

Article

Bioenergy potential and greenhouse gas emissions from intensifying European temporary grasslands

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Abstract: Agricultural intensification is considered essential for meeting growing demand for food and biomass for energy and material purposes. Intensifying grasslands is a so-far under-represented although promising option, given their large land area and relatively low management levels. This study quantifies the bioenergy potential from intensifying temporary grasslands in Europe and the integral greenhouse gas emission effects in 2030. We first conduct a literature review of intensification options for European grasslands and then apply the environmental impact assessment model MITERRA-Europe to implement the key intensification option of using multi-species grass mixtures. The results show that 853 kha (or 8%) of temporary grassland could be made sustainably available for additional biomass production. This can be translated into a bioethanol potential of 23 PJ/yr and an emission mitigation potential of 5.8 Mt CO₂-eq/yr (if conventional grass mixture from surplus temporary grassland is used for energy) or 72 PJ/yr and 4.0 Mt CO₂-eq/yr (if surplus temporary grassland is used for grassy energy crops). Although the bioenergy potential is limited, the intensification measure's key advantage is that it results in a better environmental performance of temporary grasslands. This makes it a key option for sustainably producing bioenergy in areas with high shares of temporary grasslands.

Keywords: Biomass; Biorefinery; permanent grasslands; Intensification; integral emission assessment

1. Introduction

Climate change mitigation as set out in the Paris climate agreement warrants a rapid reduction in the use of fossil fuels. Bioenergy is expected to play an important role in this mitigation alongside increasing energy efficiency, renewable electricity such as wind and solar as well as carbon capture and storage [1]. However, increasing production and use of bioenergy is associated with the risk of large-scale direct and indirect land-use change [2,3], which in turn can lead to additional GHG emissions [4,5]. To avoid land use change, particularly conversion of natural land to managed land, and the resulting emissions, there are calls for sustainable intensification of agricultural land to increase productivity and thereby make room for additional biomass for energy purposes. But intensification of the existing agriculture may also lead to adverse environmental effects, such as increased emissions and nutrient leaching due to the increased use of agrochemicals and machinery [6], or biodiversity losses [7,8]. To provide an accurate and comprehensive picture of the (indirect) impacts of bioenergy, the impacts of intensification must be integrated in the assessment of biomass production for energy purposes. So far, this integral effect of intensification and increased bioenergy production has focused on agricultural crops [9–11]. The productivity developments in the livestock sector, and particularly grasslands, are not yet properly assessed and are not included in existing modeling frameworks [12,13] – despite the vast amount of grassland used for livestock production, 70 Mha [14]. While Ketzer et al. [15], Qi et al. [16] and Hansen et al. [17] have shown substantial land and bioenergy potential of grasslands in (parts of) Europe, they did not consider the integral

environmental impacts of intensification in the livestock sector as a means to allow additional biomass for energy (or other) purposes. Gerssen-Gondelach et al. [18] did account for livestock productivity intensification in their assessment of bioenergy potential through intensification and integral emission analysis, but they only included increased livestock stocking rates. Intensification of grassland productivity and its impacts were not included.

Given the knowledge gap defined above, this paper aims to i) assess the sustainable supply potential of herbaceous energy crops resulting from the intensification of European grasslands and ii) determine the integral greenhouse gas (GHG) emission effects of grassland intensification, herbaceous energy crop cultivation on surplus grasslands and its conversion to bioethanol in 2030. We focus on Europe where future intensification seems inevitable due to its already high pressure on land use and expected increasing demand for biomass for meeting its ambitious renewable energy and climate mitigation targets. For the analysis, we first conduct a literature review of the intensification options for European grasslands. Based on this review, which indicates the limited data availability for intensification options for permanent grasslands, we limit the remainder of our analysis to temporary grasslands. We then use the MITERRA-Europe model to implement the key intensification option in order to quantify how much temporary grassland can be made available for additional herbaceous crop production for energy purposes through intensification, analyze the resulting sustainable resource and bioenergy potential, and evaluate the integral GHG emission effects from sustainable grassland intensification measures and bioenergy production. The analysis focuses on EU28 and conducts the analysis at NUTS-2 level with a time frame till 2030.

2. Sustainable intensification measures for grasslands

Grasslands differ in terms of management, yield, environmental value and biodiversity value, and therefore also the intensification measures are specific to different types of grasslands. A broad distinction of grassland types is made between semi-natural¹ and production grasslands [19]. Production grasslands are then further differentiated between permanent² and temporary³ grasslands. The intensification level in terms of manure and fertilizer inputs, grazing and cutting frequency and grassland renewal can be another level of distinction [19]. Of the production grasslands in Europe, 60 Mha are permanent grasslands and 11 Mha are temporary grasslands. For permanent and temporary grasslands it is important to note that large differences in the size of these two types exist across countries. Thus, while the area dedicated to permanent grasslands is larger than the temporary grassland area in most countries, some countries have a very large area of temporary grasslands, for example Finland, Sweden and Denmark, where 95%, 72% and 62% of the utilized agricultural area (UAA) is temporary grassland [14] (see also Table A1 in the Supporting Material).

Sustainable intensification measures are here defined as those measures that raise biomass productivity while minimizing adverse environmental effects. Three main measures for sustainable grassland intensification exist: i) use of multi-species mixtures, ii) optimization of fertilizer application, and iii) grazing and cutting management. As mentioned above, suitability of these

¹ Semi-natural grassland refers to self-seeded herbaceous and shrub vegetation used for extensive grazing by livestock and/or mowing [19]. Semi-natural grasslands are not further addressed in our study because of their high biodiversity values and our focus on sustainable measures for intensifying grasslands to create space for energy crop production.

² Permanent grasslands are defined by the European commission as “land used permanently (for five years or more) to grow herbaceous forage crops, through cultivation (sown) or naturally (self-seeded) and that is not included in the crop rotation on the holding. The land can be used for grazing or mowed for silage or hay.” [82]

³ Temporary grassland is defined by the European Commission as “grass plants for grazing, hay or silage included as a part of a normal crop rotation, lasting at least one crop year and less than five years, sown with grass or grass mixtures. The areas are broken up by ploughing or other tilling or the plants are destroyed by other means such as by herbicides before they are sown again. Mixtures of predominantly grass plants and other forage crops (usually leguminous), grazed, harvested green or as dried hay are included here.” [82]

measures depends on whether temporary or permanent grasslands are addressed and are therefore discussed separately below.

For *permanent* grasslands only optimized fertilizer application and cutting and grazing management are considered suitable. Use of multi-species mixtures is not considered for permanent grasslands because they often contain multi-species mixtures already and because they are rarely sown. Still, due to uniqueness of species mixture in every grassland, it is difficult to estimate biomass productivity and nutrient value [20] and therefore improvements in species mixtures would have potential to improve productivity and nutrition value. However, permanent grasslands are only sown if productivity becomes too low and even then farmers often choose to improve the existing grassland rather than sow new grass. As a result, this measure is not further considered for permanent grasslands. Instead, in Section 2.2 below, we address sustainable intensification of permanent grassland by improving existing grasslands through grazing & cutting management.

Temporary grasslands are sown every few years, and the use of multi-species mixtures is a suitable measure to apply to temporary grasslands. In addition, grazing & cutting management and optimizing fertilizer application are also suitable for temporary grasslands.

Below we review the measures “use of multi-species mixtures” and “grazing and cutting management”; the third measure “optimization of fertilizer application” is not addressed because of the lack of data and modelling studies on this in the existing literature.

2.1 Use Of Multi-Species Mixtures

Experimental research found a positive relationship between plant species diversity and biomass yield in extensively managed grasslands [e.g. 21–23] and intensively managed grasslands [24,25]. This relationship results from i) improved resource utilization due to niche differentiation; ii) a greater probability of showing positive inter-specific interactions (i.e. facilitation); and iii) increased probability of containing highly productive species (i.e. sampling effect) [26–28].

Both the number of species or functional groups (richness) and their relative abundance (evenness) play a role in the increased productivity of multi-species mixtures [24]. Functional diversity (i.e. the number of groups sharing the same function in an ecosystem) is found to be particularly important. Especially the combination of grasses and legumes are highly productive through the rhizobial N-fixation ability of legumes [23].

Most experimental research on multi-species mixtures has focused on nutrient-poor extensively managed sown grasslands [21,22,29,30]. These studies all show a positive effect of diversity on aboveground biomass. Spehn et al. [30] found that the diversity effect varied across countries and is stronger in grass-legume-forbs mixtures than grass-legume mixtures (Table 1).

In the last decade, two large pan-European projects were established to study the effect of multi-species mixtures on biomass yield for nutrient-rich intensively managed grasslands. According to Kirwan et al. [24] (i.e. the COST Action 852 project), the aboveground biomass of grass-legume mixtures is consistently greater than that from grass or legume monocultures across a wide geographical scale (Table 1). Nyfeler et al. [31] show that mixtures fertilized with 50 kg N ha⁻¹ yr⁻¹ attained yields comparable to grass monocultures fertilized with 450 kg N ha⁻¹ yr⁻¹ at a Swiss experimental site. In the MultiSward project, Collins et al. [32] also found transgressive overyielding⁴ of grass-legume mixtures at the experimental sites in France, Wales and Switzerland in the range of 6-46% depending on location and management. Transgressive overyielding is lower when grazing instead of cutting is applied and with high nitrogen fertilizer input. No transgressive

⁴ To measure the performance of multi-species mixtures compared to monocultures, the concepts of overyielding and transgressive overyielding are used. As the best performing monoculture can be selected in temporary grasslands, the mixture should perform better than the best-performing monoculture. This is called transgressive overyielding, where the average yield of the mixture exceeds the yield of the best-performing monoculture. Overyielding is the situation when the average yield of the mixture exceeds the average yield of the monoculture [17].

overyielding is demonstrated at the plots that were both grazed and received high nitrogen input. Higher fertilizer inputs diminish the diversity effect as explained by Nyfeler et al. [24].

The yield improvement potential from the use of multi-species mixtures are calculated per climate zone for intensively managed grasslands [33] and extensively managed grasslands [34] (Table 1). Total yields include sown and unsown species as this is a measure of the total forage availability for feed and ensiling [13]. Yield ratios for overyielding and transgressive overyielding were calculated per experimental site across seed density and experimental years. Afterwards these ratios were averaged across the countries belonging to the same climate zone to derive overyielding and transgressive overyielding ratios for each climate zone.

Table 1. Yield ratios of average mixture/average monoculture (overyielding) and average mixture/best performing monoculture (transgressive overyielding) in intensively and extensively managed grasslands per climate zone¹.

Climate zone ¹	Intensively managed grasslands ²		Extensively managed grasslands ³			
	Grass-legume mixture		Grass-legume mixture		Grass-legume-forbs mixture	
	Overyielding	Transgressive overyielding	Overyielding	Transgressive overyielding	Overyielding	Transgressive overyielding
Alpine	1.48	1.12	n.a. ^d	n.a. ^d	n.a. ⁴	n.a. ⁴
Atlantic	1.45	1.30	1.11	0.78	1.51	1.04
Boreal	1.18	1.06	2.95	1.28	2.04	0.88
Continental	1.54	1.31	1.98	1.38	2.25	1.57
Mediterranean	1.36	1.00	1.02	0.5	1.17	0.58

¹ Climate zones as defined in MITERRA-Europe [35,36]

² Kirwan et al. [33]

³ Spehn et al. [34]

⁴ n.a. - not available; no experimental site in the Alpine climate zone was included in Spehn et al. [34]

The nitrogen yield gain in grass-legume mixtures compared to grass monocultures has been studied by Suter et al. [37] for intensively managed grasslands. Whereas nitrogen in grass monoculture is solely derived from the soil and fertilizer, nitrogen in grass-legume mixtures originates also from atmospheric nitrogen as legumes are able to fix atmospheric nitrogen through symbiotic N₂ fixation. The nitrogen yield gain results from a linear increase with legume proportion plus a non-linear surplus from positive grass-legume interactions (e.g. stimulation of symbiotic N₂ fixation, nitrogen transfer) [37]. The average nitrogen yield gain, as derived from the 16 experimental sites quantified by Suter et al. [37], was 36%.

The area suitable for introduction of grass-legume mixtures is the area of temporary grassland that are currently sown with only grass or a mixture of only one grass and one legume species. Data on species currently sown on grassland is, however, not available for most countries. Table 2 shows a summary of FAO country pasture/forage profiles for countries with large areas of temporary grassland. For example, in France, the country with the largest temporary grassland area (see Table A1 in the Supporting Material), 30% of temporary grasslands is sown with pure grass in the period 2001-2003 [38].

Table 2. Use of multi-species mixtures in countries with large shares of temporary grasslands.

Country ¹	Use of mixtures	Source
Belgium	Mainly one or two species, except in the Ardennes (NUTS-2 region Luxembourg) where multi-species mixtures, usually up to five species, are common	[39]
Estonia	Tendency towards the use of mixtures with few species, but traditionally multi-species mixtures with 5-6 species were used	[40]
France	30% of temporary grassland is sown with pure grass in 2001-2003, 70%	[38]

	with multi-species mixtures	
Ireland	Very few pastures that derive significant nitrogen from clover	[41]
Latvia	Sown grasslands for grazing are usually sown with a mixture of 4-6 species, while grasslands for cutting are sown with 2-species mixtures	[42]
Lithuania	Seed mixtures tend to contain several species	[43]
Slovakia	Seed mixtures are based on complex combinations and consists more species than typical for Western European mixtures. However, grasslands for grazing could be improved by using limited species than the current seed mix	[44]
United Kingdom	Temporary grassland usually consists of perennial ryegrass only	[45]

¹ Other countries with high shares of temporary grassland area that are missing here due to lack of data on the use of multi-species mixtures are Denmark, Finland, Sweden, Norway, Italy, Luxembourg, the Netherlands, Switzerland.

2.2 Optimized Grazing And Cutting Management

Practices to optimize grazing and cutting management include adjusting grazing and mowing frequency, grazing regime (e.g. continuous, rotational grazing), pre-grazing herbage mass and stocking density. Studies examining the relation between grazing and cutting management and productivity specific to Europe are limited and generate diverse conclusions. For example, increasing the mowing frequency in grass-legume swards may either result in small positive productivity effects [46] or negative results [47]. Productivity in pure swards is positively affected when changing mowing frequency from one to two cuts per year, but negatively affected when changing from two to four cuts per year [47]. In rotational grazing systems with perennial ryegrass, a decrease in grazing frequency (i.e. longer rotations) results in a decrease in grass growth [48–50]. This is caused by the growth pattern of perennial ryegrass - starting slowly after which the grass grows exponentially - prohibiting the ryegrass to reach maximum growth rate [49]. Changing the grazing regime did not significantly affect grass growth [50,51] or only grass growth in meadows with certain grass species [52].

In addition to these scattered results on the relation between grazing management and grass productivity, it seems that the use of legumes has a stronger effect on productivity than grazing management. Weigelt et al. [47] concluded that increasing species richness in grassland has a stronger effect on productivity than management intensity (i.e. fertilizer application and mowing frequency). A similar observation has been found by Henderson et al. [53]. They estimated the carbon sequestration potential of improved grazing management, the use of legumes and optimized nitrogen (N) fertilization. They found a small potential from improved grazing management in Western Europe (0.05 Mg CO₂ ha⁻¹), while the use of legumes has a larger carbon sequestration potential (3.5 Mg CO₂ ha⁻¹) [53]. The highest carbon sequestration potential from the use of legumes was found for the Atlantic and Continental climate zones, thereby confirming the literature findings that management practices enhancing carbon sequestration often also enhance grass productivity [53,54].

3. Materials and Methods

The methodological framework of this study builds on de Wit et al. [11] who assessed the GHG emission balance of food and feed crop productivity increases combined with an expansion of energy crop production on the arable land that becomes available as a result of the productivity increases with the use of MITERRA-Europe. In the present study, we apply a similar approach but focus on the effect of increased grassland productivity on land availability for additional grass or grassy energy crop production and their environmental impacts, also using the MITERRA-Europe model. The detailed setup of the analysis is described below.

3.1 Modeling framework: Miterra-Europe

The environmental impact assessment model MITERRA-Europe [55] is used to assess the effect of increased grassland productivity on the net *GHG mitigation* balance, changes in *N-leaching* and resulting nitrous oxide (N₂O) as well as changes in *soil organic carbon (SOC) stocks*. Also the impact of conversion of temporary grassland to perennial herbaceous energy crops was assessed for N₂O soil emissions and soil carbon emissions/sequestration.

3.1.1 General overview

MITERRA-Europe is an environmental assessment model which calculates emissions of nitrogen (N₂O, NH₃, NO_x and NO₃) and greenhouse gasses (CO₂, CH₄ and N₂O) on a deterministic and annual basis using emissions and leaching factors. The model was developed to assess effects and interactions of policies and measures in agriculture on nitrogen losses on a NUTS-2 level in the EU-27 [55,56]. MITERRA-Europe is partly based on CAPRI, the Common Agricultural Policy Regionalised Impact model, and GAINS, the Greenhouse gas-Air pollution Interactions and Synergies model, and supplemented with an nitrogen leaching module, a soil carbon module and a module for mitigation. CAPRI is an agricultural economic model, which can provide the activity data to MITERRA. GAINS is an emission model to assess control strategies to combat air pollution and climate change.

Input data consists of activity data such as livestock numbers, crop areas, animal production and crop yields derived from Eurostat and FAO, spatially explicit environmental data such as soil data from the European Soil Database and climate data, and for N₂O and CH₄ emission factors from IPCC and NH₃ emission factors and excretion factors from GAINS. MITERRA-Europe has its own approach for handling nitrogen leaching and nitrogen surface runoff and does not use the default IPCC leaching factor of 30% of nitrogen input. Instead, leaching fractions are determined based on soil texture, land use, precipitation surplus, soil organic carbon content, temperature and rooting depth. Surface runoff fractions are calculated based on slope, land use, precipitation surplus, soil texture and soil depth [55,57]. The model includes measures to mitigate GHG and NH₃ emissions as well as NO₃ leaching.

Three types of grassland are currently represented in MITERRA-Europe, namely temporary grasslands (which are part of the category “other fodder on arable land”), managed grasslands and natural grasslands, where managed grasslands and natural grasslands together make up permanent grasslands. Average grassland yields (in ton dry matter (DM) ha⁻¹) and nitrogen yield (in kg N ha⁻¹) per NUTS-2 region are calculated based on i. grasslands yields estimated by Smit et al. [58], and ii. areas of managed grassland and natural grasslands (rough grazing) derived from Eurostat [59] (Eurostat identifier “ef_lus_peggrass”). Based on the limited information on the current use of grass mixture (Table 2), we assumed that on 50% the grass-legume mixtures can be applied. For these areas the average overyielding factor for intensive grasslands from Table 1 was applied for all climate zones. As the grass-legume mixtures can fix nitrogen through biological N fixation, less mineral fertilizer is required. Based on the N gain of 36% as found by Suter et al. [37], the mineral N fertilizer input was reduced by 26% (1/1.36).

3.1.2 N₂O emissions

N₂O emissions from agricultural soils consist of direct soil emissions from application of nitrogen fertilizer and animal manure, crop residues and cultivation of organic soils, urine and faeces produced during grazing, and indirect emissions from nitrogen leaching and runoff as well as from atmospheric deposition of nitrogen volatilized from managed soils. The N₂O emissions were calculated from using the IPCC [60] emission factor of 1%. Indirect N₂O emissions from leaching and runoff (EF = 0.75%) and from atmospheric deposition of nitrogen volatilized from managed soils (EF = 1.0%) were also taken into account. Nitrogen fertilization for the 2030 scenario is based on the

concept of balanced fertilization in which nitrogen fertilizer application is equal to nitrogen demand of the crop times a crop specific uptake factor. This uptake factor is 1 in the case of grasses, meaning that grassland is able to take up all plant-available nitrogen [55].

3.1.3 Soil organic carbon stock changes

For soil carbon the RothC model [61] was implemented in MITERRA-Europe. RothC (version 26.3) is a model of the turnover of organic carbon in non-waterlogged soils that allows for the effects of soil type, temperature, moisture content and plant cover on the turnover process. It uses a monthly time step to calculate total organic carbon (ton C ha^{-1}) on a years to centuries timescale [61]. In RothC model, SOC is split into four active compartments (Decomposable Plant Material, Resistant Plant Material, Microbial Biomass and Humified Organic Matter) and a small amount of inert organic matter. Each compartment decomposes by a first-order process with its own characteristic rate. RothC was used to calculate the SOC balance for the scenario year 2030 based on the carbon inputs from manure and crop residues.

The soil carbon balance is determined for 2030. However, soil organic carbon continues to change even many years after an intervention. The period for reaching a new equilibrium is here set as 20 years, the IPCC default.

3.2 Applied sustainable intensification measures

Based on the literature review of sustainable intensification measures for grasslands (Section 2), we focus on the measure of using multi-species mixtures for temporary grasslands. For other measures, the existence of scientific literature and data was limiting the implementation of the measures. The yield effect from introducing multi-species mixtures is based on the data derived from large scale experiments at 33 sites [33], see Table 1. In the modeling, we assumed the average of overyielding and transgressive overyielding for intensively managed grasslands.

Data limitation and scattered experimental results on grazing management, together with a higher potential from the use of legumes in multi-species mixtures leads us to exclude optimized grazing management as a sustainable intensification measure in this study.

3.3 Land use scenarios

Once MITERRA-Europe implemented the sustainable intensification measures, it can spatially explicitly (NUTS-2) assess how much surplus grassland can be generated. This land can be used in different ways: e.g. left fallow, growing and harvesting regular grass mixture or planting grassy energy crops. To assess how the different land uses affect the energy potential and resulting GHG balance from European grasslands, we assessed three scenarios for 2030 (Table 3).

The scenarios build on the CAPRI reference scenario for 2030 as a basis for the representation of agricultural land use and livestock production in 2030. The *reference 2030* scenario assumes similar management practices in 2030 as today, and grassland areas are based on the CAPRI reference scenario. The *reference 2030* scenario is used for comparison with *scenario 1* and *2* to determine surplus grassland area generated from intensification and resulting changes in emissions. *Scenarios 1* and *2* assume increased grass productivity through the implementation of sustainable intensification measures (Section 3.2), fulfilling livestock demand in the CAPRI reference 2030 run. The difference between scenario 1 or 2 and the reference gives the surplus grassland area that in our study is used in two different ways: In *scenario 1*, the total area of surplus grassland is continued to be managed as before and the grass mixture is used for energy purposes. In *scenario 2*, the surplus grassland area is used for the production of herbaceous energy crops. The suitability of herbaceous energy crop cultivation depends on climatic and agro-ecological factors. This suitability, the cultivation requirements and resulting yields for the herbaceous energy crops miscanthus, switchgrass and reed canary grass are incorporated in MITERRA-Europe [11]. Thus for each region it is assessed which herbaceous energy crop is most suitable, which is in turn selected and used for further calculations.

Table 3. Overview of the land use scenarios for 2030.

Land use scenario	Description
<i>Reference</i> excl. intensification measures	<ul style="list-style-type: none"> Assumes changes in land use and grassland productivity based on CAPRI reference scenario for 2030.
<i>Scenario 1</i> Intensification & conventional grass (mixture)	<ul style="list-style-type: none"> Assumes augmented grassland productivity increases through implementation of all intensification measures. Surplus grassland are continued to be managed as before and grass mixture is used directly to produce biofuels.
<i>Scenario 2</i> Intensification & herbaceous energy crop	<ul style="list-style-type: none"> Assumes augmented grassland productivity increases through implementation of all intensification measures. Surplus grassland is used for herbaceous energy crop cultivation.

3.4 Grass options & conversion techniques

In order to determine the energy potential and GHG emission abatement, this study considers grass from surplus temporary grasslands to be used for advanced biofuel production. Here we consider the biochemical conversion route because the technology is currently more advanced than the thermochemical conversion route [62]. Biochemical conversion of lignocellulosic biomass (i.e. here grasses) is based on enzymatic hydrolysis of pretreated biomass and then fermentation of the simple sugars. During the distillation of the fermentation broth, ethanol is extracted. The solid waste from the distillation (e.g. lignin, unreacted cellulose and hemicellulose) are combusted for electricity and heat, which fuel the conversion process [62]. Research has focused on herbaceous energy crops (switchgrass, miscanthus, reed canary grass, *scenario 2*), but also conventional grass mixtures can be used for ethanol production [63], as tested in *scenario 1* (Table 3). Energy content and conversion efficiency for grasses to ethanol is provided in Table 4.

Additional options for using the grass for energy and/or material/chemical purposes are based on grass biorefinery processes (see e.g. [63–68]). In a grass biorefinery process, the grass is split in grass juice and grass fibres. From the grass juice, proteins are extracted and used for producing high-value protein-rich livestock feed, and the phosphate and nitrogen may be extracted and used for fertilizer [67]. The grass fibers are used either for livestock feed (e.g. Grassa [69]) or for biogas (e.g. Harvestagg [70]). Alternatively, the cellulose and hemicellulose from the fibres can be used for ethanol production (see e.g. Grass [71]). While some of these options are in an early commercialization stage, little or inconsistent data is available in the literature on the juice and fibre fractions, extraction rates, conversion efficiencies and substitution ratios. Therefore, this conversion route is not included in the analysis. However, a more detailed discussion of the options is given in Section 5.

Table 4. Input data for converting grass to ethanol.

Parameter	Unit	Value	Source
Energy content miscanthus	MJ/kg DM (HHV)	19.1	[72]
Energy content switchgrass	MJ/kg DM (HHV)	18.4	[72]
Energy content reed canary grass	MJ/kg DM (HHV)	18.1	[72]
Energy content grass mixture	MJ/kg DM (HHV)	18.0	²
Conversion efficiency of bioethanol (biochemical conversion)	MJ ethanol / MJ raw biomass (HHV)	0.34 ¹ (0.34 – 0.39)	[18]

¹ Based on a brief literature review of recent publications on advanced bioethanol conversion, Gerssen-Gondelach et al. [18] applied a grass-to-bioethanol conversion efficiency (HHV) of 35% for the short term. However, they also accounted for grass storage losses of 3%, which is considered in the value presented here. Other studies have applied higher conversion efficiencies. For example, de Wit et al. [11] applied 0.43 (0.38–0.48) MJ_{fuel}/MJ_{raw biomass} based on JRC (2008 in [11]) results for farmed wood ethanol and farmed wood Fischer-Tropsch diesel (range). Given the more recent review by Gerssen-Gondelach includes also data from the first commercial lignocellulosic biofuel plants, these values are considered more realistic estimates.

² The energy content of different grass species can vary strongly [73]. As a mixture of species is applied here, but shares and species are not defined, we make an assumption on the energy content of the grass mixture being slightly lower than the average of miscanthus, switchgrass and reed canary grass. We acknowledge that this may still be an optimistic estimate (see e.g. [74] who apply a value for a grass/clover grass = 13.5 MJ kg⁻¹ (LHV); no indication is given though whether this is dry or fresh biomass).

3.5 GHG emission abatement through biofuels from surplus grasslands

GHG emissions from intensification of temporary grasslands in Europe, specifically changes in N₂O and soil organic carbon (SOC) are determined with MITERRA-Europe as described in Section 3.1. In order to determine the overall GHG emission balance of bioethanol made from grass (whether conventional grass mixture or herbaceous energy crops) grown on surplus grasslands made available through intensification, also the emissions from the crop-to-biofuel supply chain need to be determined. The emissions from the crop-to-biofuel supply chain are determined based on Gerssen-Gondelach et al. [18] (Table 5) where we here exclude emissions from fertilizer application for feedstock production as these are already determined by MITERRA.

We calculate total emissions from grassland intensification, herbaceous energy crop production and supply chain emissions for a net balance of GHG emissions. We compare this to the emissions from fossil fuels (Table 5) in order to determine the total GHG emission abatement of intensifying temporary grasslands in Europe. In addition, we determine the average supply chain emissions from bioethanol by first summing up the total emissions caused by changes in N₂O and SOC (from MITERRA) and the supply chain emissions for bioethanol, and then dividing by the total bioethanol production potential. This emission factor is then compared to the fossil fuel comparator to assess the average, per unit bioethanol emission reduction potential.

Table 5. Input data for GHG emission balance.

Parameter	Unit	Value
Emission factor ethanol (without emissions from fertilizer use)	g CO ₂ -eq/MJ	-2.1
- Cultivation (without emissions from fertilizer use) ¹	g CO ₂ -eq/MJ	5.8
- Processing ²	g CO ₂ -eq/MJ	1.0
- Conversion ³	g CO ₂ -eq/MJ	-9.1
- Transport ²	g CO ₂ -eq/MJ	0.2
Fossil fuel comparator (average diesel and gasoline, including supply chain and combustion) ⁴	g CO ₂ -eq/MJ	83.8

¹ The emissions for cultivation excludes emissions from fertilizer application in the cultivation stage and from changes in soil organic carbon because these emissions are determined by MITERRA. Other emissions from cultivation (e.g. fertilizer production, grass rhizome production and diesel consumption) are based on [18].

² Processing and transport emissions are based on [18]

³ The emissions from converting grass to ethanol account for the benefits from co-produced electricity (part of it is used in the conversion process, part is surplus), which is why the emission factor without fertilizer use is negative. For a detailed description of how the emission factor is determined and what assumptions it is based on, see Table 4 in [18].

⁴ Fossil fuel comparator is taken from [75].

3. Results

Intensification of temporary grasslands can make a total of 853 kha surplus area available for energy production (Figure 1). The largest surplus area is found in France (386 kha), Poland (117 kha) and Italy (94 kha), which together make up 70% of the surplus grassland. Switchgrass and miscanthus are the most suitable grasses for these surplus areas, both making up 44% of the surplus area. The remaining 12% are most suitable for canary reed. In two of the countries with the largest

surplus areas France and Italy, large shares of miscanthus can be seen, while in Poland, switchgrass is more suitable.

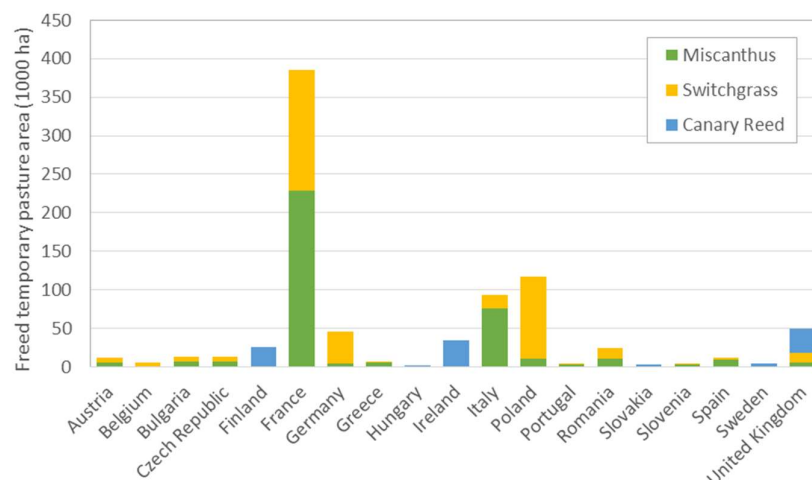


Figure 1. Surplus temporary grassland from sustainable intensification measures, by country and type of energy grass that is suitable on the surplus land in 2030.

Spatial distribution of the surplus areas and yields result in biomass potentials by NUTS-2 regions as shown in Figure 2. Besides large potentials in the above-mentioned three countries, there are also significant potentials in e.g. Scotland; Border, Midland and Western region of Ireland; and Northeast Romania.

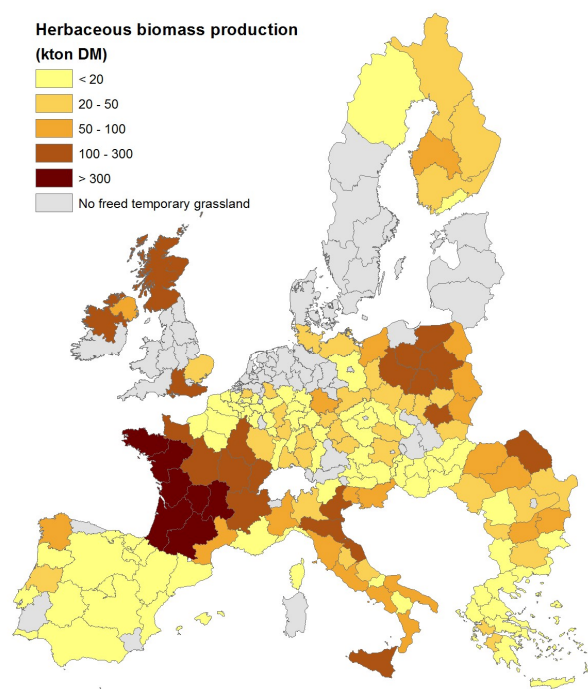


Figure 2. Spatial distribution of herbaceous biomass production on surplus temporary grasslands made available through sustainable intensification in 2030 (scenario 2).

The total surplus area of 853 kha temporary grasslands in the EU-28 is estimated to produce 3.7 Mton dry matter of biomass from conventional grass species (scenario 1) or 11 Mton dry matter of biomass if grassy energy crops are grown (scenario 2). The biomass energy potential is 67 PJ/yr for

scenario 1 and 213 PJ/yr for scenario 2 (Table 6). The results of this study are also compared to previous estimates of European biomass potentials (Figure 3). This shows that sustainable intensification of temporary grasslands can provide small additional sources of biomass. The share of the total potential shown in Figure 3 is 0.8% for conventional grass (scenario 1) or 2.5% for energy crops (scenario 2). Although these potentials are limited, it is important to emphasize that the applied measures enhance the environmental performance of temporary grasslands and the potentials are therefore considered sustainable potentials, as can be seen from the analysis of GHG emission impacts presented next.

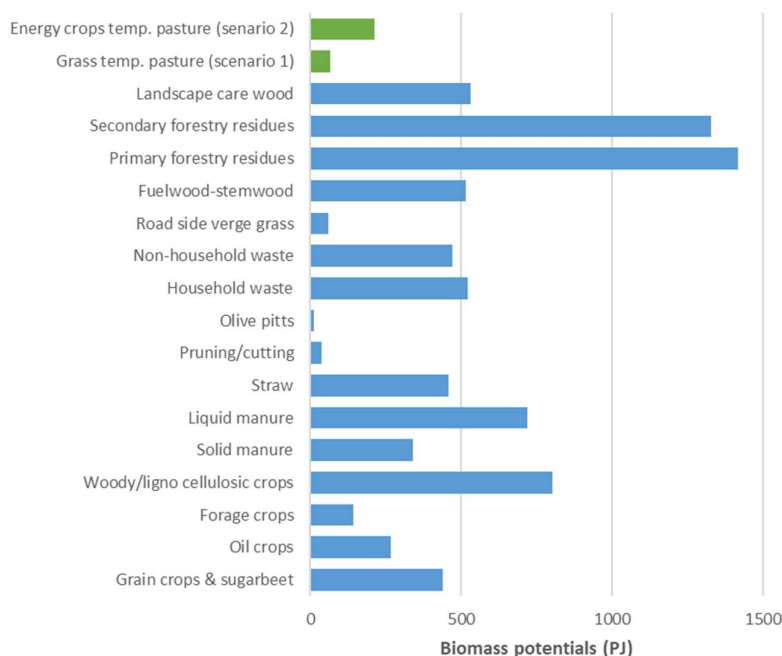


Figure 3. Biomass production potential from sustainable intensification of temporary grasslands (in green) compared to other biomass potentials (in blue) as determined in the BiomassPolicies project [83].

Table 6 presents an overview of the key results for the two scenarios in terms of i. potential biomass and bioethanol production, and ii. the GHG emission impacts from sustainably intensification grassland and producing bioethanol from additional grass production on surplus grassland. Using the conventional grass species indicates a much lower potential, which is not only due to lower grass yields but also due to a lower conversion efficiency.

The overall net GHG emission balance is in both scenarios negative, indicating that the implementation of the intensification measures results in an overall carbon sequestration. This is largely due to increased soil organic carbon and due to avoided emissions from substituting fossil fuels. In the scenario of using surplus grass directly for energy rather than growing grassy energy crops, also the nitrous oxide (N_2O) emissions are lower than in the reference scenario. This is due to requiring less fertilizer for multi-species mixtures where legumes help fix nitrogen. The trade-off is that less biomass and bioenergy is produced as a result of lower yields and lower conversion efficiencies.

Overall, using conventional grass from surplus grassland for bioethanol production (scenario 1) reduces more emissions than growing grassy energy crops like switchgrass, miscanthus and canary reed (scenario 2) when compared to the reference scenario. Scenario 1 mitigates 5.8 Mt CO_2 -eq/yr while scenario 2 mitigates 4 Mt CO_2 -eq/yr. For scenario 1, these emission savings largely come from reduced N_2O emissions and to a smaller extent from replacing fossil fuels. For scenario 2, emission mitigation comes from a large amount of avoided emissions from fossil fuels, which compensates for increased N_2O emissions. These findings are also represented in the average supply chain emissions

for bioethanol (Table 6): scenario 1 has a large negative emission factor of approximately -170 g/MJ while this is 28 g/MJ for scenario 2. This results in emission reductions compared to fossil fuels of 302% and 66%, respectively. When the focus is more on mitigating emissions, scenario 1 is preferred; while scenario 2 performs better in terms of the bioethanol potential. Still, bioenergy produced in scenario 2 still meets the 65% emission savings threshold mandated by the European Renewable Energy Directive II.

Table 6. Biomass and bioethanol production from grassland intensification and resulting changes in GHG emissions, by scenario.

Parameter	Unit	Scenario 1: Intensification and use surplus grass for energy	Scenario 2: Intensification and use of land for grassy energy crops
Area addressed by measures	Mha	0.85	0.85
Biomass production and conversion to ethanol			
Biomass production (mass)	Mt DM/yr	3.7	11
Biomass production	PJ/yr	67	213
Bioethanol production	PJ ethanol/yr	23	72
GHG emissions from intensification, bioethanol production and replacement of fossil fuels			
A: Change in N ₂ O emissions compared to reference ¹	Mt CO ₂ -eq/yr	-2.8	3.5
B: Change in SOC compared to reference ¹	Mt CO ₂ -eq /yr	-1	-1.3
C: Supply chain emissions bioethanol (without fertilizer & SOC)	Mt CO ₂ -eq/yr	0.0	-0.2
D: Avoided emissions from replacing fossil fuels	Mt CO ₂ -eq/yr	1.9	6.1
Net emission balance (=A+B+C-D) ¹	Mt CO ₂ -eq/yr	-5.8	-4.0
Average supply chain emissions from bioethanol (= (A + B + C)/ total bioethanol production) ²	g CO ₂ -eq/MJ	-168.9	28.3
Emission reduction compared to fossil fuel comparator	%	302	66

¹ Negative emissions refer to less emissions than in the reference scenario.

² Negative emissions refer to carbon sequestration from the production of the biomass.

4. Discussion

In order to interpret these results, three main points of discussion are important to consider. First, regarding intensification options, overall data availability on grassland yields and management practices is low, which is a key point of uncertainty related to this study and requires discussion. In order to estimate the potential yield increases from introducing multi-species mixtures, we applied the average of overyielding and transgressive overyielding in this study (see also Table 1). This assumption was made because farmers do not necessarily choose to sow the best-performing monoculture. Finn et al. [25] argue “this is because farmers may not be able to correctly predict in advance of sowing which of the available species will perform best over several years, but also because they may use selection criteria other than highest yield (such as economic return, forage quality and/or digestibility).”

Also time has an effect on the productivity of grass-legume mixtures, although differences exist for different management levels: Extensively managed grasslands show that the relationship between number of species and productivity becomes more positive over time [30,76]. However, for intensively managed grasslands “the diversity effect declined in year 3 (at least partially reflecting a

general decline in yield across sites over time [...] but was highly significantly related to evenness within each year" [25], as also found by Suter et al. [37] and Kirwan et al. [24].

In addition to assessing the effect of multi-species use in temporary grasslands, this study also made a rough estimate of productivity increases for permanent pastures. Suitable measures are increased and/or improved fertilizer application, and improved grazing and cutting management (for a description of these options, see Section 2). For both options, data availability was very low (especially fertilizer management) and results of a few existing studies on grazing and cutting management show such different trends that it was not possible to determine precise estimates of the effects on productivity. However, in order to compare the results from our assessment of temporary grasslands, we made a rough estimate for intensifying permanent grassland by increasing productivity by 5% over the study period (2015-2030). The additional grass could be used for ethanol production; conversion to herbaceous energy crops is not considered, as this would require ploughing of the soil for the planting and lead to large carbon losses in the soil. This measure result in roughly 162 PJ/yr grass biomass or 55 PJ/yr bioethanol. This is lower than bioethanol potential from intensifying temporary grasslands and using the surplus area for herbaceous energy crop production (72 PJ/yr bioethanol). But there is a large additional benefit of soil organic carbon sequestration though, which could amount to 4 MtCO₂-eq/yr. This is 3-4 times higher than what can be achieved in temporary grasslands. The most promising option for increasing productivity of permanent pastures to make this potential possible is fertilizer management. Grazing and cutting management might also contribute but, in order to be able to more precisely estimate its contribution, it must first be investigated in detail under which conditions productivity is actually increased.

Besides intensification measures, an important element in grassland availability for bioenergy production is the observation that there is a general decline in grazing lands in Europe. Reasons for this decline are i) the difficulties of managing large herds even with automatic milking systems, ii) less control over feed rations, iii) uncertainty if grass supply meets feed demand of grazing cows in countries where grass growth is delayed in summer, iv) better grassland utilization, v) environmental restrictions on reducing mineral losses and vi) labor intensity [77]. These reasons indicate that there is a risk of abandoning more of these pastures in the future. This might provide opportunities for introducing herbaceous energy crops.

Second, an important point of discussion also relates to the farmer's perception on the use of grass-legumes mixtures and, if surplus grassland becomes available, on farming grassy energy crops. Regarding the use of grass-legume mixtures, van den Pol-van Dasselaar et al. [78,79] have found that farmers often perceive grass-legume mixtures to have a greater temporal and spatial variation than grass only, legumes are more susceptible to diseases and have less resistance to winter stress than grasses, and grass-legume mixtures are less productive but more difficult to cultivate than grass only. Thus, a lot of different points are raised that are not necessarily in line with research findings, especially those on yields as described in Section 2. Promotion and implementation of multi-species mixtures must therefore include further knowledge transfer and working with farmers in order to overcome potential implementation barriers. Regarding the farmer's perspective on farming grassy energy crops, it must be assessed what their interest and willingness to do so is, what they perceive as implementation barriers and how these can be overcome.

Third, regarding alternative uses of grasses, as mentioned earlier, grasses are not only suitable for direct energy conversion, but can also be used as feedstocks for grass biorefineries. Various concepts exist, but they are all largely based on splitting the grass in grass juice and grass fibres and then further refining these to produce high value products [68,80]. Interest and efforts have been put increasingly into investigating higher value applications of the fibers. Klop et al. [67] have shown that the grass fibers can be fermented (silage) and then used as livestock feed without effects on feed uptake by dairy cows and milk production. This could be also economically more interesting than energy due to the higher value of feed than energy. A first order estimate by Sanders et al. [66] at least shows the economic feasibility of the process and economic benefits of higher value end-products. In addition, the biorefinery process has additional environmental impacts as a result

of reduced soy imports (the high protein feed from biorefinery can substitute soy meal) while also producing roughage, and phosphate recovery [66]. Particularly the displacement of soy meal is interesting from an environmental perspective given that soy production in Latin America is associated with (directly or indirectly) causing deforestation [81] and therefore high land use change emissions. A co-product is biogas or, if upgraded, biomethane [74]. More research is needed in order to better understand the net environmental impacts and the economic performance of grass biorefineries. This includes analysis of the system performance of different grass biorefinery options over the entire life cycle and its sensitivities to assumptions on grass yields, grass type, fractions of grass fibres and juice, conversion efficiencies to protein feed, biogas and other products, substitutability of soy meal and other feed by protein feed from grass biorefinery, and nutrient efficiency/recovery. Based on such assessments, a comparative analysis of costs and different environmental impacts of different grass biorefinery options and bioenergy production systems can then shed light into the advantages and disadvantages of different options.

5. Conclusions

Our study assessed the sustainable bioenergy potential from intensifying European temporary grasslands and the integral greenhouse gas (GHG) emission effects of both grassland intensification and resulting biomass production for energy in 2030. The key measures to intensify temporary grasslands are the use of multi-species mixtures, optimization of fertilizer application, and grazing and cutting management. Of these measures, this study focused on multi-species mixtures only. For the two other measures not enough data was available or inconclusive results were found so that a model analysis is not feasible.

When applying the intensification measure of multi-species mixtures, this study found that 853 kha (or 8%) of temporary grassland could be made sustainably available for additional herbaceous biomass production for energy and material purposes. This can be translated to a bioethanol potential of 23 PJ/yr (if conventional grass mixture from surplus temporary grassland is used for energy, scenario 1) or 72 PJ/yr (if surplus temporary grassland is used for grassy energy crops, scenario 2). The increased bioenergy potential in scenario 2 however comes with a trade-off in terms of GHG emissions. The overall net emission balance is negative in both scenarios, indicating that the implementation of the intensification measures results in an overall emission mitigation. However, more emissions can be mitigated when growing the conventional grass mixture in scenario 1, namely 5.8 Mt CO₂-eq/yr compared to the reference scenario. In case of growing grassy energy crops (scenario 2), 4.0 Mt CO₂-eq/yr are sequestered. This is largely due to increased soil organic carbon and due to avoided emissions from substituting fossil fuels. The main reason for scenario 1 using the conventional grass mixture for bioethanol to perform better is a strong reduction in nitrous oxide emissions.

This study shows that sustainable intensification of temporary grasslands can provide additional sources of biomass. However, the potential is limited compared to the total European bioenergy potential of other measures such as using agricultural and forestry residues or intensifying crop production. Still, using multi-species mixtures for intensifying temporary grasslands and growing grassy energy crops on surplus land could account for 2.5% of the total European bioenergy potential estimated in the literature while also enhancing the GHG emission performance of temporary grasslands. Moreover, our analysis shows that particularly in France, Poland and Italy as well as in the regions of Scotland, Northeast Romania, and the Border, Midland and Western region of Ireland large potentials can be found, indicating that regionally this measure could have high added value.

In addition, given that the intensification of temporary grasslands is based on introducing multi-species grasses, this measure does not have the risk of causing biodiversity losses; on the contrary, it is beneficial for biodiversity. Thus, the potential determined in this study is considered sustainable and therefore may be given preference over other measures to increase biomass production for energy. Important next steps are the assessment of costs, identification of other implementation barriers for farmers and strategies for promoting multi-species grass production.

We also discussed additional options for productivity improvements, which can provide further contributions to feedstock production for a biobased economy. However, these measures could not be assessed quantitatively due to the lack of data in the literature. Therefore, more bottom-up research is needed to assess how other intensification measures might affect grassland productivity and how this would influence the bioenergy potential from grasslands. Additional topics for research include the performance of alternative grass uses (e.g. green refinery) and the effects of intensifying permanent grasslands.

Supplementary Materials: Figure S1: Distribution of grasslands by type, Table S1: Utilized agricultural area and area of permanent and temporary grasslands in EU-28 Member States, Norway and Switzerland in 2013

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