very high", on 50% of the lands where it is classified as "high", and on 25% of the lands where it is classified as "medium" - the total area under grass production amounts to 15 Mha, corresponding to 16% of the area under annual crops in the affected landscapes and 13% of the total area under annual crops in Europe. The corresponding grass biomass production is 100 Mt DM y^{-1}, equivalent to about 1.9 EJ. Biogas output is about 1 EJ. Extractable crude- and true protein amounts to about 20 Mt and 10 Mt, respectively. The SOC increase amounts to about 140Mt C by 2050, and 190 Mt by 2080.

In a “high estimate” deployment scenario – in which the 2/6 system is implemented on all land currently under annual crop production where the accumulated SOC loss is classified as "medium", the 3/7 system is implemented where it is classified as "high", and the 4/8 system is implemented where it is classified as "very high"- the total area under grass production amounts to 38 Mha, corresponding to 41% of the area under annual crops in the affected landscapes and 35% of the total area under annual crops in Europe. The corresponding grass biomass production is 290 Mt DM y^{-1} corresponding to about 5.3 EJ. Biogas output is about 2.6 EJ. Extractable crude- and true protein amounts to about 60 Mt and 40 Mt, respectively. The SOC increase amounts to about 360Mt C by 2050, and 500 Mt by 2080.

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

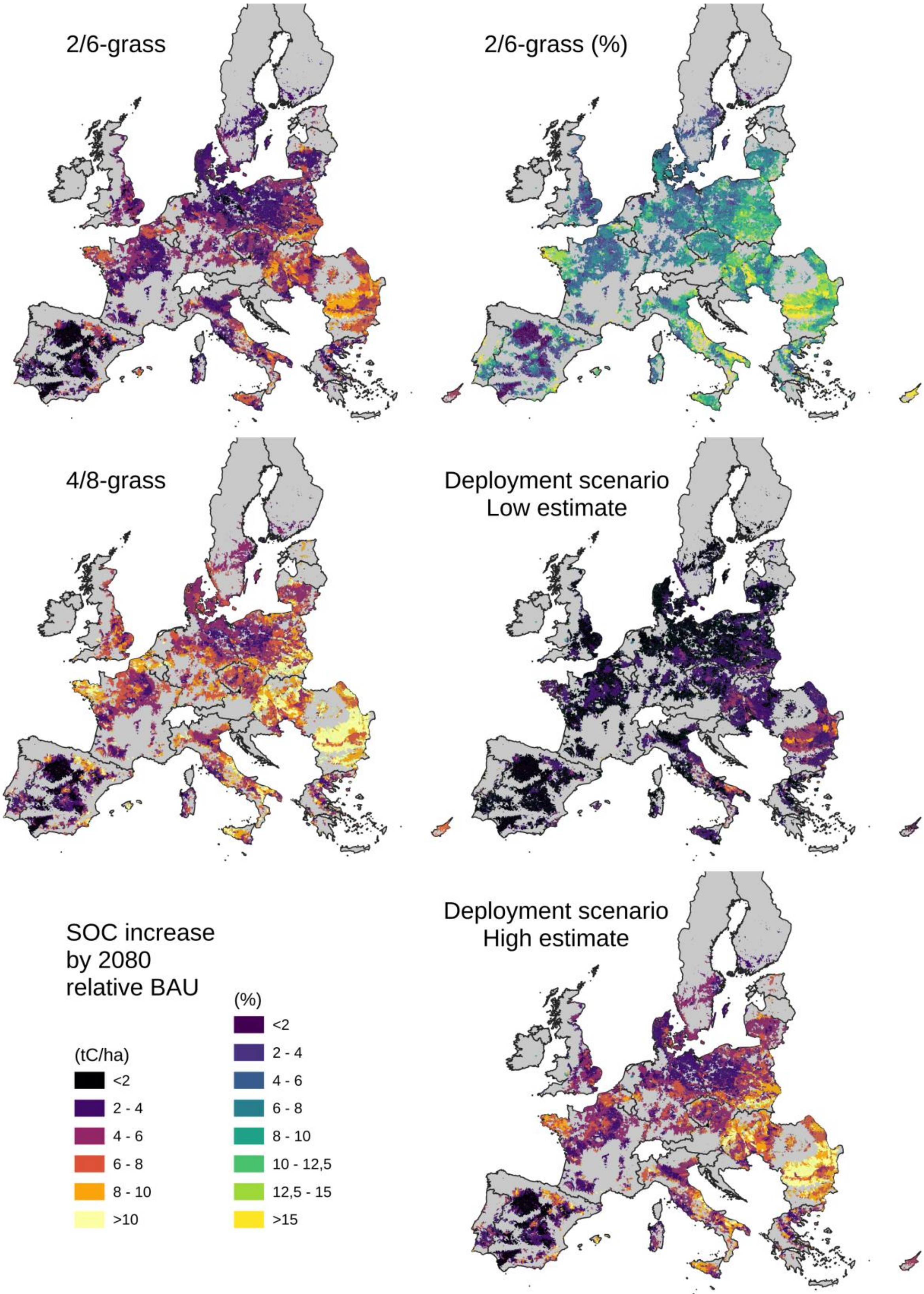

Figure 6. Soil organic carbon (SOC) increase by introducing grass production in crop rotations, relative a BAU scenario with continued land-use. (Englund et al. 2021a).

Effects on SOC

Effects on SOC vary substantially between the different systems and deployment scenarios, as well as between different regions and individual landscapes (Figure 6). Naturally, areas subject to the largest accumulated SOC losses (Figure 1) also show the greatest potential for SOC increase. Since the calculations were made on a landscape scale, the density of annual crop production in each landscape also affects SOC increases. Higher densities result in larger areas of grass production in rotations, causing larger SOC increases compared with landscapes with lower densities. In the deployment scenarios, higher implementation results in larger areas under grass production in rotations, and consequently larger SOC increases.

At the landscape scale, the average SOC increase in the 2/4 system at 100% implementation is 3 t ha^{-1} by 2050, and 4.1 t ha^{-1} by 2080. For the 4/8 system, the corresponding increases are 4.6 t ha^{-1} and 6.2 t ha^{-1}. In most landscapes (80%), SOC increases by 2080 are between 2.1-7.3 t/ha for the 2/6 system and 3.1-11 t ha^{-1} for the 4/8 system. In the low estimate deployment scenario, the average SOC increase is 1.4 t ha^{-1} by 2050 and 1.9 t ha^{-1} by 2080. In the high estimate deployment scenario, the corresponding increases are 3.7 t ha^{-1} and 5.1 t ha^{-1}. In most landscapes (80%), SOC increases by 2080 are between 0.8-2.6 t/ha (low estimate) and 2.2-6.3 t ha^{-1} (high estimate).

Bulgaria, Romania, Belgium, Slovakia, and Hungary have the greatest average SOC increase in the two deployment scenarios. Finland, Estonia, Slovenia, and Sweden have the lowest. In total, 80 % of the modelled SOC increases takes place in France, Romania, Poland, Denmark, Italy, Spain, Hungary, and Bulgaria (Figure 6).

Total average annual SOC sequestration in the high- and low estimate deployment scenarios amounts to 12.1 and 4.7 Mt C y^{-1}, respectively, by 2050, relative a BAU scenario with continued land use. This is equivalent to 4.0-10.3 % of total current GHG emissions from agriculture in EU27+UK (EEA 2021). Comparing with 2020 levels instead of BAU results in slightly higher values. The combined GHG savings from SOC increase and biogas use is equivalent to 13-48% of current GHG emissions from agriculture. The range depends on the deployment scenario, whether biogas displaces natural gas in power plants or is upgraded to vehicle fuel displacing petrol and diesel in cars, and whether SOC increases is calculated relative BAU or 2020 levels.

Co-benefits

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

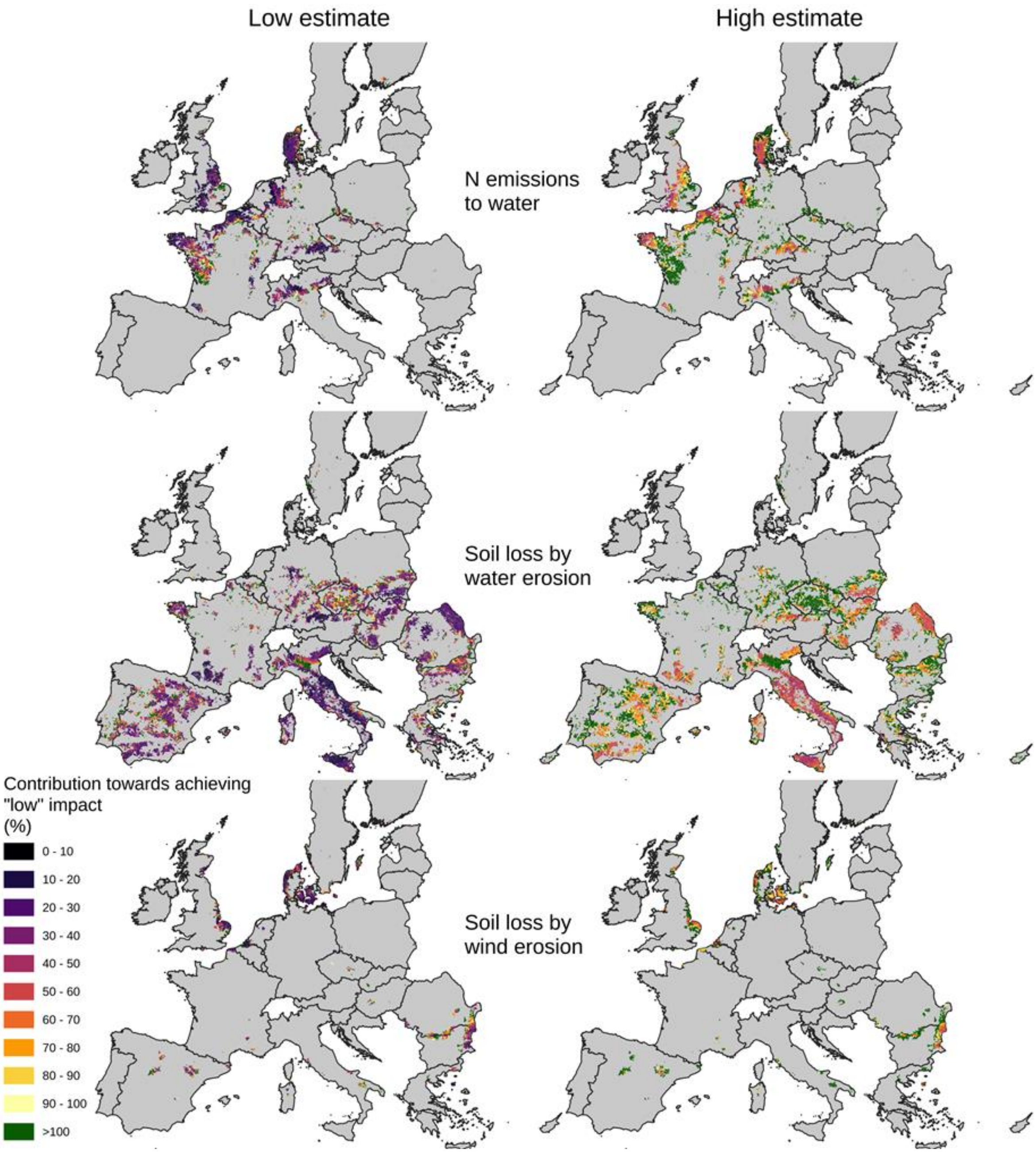

Figure 7. Co-benefits of introducing grass production in crop rotations with the primary objective to enhance soil organic carbon. The figure shows the relative contribution towards achieving a "low" impact at the landscape scale for N emissions to water, soil loss by water erosion, and soil loss by wind erosion, respectively, in the low estimate (left) and high estimate (right) deployment scenarios. Landscapes already having a "low" or lower impact are excluded. (Englund et al. 2021a).

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

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

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

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

Displacement effects

The introduction of grass/legume species into annual crop rotations reduces the harvested area of cereal crops, as described above. This cropland displacement may counteract environmental benefits, including reduced pesticide use, by causing cropland intensification or expansion elsewhere. However, this effect can to some extent be counterbalanced. Changes to more diversified crop rotations are known to enhance the yield of grain crops, such as wheat. The principal mechanisms behind these yield gains include enhanced disease control and improved supply of nitrogen and water. There are, however, also other "rotation effects" that are not yet fully understood (see Englund et al 2021b for further discussion). The food/feed crop displacement effect is further reduced when grass biomass is used in biorefineries that can produce food and feed along with bioenergy and other biobased products, here exemplified by protein feed and biogas production, leading to reduced need of imported plant protein, mostly soymeal. However, these potential displacement effects depend on many factors and transcend regions as well as continents. Complementary studies, such as integrated assessment modeling, can provide important insights about land-use consequences of widespread deployment of grass cultivation via changes in existing crop rotations.

2.3 BENEFICIAL LAND USE IN SWEDEN

The model described in the previous section has here been applied to Sweden. The below results are not yet published and should therefore be considered tentative.

Environmental impacts identified by the model are presented in Figure 8. Compared with many other countries in Europe (Figure 1), Sweden is generally subject to rather few severe impacts, but accumulated losses of SOC are widespread in all agricultural areas.

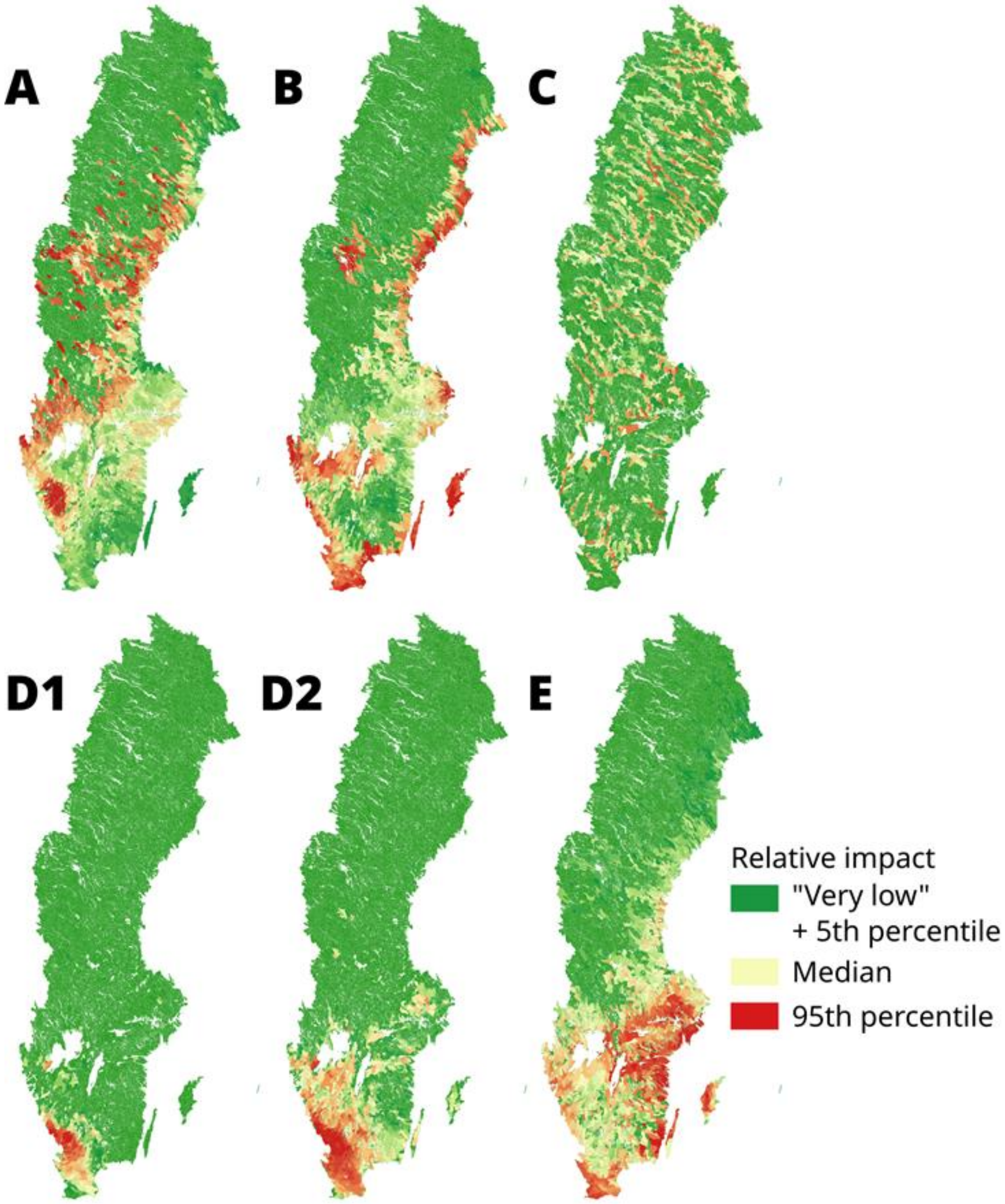

Figure 8. Relative environmental impacts in Sweden visualized using 20 percentiles (excluding values under the threshold for "very low impact") aggregated to landscape (sub-catchment) scale. A: Soil loss by water erosion; B: Soil loss by wind erosion; C: Recurring floods; D1: Nitrogen emissions to water;

D2: Nitrogen emissions to water using 50% lower threshold for "very low impact"; E: Accumulated losses of SOC.

The general effectiveness of strategic introduction of multifunctional perennial production systems in mitigating environmental impacts is presented in Figure 9. The greatest impact mitigation potential was found for SOC losses, but we see a clear potential for mitigation of all assessed impacts, to varying extents, in all the main agricultural areas.

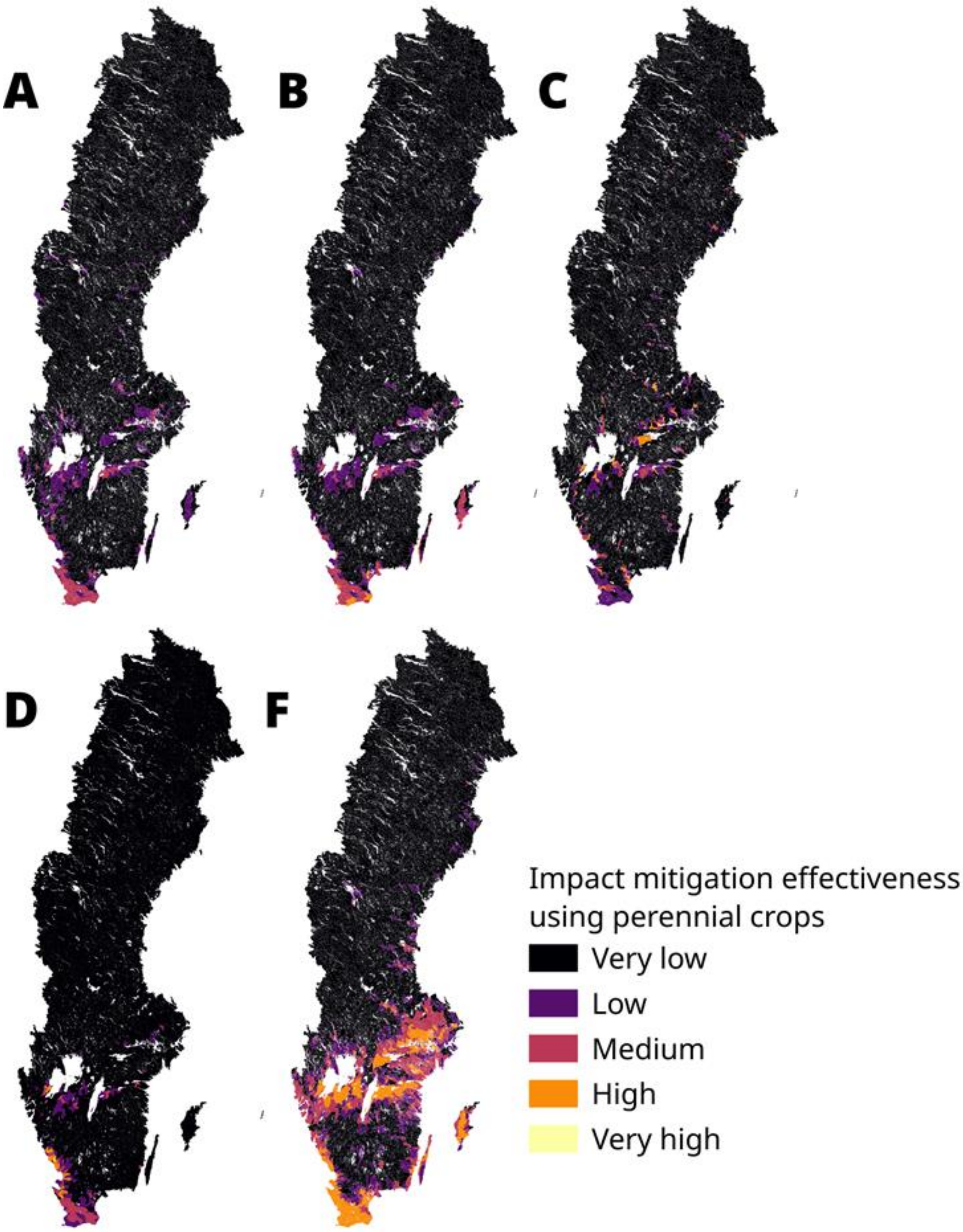

Figure 9. The effectiveness of using strategic cultivation of perennial crops for mitigating specific environmental impacts at landscape (sub-catchment) scale. A: Soil loss by water erosion; B: Soil loss by wind erosion; C: Recurring floods; D: Nitrogen emissions to water; E: Accumulated losses of SOC.

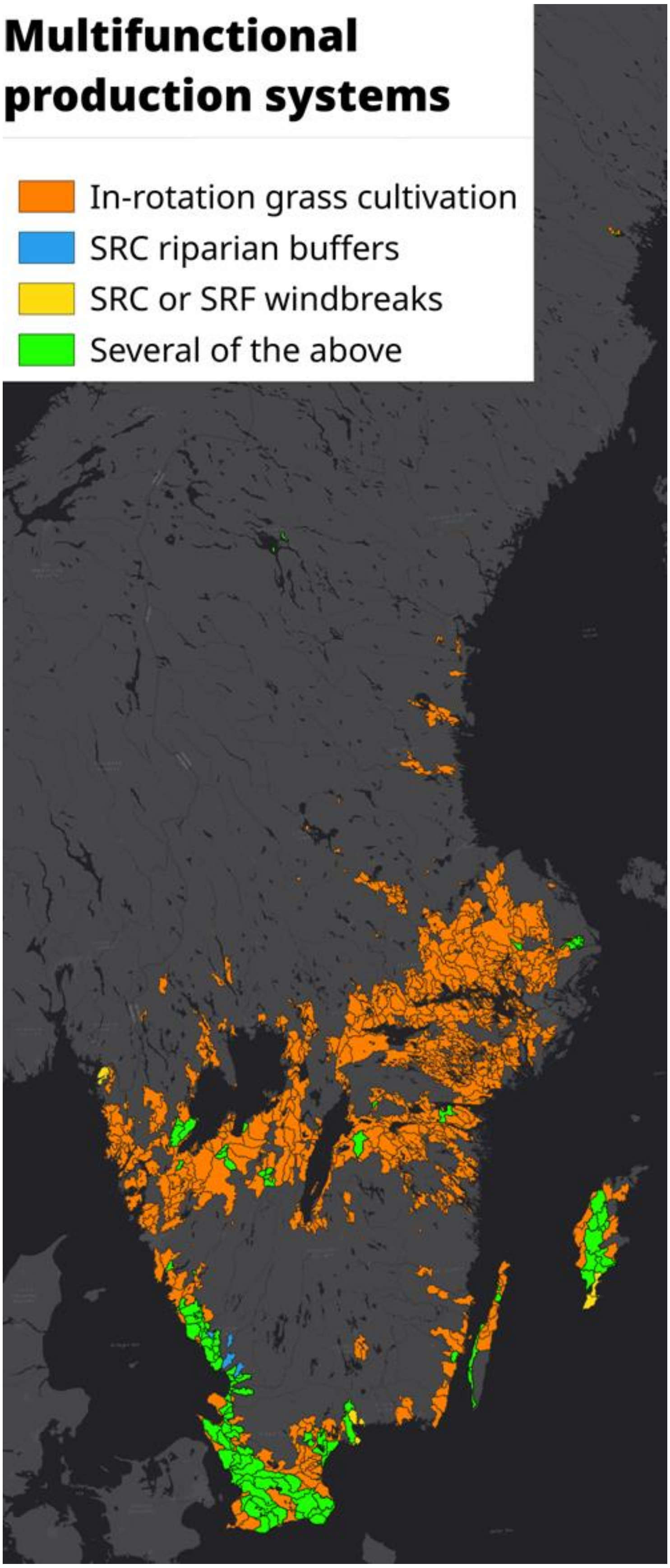

Figure 10. Model results: Widespread implementation of different multifunctional production system in Sweden.

The model suggests that 342-900 kha of ley can be introduced in crop rotations to enhance SOC in Sweden, in the landscapes illustrated in Figure 10. This would yield a total of 1.8-5.3 Mt DM grass biomass annually and increase SOC with 2.6-6.7 Mt C until 2050, relative a BAU scenario. N emissions to water would be reduced by 2.8-7.4 kt N y^{-1}. It would also result in avoided soil loss: 310-816 kt by water erosion and 289-763 kt by wind erosion, annually (Table 5).

Considering riparian buffers and windbreaks (Figure 10), there is a large variation between the different scenarios. The highest estimate of riparian buffers is 14 770 ha and the lowest is 375 ha. The corresponding numbers for windbreaks are 61 150 and 876, respectively (Table 6).

In the high estimate scenario, 14.8 kha of riparian buffers could produce a total of 147.1 kt DM biomass (2 750 TJ). This would result in 6.3 kt avoided N emissions to water, an increase in SOC of 219.5 kt C by 2050 (relative BAU), 12.5 kt avoided soil loss by water erosion, and 312 kt of retained sediments. In the other scenarios where the buffer areas are smaller, all these numbers are naturally much lower. Avoided N emissions to water are, however, relatively high even in the lower estimates (1.2 kt y^{-1}) because the model, in these scenarios, incentives implementation where N emissions to water are the greatest (Table 6).

Similarly for windbreaks, 61.2 kha of windbreaks could produce a total of 599 kt DM biomass (11 201 TJ) annually. This would result in 258 kt y^{-1} of avoided soil loss by wind erosion. It would also result in 435 t y^{-1} avoided N emissions to water, a SOC increase of about 1 Mt C by 2050 (relative BAU), and 33 kt y^{-1} avoided soil loss by water erosion. Note that avoided soil loss by wind erosion is identical in all scenarios, even though the windbreak area differs massively. This is caused by a model assumption that windbreaks are unable to reduce soil loss by wind erosion below a certain threshold. The effect is that windbreaks in some landscapes have zero effect on wind erosion (if it is below the threshold where windbreaks are assumed to have an effect), even though the model classifies the landscape as suitable for windbreak implementation (Table 6).

Table 5. Model output for widespread deployment of in-rotation grass production. All values aggregated to Sweden.

	2/6	3/7	4/8	Low estimate	High estimate
Average area under ley production (kha)	712	915	1,068	342	900
Biomass output from ley production (kt)	3 827	5 468	6 698	1 844	5 348
Total SOC increase relative BAU in 2050 (kt)	5 322	6 842	7 983	2 554	6 719
Total SOC increase relative BAU in 2080 (kt)	7 879	10 131	11 819	3 776	9 943
Annual avoided soil loss by water erosion (kt $year^{-1}$)	647	832	970	310	816
Annual avoided soil loss by wind erosion (kt $year^{-1}$)	605	779	908	289	763
Annual avoided N emissions to water (t N $year^{-1}$)	5 839	7 507	8 759	2 791	7 360

Table 6. Model output for three scenarios of widespread deployment of riparian buffers and wind-breaks. All values aggregated to Sweden.

Production system	Model output	Deployment scenario		
		Biomass	Low-impact	Food-first
Riparian buffers	Buffer area (ha)	14 770	303-1 910	375
	Biomass production SRC (kt DM | TJ)	147.1 | 2 751	3.1-18.6 | 57-347	3.8 | 70
	Buffer area relative area under annual crops in landscapes where riparian buffers could be established (%)	3.4	0.2-1.5	0.3
	Avoided N emissions to water (kt N)	6.3	1.2	1.2
	SOC increase by 2050(kt C | average t C year^{-1})	219.5| 7 315	4.5-27.3 | 151-909	5.6 | 186
	Avoided soil erosion by water (kt | median % of mitigation necessary for achieving a low impact level)	12.5	0.4–2.3	0.5
	Retained sediment (kt)	312	35-44	42
Windbreaks	Windbreak area (ha)	61 150	356-1 072	867
	Biomass production (kt DM | TJ)	599 | 11 201	28-104 | 524-1 945	64 | 1 197
	Windbreak area relative area under annual crops in landscapes where windbreaks are established (%)	33	1.9-5.8	3.8
	Avoided soil loss by wind erosion (kt)	258	258	258
	Avoided N emissions to water (t N)	435	33-99	54
	SOC increase by 2050 (kt C | average kt C y^{-1})	1 030 | 34	58-174 | 1.9-5.8	117 | 3.9
	Avoided soil erosion by water (kt)	33	2.2-6.7	4.1

3 CASE STUDY: INTEGRATED BIO-OIL PRODUCTION IN AN EXISTING HEAT AND POWER PLANT IN SOUTHERN SWEDEN (SCANIA) UTILIZING LIGNOCELLULOSIC ENERGY CROPS

3.1 BACKGROUND

Combined heat and power (CHP) production in combination with a district heating (DH) grid is an energy efficient use of wood fuels. The heat demand in the DH grid is, however, expected to decline over the coming decade due to energy savings in the residential sector and reduced heat demand due to climate change (Sköldberg et al, 2013). Recent studies show that the long-term DH demand is hard to predict due to uncertainties regarding the future Swedish energy system, where the DH demand may potentially increase slightly again after 2030 (Hagberg and Unger, 2021). However, many DH grid operators are looking for additional heat sinks in their strategic planning to optimize their use of investments in CHP plants and the surrounding infrastructure (Zetterholm et al, 2018). Furthermore, many plants are not delivering district heat during the warmer summer months leading to spare capacity for the integration of complementary heat-demanding processes. In parallel, the demand for sustainably produced bio-oils with a low carbon footprint is expected to increase rapidly in the near future, driven by new policy goals and incentives. Examples are the GHG emission reduction obligation systems in the Swedish road transport sector, implemented 2018, and in the aviation sector implemented 2021. The reduction target for 2030 is 28%, 66% and 27% for petrol, diesel and jet fuels, respectively, compared to 2010 (The Swedish Government, 2020). This, in turn, leads to a significant increase in the demand of biofuels and biojetfuels having low fuel cycle GHG emissions.

A study by Björnsson et al (2021a,b) has investigated the possibility of integrating a pyrolysis unit into an existing CHP plant located in Örtofta (see Figure 11) close to the city of Lund in the county of Scania, southern Sweden, operated by Kraftringen AB. The DH season is relatively short compared to that in the north of Sweden, leading to a low degree of utilization during the summer months, and the plant has a well-developed infrastructure for handling large volumes of wood fuels. This together makes the Örtofta CHP plant potentially suitable for an integrated production of bio-oil by pyrolysis. The results from the study show an overall high energy efficiency, at least 80%, in the integrated production of heat, electricity and bio-oil (Björnsson et al, 2021a,b). Extending the use of the pyrolysis unit to stand-alone operation during the summer months improves the use of exiting installations and infrastructure, but at the cost of a somewhat reduced overall energy efficiency. The carbon footprint of the bio-oil was shown to be very low, between 1.7-4.0 g CO2 equivalents per MJ, which would make it attractive as feedstock for biofuel and biojet fuel production. For comparison, the carbon footprint of fossil oil is calculated to approximately 84 g CO2 equivalents per MJ.

Figure 11. The Örtofta combined heat and power plant run by Kraftringen AB (Photo: Anna Terstad).

An increase in the domestic production of bio-oil will increase the competition for biomass. The Swedish domestic biomass potential consists, to a large extent, of wood fuels such as logging residues from final felling in forestry, and by-products of the forest industry (Börjesson, 2016, 2021a). A prerequisite for a sustainable increase in the supply of biomass feedstock is that the increased supply meets all the critical environmental objectives, not only climate goals. The study by Björnsson et al (2021a,b) include an increased use of sustainably produced woody biomass in form of logging residues from forestry and sawdust from the forest industry (see also Börjesson, 2021b). However, an alternative feedstock is lignocellulosic biomass from agriculture, such as short rotation coppice (SRC) willow. The Örtofta plant is located in a region with intense agriculture dominated by arable land, but the current cultivation of willow is marginal representing 0.4% of today's arable land use (Swedish Board of Agriculture, 2019). A strategic expansion of perennial energy crops, such as willow, in the agricultural landscape may lead to land-use related environmental benefits, in addition to the provision of biomass feedstock. Examples are reduced nutrient leaching and water purification, water and wind erosion, loss of soil organic carbon etc. (Styles et al, 2016; Englund et at, 2020; 2021). Such beneficial land use changes will make this biomass feedstock especially attractive from a sustainability point of view, reducing the overall negative environmental impact from current agriculture production and land use.

Another potential feedstock is fast growing deciduous trees, such as poplar and hybrid aspen, cultivated on abandoned arable land. According to a study by Olofsson and Börjesson (2016), around 90 000 hectares of abandoned arable land could potentially be available in Sweden for the cultivation of poplar and hybrid aspen thereby producing some 2.0 TWh biomass per year. A large part of this potential is found in southern Sweden, e.g., in the county of Scania. A potential additional environmental benefit from the cultivation of fast-growing deciduous trees on abandoned arable land is increased soil carbon sequestration, thereby improving the overall carbon balance for this biomass feedstock (Börjesson et al, 2012).

To sum up, the objectives with this case study are to investigate (i) the amount of arable land in Scania needed to produce biomass feedstock in form of willow, also including abandoned arable land for poplar plantations, to fulfil the increased demand of biomass feedstock in a potential development of the Örtofta CHP plant into a bio-refinery also producing bio-oil, (ii) the possibilities to locate and design the biomass energy plantations to achieve additional environmental benefits, (iii) to quantify such benefits focusing on water purification and soil carbon sequestration, together with the biomass feedstock produced.

3.2 INCREASED DEMAND OF BIOMASS-BASED FEEDSTOCK FOR INTEGRATED BIO-OIL PRODUCTION AT THE ÖRTOFTA CHP PLANT

The study by Björnsson et al (2021a,b) analyzing the possibility of integrating a pyrolysis unit into the existing Örtofta CHP plant include different scenarios regarding yearly production volumes of bio-oil, which are compared with the current reference case producing only heat and power. The scenarios range from small-scale integrated production in a small pyrolysis unit during the winter months' design to cover the current internal bio-oil demand at peak loads within Kraftringen's DH grid, up to large-scale integrated production in a large pyrolysis unit during the winter months with a DH demand and with or without stand-alone production during the summer months with no DH demand (and when the plant is normally closed). The corresponding increased biomass demand, in form of logging residues, in the two high bio-oil production scenarios are shown in Table 7, together with the total amount of bio-oil produced.

Table 7. Yearly increased demand of woody biomass feedstock for the production of bio-oil at Örtofta CHP according to the two high scenarios assessed by Björnsson et al (2021a,b), and corresponding amount of bio-oil produced.

Scenarios	Crude bio-oil production	Biomass demand	
	GWh/yr	1000 ton DM/yr	GWh/yr[a]
1. Large-scale Integrated pyrolysis production during winter months	480	100	550
2. Large-scale integrated pyrolysis production during winter months and stand-alone production during summer months	700	160	920

[a] Higher heating value (HHV), 5.6 kWh/kg DM.

3.3 ENERGY CROP YIELDS AND CORRESPONDING CROPPING AREAS

The average yield of SRC willow cultivated in Scania has been estimated by Styles et al (2016) to 8.7 ton DM per ha*year referring to fertilized cultivations. When willow cultivations are used as buffer strips along open waterways for purification of nutrient-rich runoff, the average biomass yield is estimated to amount to, on average, 5.1 ton DM per ha*year, due to no use of external fertilizers. Another alternative is to use willow cultivations as filter zones where drainage water is collected and used for irrigation, leading to an estimated yield of, on average, 6.6 ton DM per ha*year (Styles et al, 2016). In 8, the corresponding areas of SRC willow cultivations needed to fulfill the biomass demand for bio-oil production in the Örtofta CHP plant (see Table 7) are presented. Figure 12 shows willow cultivation on arable land in Sweden.

Table 8. Cultivation areas (hectares) of SRC willow in Scania needed to fulfill the biomass feedstock demand for bio-oil production at the Örtofta CHP plant.

Scenarios	Willow cultivation area		
	Yield: 8.7 ton DM yr-1	Yield: 6.6 ton DM yr-1	Yield: 5.1 ton DM yr-1
1. 100 000 ton DM/yr	11 500	15 200	19 600
2. 160 000 ton DM/yr	18 400	24 200	31 400

Figure 12. Willow cultivation on arable land in Sweden (Photo: JTI).

Data regarding average biomass yields in poplar plantations on abandoned arable land in Scania is here based on Olofsson and Börjesson (2016). Here, the poplar biomass yield is estimated to be, on average, 6.5 ton DM per ha* year in Scania. The corresponding cultivation areas needed to fulfill the biomass feedstock demand for bio-oil production at the Örtofta CHP plant will then be almost the same as for willow, or 15 400 and 24 600 hectares, respectively.

3.4 CURRENT AMOUNT AND USE OF ARABLE LAND IN SCANIA

The current amount of arable land in Scania is 437 000 hectares, of which roughly half is utilized for cereal production and one quarter is used for ley crops (see Table 9). The remaining quarter is used for, in descending order, oil crops, sugar beets, legumes and maize, fallow, vegetables and potatoes. The current cultivation of SRC willow amount to some 1 900 hectares, equivalent to 0.4% of the total arable land. This cultivation area can be compared with the estimated required areas for biomass feedstock production for the two pyrolysis oil production scenarios presented in Table 8, varying from 11 500 to 18 400 hectares referring to fertilized willow cultivations. These areas are equivalent to 2.6 to 4.2% of the total arable land in Scania. If the willow crop yields are reduced, such in willow buffer zones, the required areas will increase to 4.5 to 7.2%.

Table 9. Total arable land in Scania and its use in 2019 (Swedish Board of Agriculture, 2019).

	Hectares	%
Cereals	211 000	48
Ley crops	104 000	24
Oil crops	43 600	10
Sugar beets	26 100	6
Legumes and maize	16,700	4
Fallow	11 400	3
Vegetables etc.	11 400	3
Potatoes	10 700	2
SRC willow	1 900	0.4
Total	437 000	100

The density of arable land in different regions in Sweden, expressed as per cent of total land area, is shown in Figure 12 and

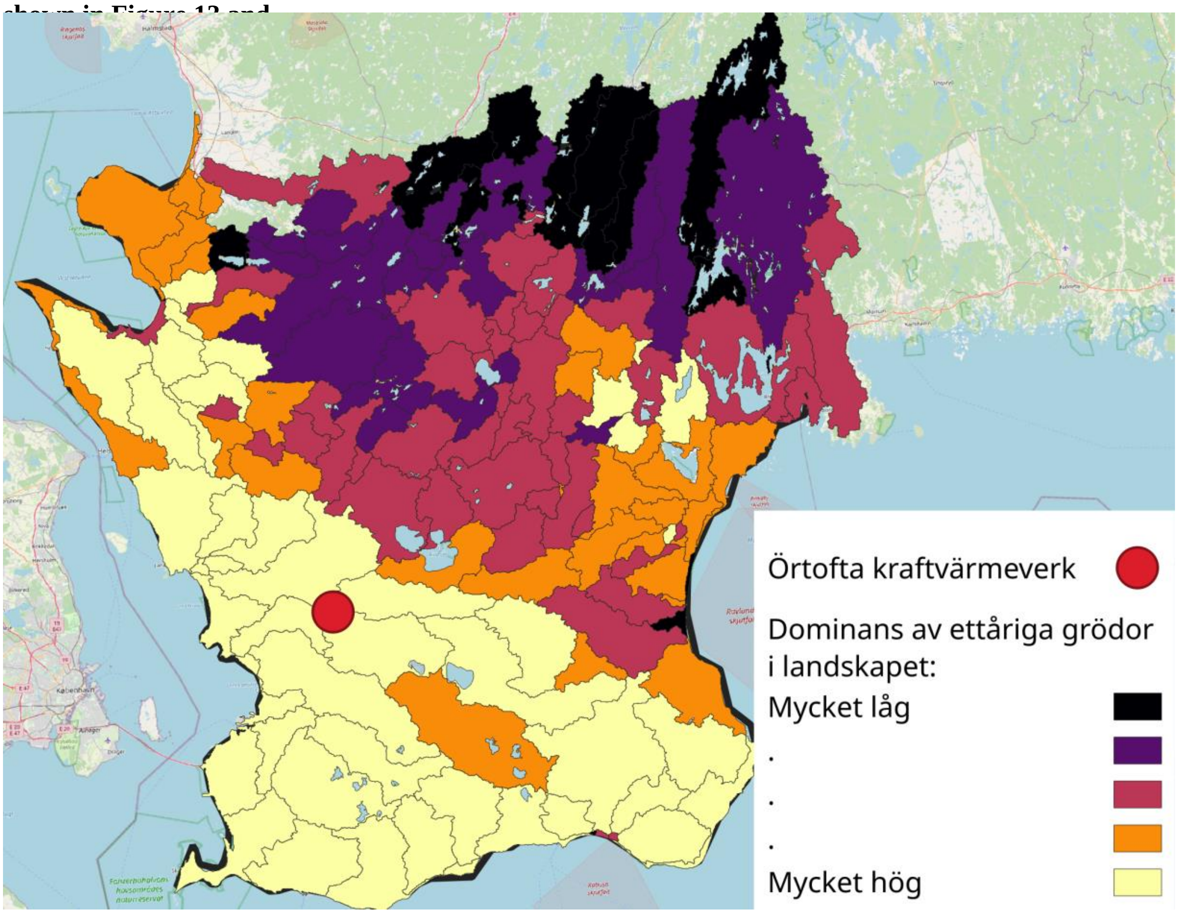

Figure 14 where also the location of the Örtofta CHP indicated (close to the city of Lund in Scania). The density of annual crops in Scania is shown in

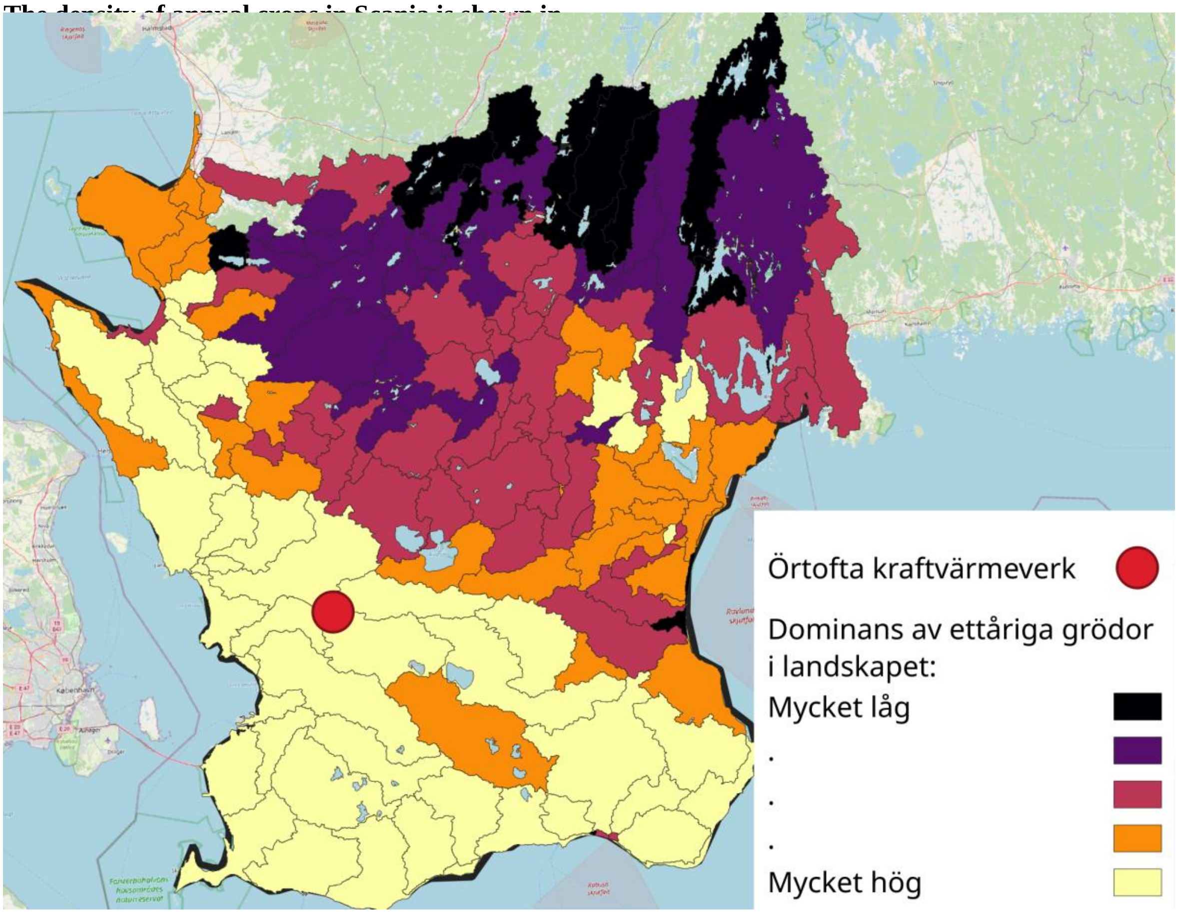

Figure 14. As can be seen, the share of arable land is high in the Örtofta region, varying between 40 to 59%, as well as the density of annual crops. This, in turn, leads to potentially high density of biomass feedstock production from SRC willow, as well as reduced transportation distances.

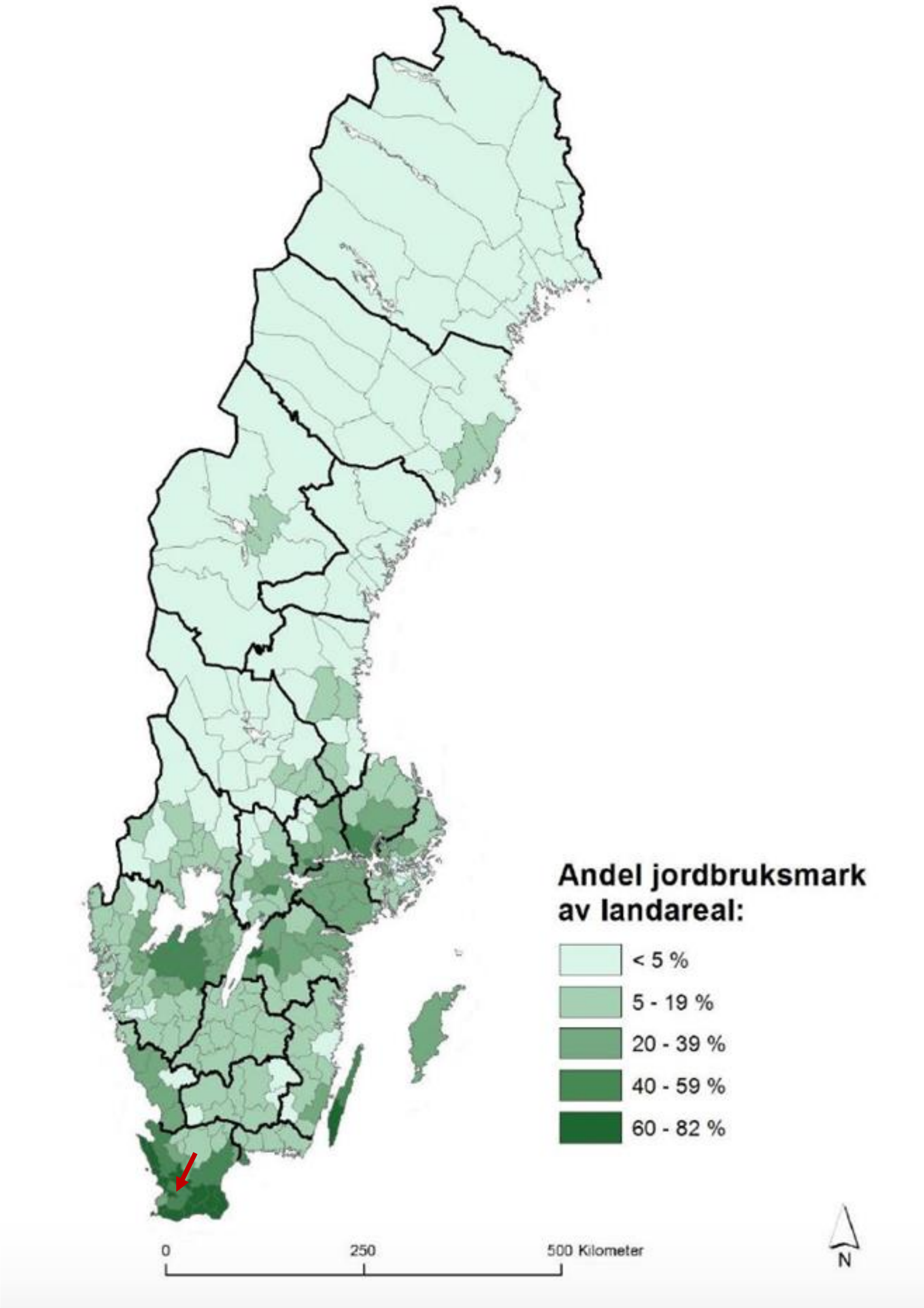

Figure 13. Share of land in different regions of Sweden that was arable land in 2019 (Swedish Board of Agriculture, 2019). Red arrow indicates the location of the Örtofta CHP plant in the county of Scania.

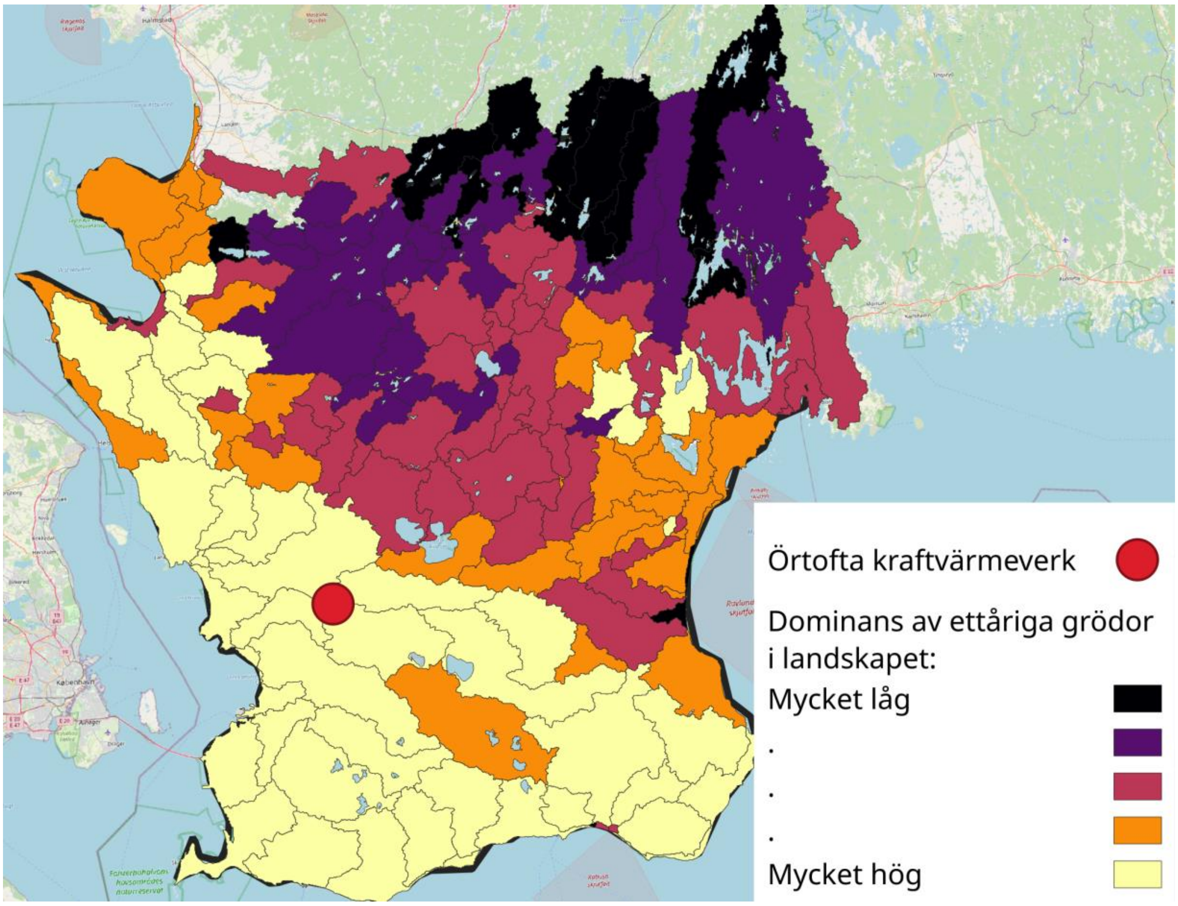

Figure 14. Density of annual crop production in Scania and the location of Örtofta CHP plant.

The amount of abandoned arable land in Scania is estimated to some 6 800 hectares (Olofsson and Börjesson, 2016). This is equivalent to 1.6% of the existing arable land (see Table 9). This potential land for biomass production can be compared with the poplar cultivation areas needed to fulfil the biomass feedstock demand for bio-oil production at the Örtofta CHP plant, or 15 400 and 24 600 hectares in scenario 1 and 2, respectively. Thus, 44% or 28% of the biomass feedstock demand in the two scenarios could potentially be supplied from poplar plantations on abandoned arable land.

3.5 POTENTIAL OF STRATEGIC ESTABLISHMENT OF PERENNIAL ENERGY CROP CULTIVATIONS IN SCANIA

An estimation by Styles et al (2016) is that the maximum area of willow buffer strips in Scania amounts to approximately 24 000 ha where nutrient-rich water from a runoff-generating area equivalent to some 140 000 ha can be treated. This estimation builds on the occurrence of open waterways in the agricultural landscape and the amount of land that lacks covered-drain systems. The corresponding theoretical maximum area of arable land in Scania where drainage water can be collected and used for irrigation, thus containing covered-drain systems, has also been estimated to roughly 140 000 ha, which would require a willow vegetation filter area of approximately 32 000 ha to treat. Taking into account various practical limitations (e.g., technical, economic etc.), the estimated realistic area of buffer strips and filter zones are, according to Styles et al (2016), 9 600 and 6 400 ha, respectively, or 16 000 ha in total (Table 10).

The total biomass potential from these cultivations in form of willow buffer strips and filter zones are estimated to amount to some 49 000 and 42 000 ton DM per year, respectively, or 91 000 ton DM per year in total. Thus, this amount of biomass may fulfill approximately 91% and 57% of the Örtofta biomass demand for bio-oil production in Scenario 1 and 2, respectively. However, this biomass potential is distributed over the county which will affect the transportation distances of the biomass.

The average transportation distance of wood fuels to the Örtofta CHP plant is today approximately 70 to 85 km (Björnsson et al, 2021a). Assuming equivalent transportation distances also for perennial energy crops (based on economic realistic conditions), the maximum radius of the biomass recovery area, having the Örtofta plant in the center, will then correspond to roughly 100 km. This, in turn, leads to the conclusion that the potential biomass recovery area covers more or less the complete county of Scania and that the whole biomass potential from willow buffer strips and vegetation zones in Scania could be available for the bio-oil production at Örtofta. In reality, the average transportation distance will be shorter for the perennial energy crop-based biomass since the density of arable land is much higher in the southern part of Scania, where Örtofta is located, than in the northern part (see Figure 13 and

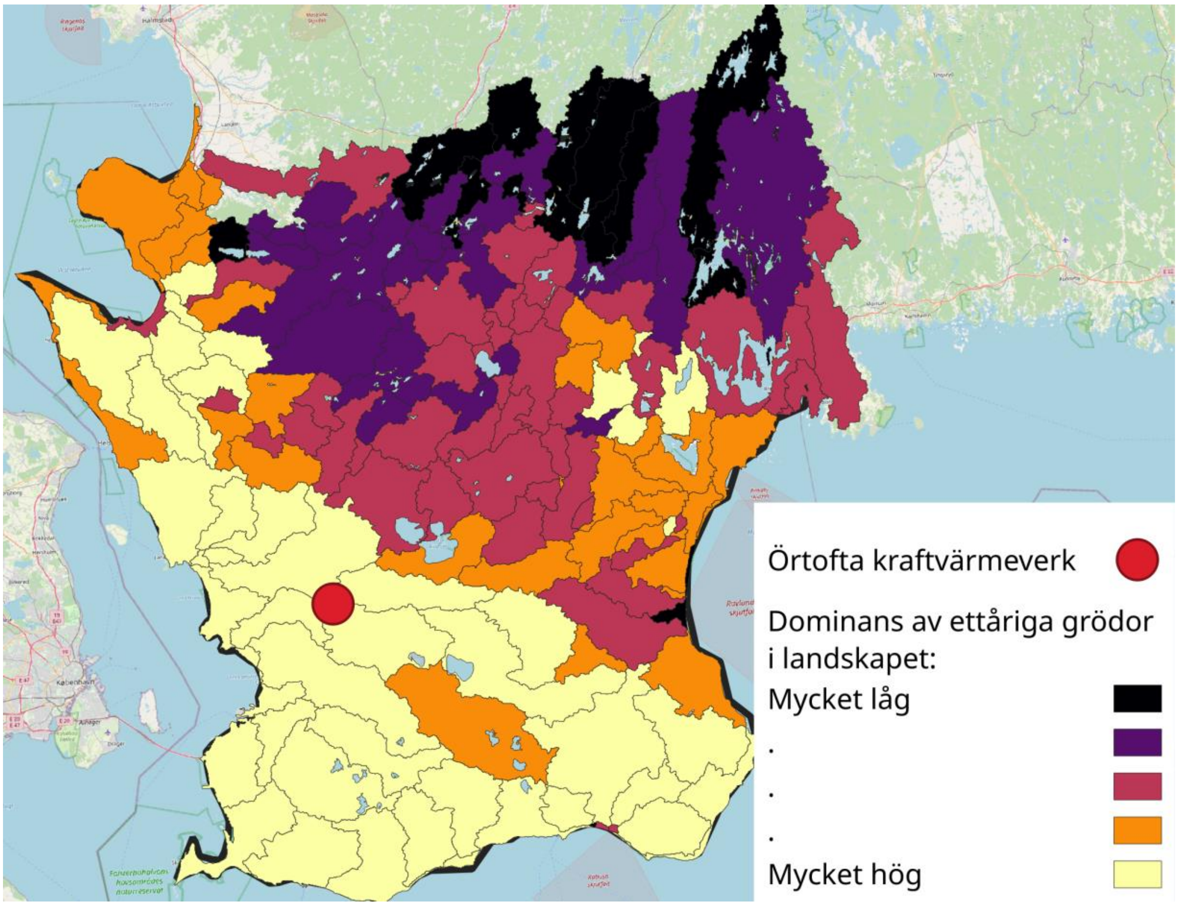

Figure 14). If the radius of the biomass recovery area is reduced to 50 km, then approximately 55% of the total land area of Scania is covered, but the share of arable land covered is much higher, roughly 75%. An estimation is therefor that the average transportation distance for the biomass from willow buffer strips and filter zones in Scania to the Örtofta plant will be shorter than today's biomass transportation distances for wood fuels, or approximately 50 km.

The potential of water purification willow plantations of 16 000 ha in Scania can be compared with the current area of fallow land which amount to 11 400 ha (see 9). It is here estimated that fallow land can be utilized for willow buffer strips and filter zones since this will be in line with the implementation of ecological focus areas (EFAs) in the EU Common Agriculture Policy (CAP) (EC, 2017). To comply with the EU CAP regulations, at least 5% of the arable land should be EFAs (on farms exceeding 15 ha arable land), which corresponds to approximately 20 600 ha in Scania (Swedish Board of Agriculture, 2019). It is here assumed that fallow land will be equivalent to EFAs and increase to 20 600 hectares within the coming years. The purpose with the EFAs is a greening of agriculture and deliver additional environmental services (e.g. increased biodiversity, reduced nutrient leaching etc.) and it is allowed to harvest the biomass for, for example, energy purposes. To conclude, a future expansion of willow buffer strips and filter zones in Scania, equivalent to a potential of 16 000 ha, could theoretically be located on ecological focus areas which are expected to amount to 20 600 ha.

To meet the complete demand for biomass in Scenario 1 and 2, additional 9 000 and 69 000 ton DM biomass is needed, respectively, besides biomass from willow buffer strips and filter zones. When this biomass is produced in fertilized willow plantations, a cultivation area equivalent to approximately 1 000 ha and 8 000 ha is then required. Compared with the total amount of arable land in Scania, these cultivation areas represent 0.2% and 1.8%, respectively. If these willow plantations are located on arable land currently utilized for annual crops, such as cereal production, an additional environmental benefit in form of increased soil carbon sequestration is achieved. In this case, approximately 0.5% and 3.8% of the current arable land for cereal production needs to be converted into willow cultivation. Table 10 summarizes the potential establishment of willow cultivations leading to maximized water purification services and soil carbon sequestration, together with biomass feedstock supply to the Örtofta plant for bio-oil production. A conclusion from Table 4 is that 78% of the EFAs will be needed in both scenarios, together with 0.5% and 3.8% of current cereal cultivation area.

Table 10. Strategic establishment of willow cultivations (in hectares) to deliver biomass to the Örtofta CHP plant for bio-oil production and maximizing additional environmental services in form of water purification and soil carbon sequestration. Buffer strips and filter zones are assumed to be located on Ecological Focus Areas (EFAs) and fertilized plantations on cereal cultivations, where the resulting percentage of land needed are shown within parentheses.

Scenarios	**Willow cultivations - hectares**		
	Buffer strips	Filter zones	Fertilized plantations
1. 100,000 ton DM yr-1	9 600 (47% of EFAs)	6 400 (31% of EFAs)	1 000 (0.5% of cereal cult.)
2. 160,000 ton DM yr-1	9 600 (47% of EFAs)	6 400 (31% of EFAs)	8 000 (3.8% of cereal cult.)

As described in previous sections, the potential amount of biomass produced from poplar cultivation on abandoned arable land in Scania amount to some 44 000 ton DM per year. Together with the potential biomass production from willow buffer strips and filter zones (in total 91 000 ton DM per year), this amount of biomass equivalent to 135 000 ton DM per year exceeds the biomass demand in Scenario 1 leading to no additional demand of willow biomass from fertilized plantations. Regarding Scenario 2, approximately 84% of the biomass demand is fulfilled but where an additional some 3 000 ha fertilized willow plantations are needed. Similar to the case of fertilized willow plantations on previous cereal cultivation land, poplar plantations on abandoned arable land is estimated to generate additional environmental benefits in form of increased soil carbon sequestration. Figure 15 shows poplar plantations located on previous arable land in Sweden.

Figure 15. Poplar plantations on previous arable land in southern Sweden (Photo: Lars Rytter).

3.6 WATER PURIFICATION EFFECTS AND SOIL CARBON SEQUESTRATION

The additional environmental services achieved in the strategical establishment of SRC willow cultivations are summarized in 11. According to Styles et al (2016), the reduction of nutrient loadings to waters is equivalent to, on average, 34 kg phosphate (PO4) equivalents per hectare and year in willow buffer strips established in Scania. Corresponding reduction in filter zones is estimated to be, on average, 47 kg PO4-equivalents per hectare and year. When replacing annual arable crops, fertilized willow is estimated to result in soil organic carbon (SOC) accumulation in the region of, on average, 500 kg C per hectare and year (Styles et al, 2016). The corresponding SOC accumulation in willow buffer strips and filter zones is taken to be, on average, 290 and 380 kg C per hectare and year, respectively, adjusted based on the relative differences in the above-ground biomass yields.

The total reduction of nutrient loadings to waters in Scenario 1 and 2, equivalent to 627 ton PO4-equivalents per year, correspond to approximately 5.3% of the total loadings from arable farming in Scania (Styles et al, 2016). Expressed per ton DM biomass produced in the respective Scenario 1 and 2, the reduced nutrient loadings are equivalent to 6.3, and 3.9 kg PO4-equivalents. The total soil carbon sequestration in Scenario 1 and 2, equivalent to 5.7 and 9.2 kton C per year, respectively, represents roughly 0.4% and 0.6% of the total annual GHG emissions from Scania (Swedish Environmental Protection Agency, 2020). Expressed per MJ of biomass, the soil carbon sequestration is equivalent to roughly 3 g CO2-equivalents in both scenarios. This can be compared with the

GHG emissions from fossil oil equivalent to some 84 g CO2-equivalents per MJ. Thus, soil carbon sequestration adds another 4% climate benefit when the willow biomass is replacing fossil oil as energy feedstock.

Table 11. Summary of additional environmental services, in form of water purification and soil carbon sequestration, in strategic establishment of SRC willow in Scania for the delivery of biomass feedstock to the Örtofta CHP plant for bio-oil production.

Scenarios	Willow cultivations			
	Buffer strips	Filter zones	Fertil. plant.	Total
1. 100,000 ton DM yr-1				
Reduced nutrient loading (ton PO4-equivalents yr-1)	326	301	-	627
Soil carbon sequestration (kton C yr-1)	2.8	2.4	0.5	5.7
2. 160,000 ton DM yr-1				
Reduced nutrient loading (ton PO4-equivalents yr-1)	326	301	-	627
Soil carbon sequestration (kton C yr-1)	2.8	2.4	4.0	9.2

The soil carbon sequestration in poplar plantations on abandoned Swedish arable land has in previous studies been estimated to some 200 kg C per hectare and year (Börjesson et al., 2012). Thus, producing 44 000 ton DM poplar biomass on 6 800 hectares abandoned arable land in Scania will then lead to an estimated soil carbon sequestration of some 1.4 kton C per year. Expressed per MJ of biomass, this soil carbon sequestration is equivalent to roughly 1.6 g CO2-equivalents. Compared with the GHG emissions from fossil oil (84 g CO2-equivalents per MJ), this soil carbon sequestration adds another 2% climate benefit when the poplar biomass is replacing fossil oil as energy feedstock.

3.7 SENSITIVITY ANALYSIS

The results presented above contains various uncertainties, both inherent due to natural variations in local cultivation conditions etc., and due to limited input data from field trials etc. Thus, the results must be interpreted with caution and should be seen as reasonable estimations. For example, the biomass yield in willow and poplar cultivations may differ by +/- 20% or more depending on actual local climate and soil conditions (Börjesson, 2016; 2007). Also, the magnitude of additional environmental services in form of reduced nutrient leaching and increased soil carbon sequestration may differ by +/- 20% or more due to varied local conditions (Styles et al, 2016). Therefore, a sensitivity analysis is presented in 12 showing how variations in biomass yields are affecting the possibility to supply a future Örtofta CHP plant also producing bio-oil using biomass from different willow plantations.

Table 12. Sensitivity analysis showing the share of biomass (in %) from willow buffer strips and filter zones when the biomass yield varies and resulting share of fertilized willow cultivations to fulfill the increased biomass demand from integrated bio-oil production at the Örtofta plant.

Scenarios	Willow cultivations		
	Buffer strips	Filter zones	Fertil. plant.
1. 100,000 ton DM yr-1			
Base case	49	42	9
20% lower harvest yields	39	34	27
20% higher harvest yields	59	50	0
2. 160,000 ton DM yr-1			
Base case	31	26	43
20% lower harvest yields	24	21	54
20% higher harvest yields	37	31	32

If the biomass yield in poplar plantations will be 20% lower, or 20% higher, than in the base case, the potential share of poplar biomass may change from 44% to 35% or 53% in Scenario 1. Regarding Scenario 2, the corresponding numbers will be from 28% to 22% or 33%.

When the effectiveness in the additional environmental services is reduced or increased by 20% in strategically planted willow, the resulting contribution to the overall nutrient leaching and GHG emission levels for Scania is shown in 13. The reduction in nutrient leaching and GHG emissions by increased soil carbon sequestration is shown as per cent of Scania's total load.

Table 13. Sensitivity analysis showing the reduction (in %) of Scania's total impact in form of nutrient leaching and GHG emissions by strategically planted willow cultivations when the effectiveness of additional environmental services are changed.

Scenarios	Strategically planted willow cultivations[a]	
	Reduced nutrient leaching	Reduced GHG emissions by soil carbon sequestration
1. 100,000 ton DM yr-1		
Base case	5.3	0.4
20% lower effectiveness	4.2	0.3
20% higher effectiveness	6.4	0.5
2. 160,000 ton DM yr-1		
Base case	5.3	0.6
20% lower effectiveness	4.2	0.5
20% higher effectiveness	6.4	0.7

3.8 ALTERNATIVE MODELING RESULTS

Work is in progress to adapt our European model to sub-national cases such as this. Preliminary results indicate that a maximum of 283 kha of riparian buffers and 86.5 kha of windbreaks could be established in Scania with the purpose to reduce N emissions to water and soil loss by wind erosion, respectively. This corresponds to 380 kt DM of biomass (Table 14), or 2.3-3.8 times the demands of Örtofta CHP plant. This indicates that the results above are on the conservative side. However, in a low estimate scenario, where existing environmental impacts need to be higher to incentivize implementation, riparian buffers are established in much fewer locations in Scania and the biomass production is marginal, 133 t DM (Table 10). Windbreaks, however, which are not included in the calculations above, can supply Örtofta CHP plant with 26-42% of the demand even in the low estimate scenario (Table 14).

We are confident that further adapting our model to application for sub-national cases can provide more refined and reliable results than what is possible by using the approach behind the calculations above. This will be a major focus in upcoming projects.

Table 14. Model results for multifunctional riparian buffers, windbreaks, and in-rotation grass cultivation in Scania.

		Riparian buffers	Windbreaks	In-rotation grass cultivation
High estimate	Area under annual crops in landscapes used for multifunctional production (kha)	283.0	86.5	485.3
	Area with multifunctional plantations (kha)	8.5	28.8	206.6
	Corresponding biomass production (kt)	86.7	293.2	1338.2
	Share of area under annual crops	3%	33%	43%
Low estimate	Area under annual crops in landscapes used for multifunctional production (kha)	22.3	86.5	485.3
	Area with multifunctional plantations (kha)	0.010	4.3	79.6
	Corresponding biomass production (kt)	0.1	42.3	465.6
	Share of area under annual crops	0.04%	5%	16%

3.9 CONCLUSIONS

Biomass from strategic establishment of willow cultivations in form of buffer strips and filter zones on arable land, and poplar plantations on abandoned arable land in Scania, has the potential to meet all, or the majority, of the increased biomass feedstock demand for integrated bio-oil production in the Örtofta CHP plant. As shown in Figure 16, willow biomass from buffer strips and filter zones, together with poplar biomass from plantations on abandoned arable land, may amount to some 135 000 ton DM per year. This can be compared with the estimated biomass demand in Scenario 1 and 2 equivalent to 100 000 and 160 000 ton DM per year, respectively. The remaining need of biomass feedstock can be supplied by fertilized willow plantations on a limited share of arable land previously utilized for e.g., cereal cultivation.

In addition to the supply of biomass feedstock, the total nutrient load from arable land in Scania may be reduced by 5 to 6% by the strategic establishment of willow cultivations. Furthermore, the increased soil carbon sequestration in the willow and poplar plantations may reduce Scania's annual GHG emissions by 0.4 to 0.6%.

The results presented in this case study should be interpreted with caution due to various uncertainties in the assessment. Despite these uncertainties, the results clearly indicate that the potential of environmentally sustainable lignocellulosic biomass from strategic establishment of willow and poplar plantations in Scania could play an important role in the future biomass feedstock supply for an integrated bio-oil production in the Örtofta CHP plant.

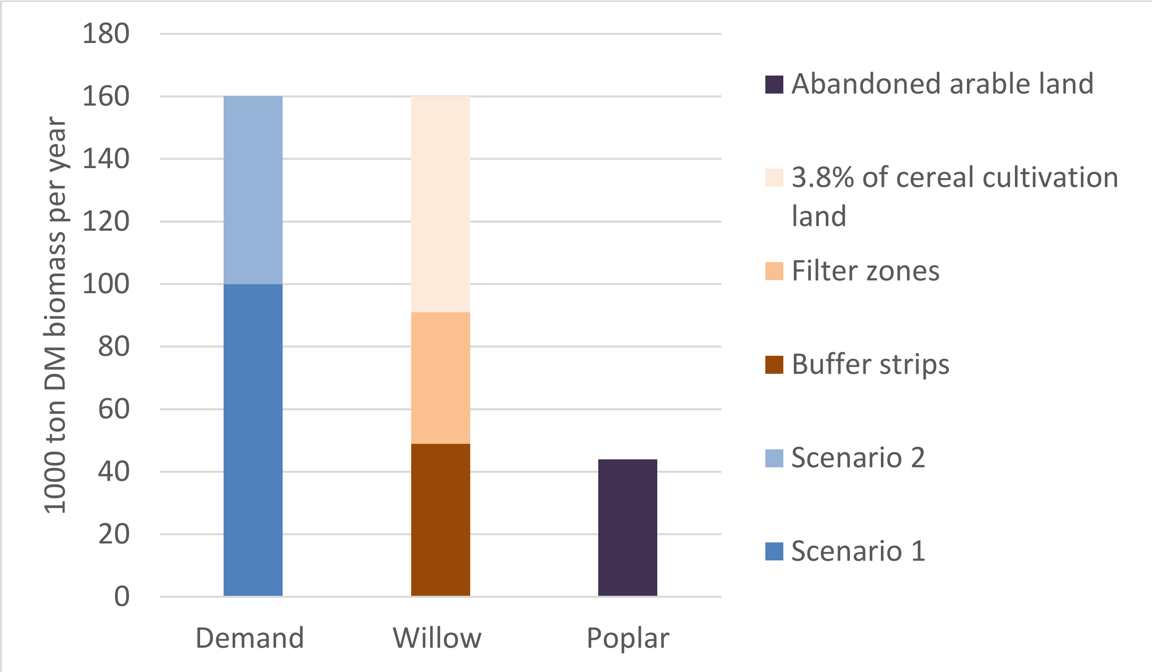

Figure 16. Potential supply of biomass from strategic establishment of willow and poplar cultivations in Scania to meet the increased biomass demand (Scenario 1 and 2) for integrated bio-oil production in the Örtofta CHP plant.

4 DISCUSSION: TOWARDS IMPLEMENTATION

As shown in this report, the introduction of multifunctional production systems with woody crops and grass-clover ley has the potential to reduce environmental impacts in agriculture landscapes. There is also potential for improved soil productivity and crop yield improvements thanks to increasing SOC-levels. Some farmers may consider these benefits sufficient motivation for implementing multifunctional biomass production systems. In general, however, the profits from the biomass production need to be at a level where farmers find it economically rational to include multifunctional biomass production systems on their lands. The required level of profit will probably include a risk premium as growing perennial biomass crops is often perceived as involving a higher risk than growing traditional annual food, such as wheat. The size of this premium depends on how farmers look at this risk, but also how they see the outlook for the new crops as well as conventional crops. Policies leading to long-term stimulation of end use markets for biomass from multifunctional systems can thus reduce farmers' risk premium requirements. Economic incentives for land use practices that cause lower environmental impacts may also increase the interest among farmers.

In relation to this, new policies at EU level may provide incentives for the establishment of multifunctional biomass production systems. In particular, the EU-CAP is expected to incentivize land use practices supporting Green Deal targets, especially those stemming from the Farm to Fork Strategy and the Biodiversity Strategy for 2030, and to fulfil climate and environmental objectives of the EU-CAP. As pointed out earlier, a large part of the buffer strips and filter zones may be located on EFAs included in the EU CAP, which should represent some 5% of the arable land and aim to protect the environment and support biodiversity.

Concerning end use markets for biomass from multifunctional systems, there are many indications that there will be an increased demand for biomass in the coming years, and also an increased interest in multifunctional land use practices. A national food strategy formulated a goal of a competitive food chain with an increase in food production while at the same time reaching relevant environmental goals and ensuring sustainable development in the whole country (Regeringskansliet, 2017). Further, several mitigation measures involving the agriculture sector were identified in a recent public enquiry on strategies for reaching the Swedish climate goal of net zero emissions by 2045, including the cultivation of cover crops, agroforestry, biochar production and incorporation in soils, bioenergy with carbon capture and storage (BECCS) and other measures for achieving negative CO2 emissions (SOU, 2020). Roadmaps for fossil free competitiveness developed by 22 different business sectors confirm the critical role of biomass as energy and industrial feedstock, enabling the phasing out of fossil resources (Fossil Free Sweden, 2020).

Specifically concerning grass-clover ley systems, the development of green biorefineries may result in relatively large increases in the use such feedstocks for the production of protein concentrate along with other products, including biofuels. Feeding trials show that protein products from green biorefineries can substitute soy feed products and thus help reducing EU's dependency on imported protein feed products associated with deforestation, biodiversity loss, extensive pesticide use, etc. (Santamaría-Fernández and Lübeck, 2020).

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