ADVANCEFUEL

Regional specific impacts of biomass feed-stock sustain-ability

D4.3 report on biomass potentials and LUC – related environmental impact

Ivan Vera, Floor van der Hilst, Ric Hoefnagels

Utrecht University
Utrecht, The Netherlands

i.c.veraconcha@uu.nl;F.vanderHilst@uu.nl;r.hoefnagels@uu.nl
https://www.uu.nl/

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ADVANCEFUEL at a glance

ADVANCEFUEL (www.ADVANCEFUEL.eu) aims to facilitate the commercialisation of renewable transport fuels by providing market stakeholders with new knowledge, tools, standards and recommendations, to help remove barriers to their market uptake. The project will look into liquid advanced biofuels – defined as liquid fuels produced from lignocellulosic feedstocks from agriculture, forestry and waste – and liquid renewable alternative fuels produced from renewable hydrogen and CO2 streams.

In order to support commercial development of these fuels, the project will start by developing a framework to monitor the current status and future perspectives of renewable fuels in Europe in order to better understand how to overcome barriers to their market roll-out. Following this, it will investigate individual barriers and advance new solutions for overcoming them.

The project will examine the challenges of biomass availability for second-generation biofuels, looking at non-food crops and residues regarding how to improve supply chains from providers to converters. New and innovative conversion technologies will also be explored in order to see how they can be integrated into energy infrastructure.

Sustainability is key to ensure the development of renewable fuels and ADVANCEFUEL will look at socio-economic and environmental sustainability across the entire value chains. Ultimately, ADVANCEFUEL aims at providing sustainability criteria and policy-recommendations to ensure that renewable fuels are truly sustainable fuels. A decision support tool will be created for policy makers to enable a full value chain assessment of renewable fuels, as well as useful scenarios and sensitivity analyses on the future of these fuels.

Stakeholders will be addressed throughout the project to involve them in a dialogue concerning the future of renewable fuels and receive feedback on ADVANCEFUEL developments in order to ensure applicability to the end audience, validate results and ensure successful transfer and uptake of the project results. In this way, ADVANCEFUEL will contribute to the development of new transport fuel value chains that can contribute to the achievement of the EU's renewable energy targets and reduce carbon emissions in the transport sector to 2030 and beyond.

To stay up to date with ADVANCEFUEL's stakeholder activities, sign up at: www.ADVANCEFUEL.eu/en/stakeholders

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Executive Summary

Biomass production in the EU will have to comply with sustainability criteria from the recently adopted EU Renewable Energy Directive on the production and promotion of energy from renewable sources (RED II).The use of marginal lands to produce lignocellulosic energy crops has emerged as a valuable strategy to deliver biomass for energy purposes while minimising competition for land and negative environmental impacts. The potential of the bioenergy sector to reduce GHG emissions without causing negative environmental impacts relies primarily on the land availability and sustainable land use for dedicated biomass production.

A spatial explicit approach was used to assess the current and future potential and environmental impacts of lignocellulosic energy crops cultivated on marginal lands in Europe. Restrictions related to the sustainability criteria of the RED II were applied and the biomass potential and environmental impacts were assessed for 2020, 2030, 2040 and 2050. Four key environmental impact categories were included: LUC-related GHG emissions, erosion risk, water consumption and biodiversity. Eight of the most representative second-generation energy crop sin Europe were considered.

A three-step aggregate approach was applied to determine the potential available land, biomass potentials and LUC-related environmental impacts of lignocellulosic energy crops production at marginal lands. Land availability for lignocellulosic energy crop production was mapped based on land marginality and RED II sustainability criteria. Crop-specific biomass potentials were calculated considering the phenological requirements of each crop and location-specific biophysical conditions. LUC-related GHG emissions were assessed, following the methods in the IPCC guidelines. Impacts on soil erosion were quantified with the Revised Universal Soil Loss Equation. A water balance approach was used to determine the impacts on local water quantity. Biodiversity was considered in an indirect manner and addressed within the land availability assessment.

The total available marginal land that meets RED II sustainability criteria is projected to vary between 208 thousand km^2 in 2020 to 210 thousand km^2 in 2050. However, approximately only one third (± 75 thousand km^2) of the available land area is projected to be suitable for lignocellulosic energy crop production. Biomass potentials (Figure 1) are estimated to vary between 1385 PJ/year in 2020 and 1610 PJ/year in 2050; considering for each plot of available land the crop with the highest yield. A large variability in magnitude and direction (i.e. positive and negative) was found for all LUC related environmental impacts of lignocellulosic energy crop production. The average carbon sequestration varies between -7.1 t CO_2/ha year and -0.23 t CO_2/ha depending on crop type. However, there are also locations where LUC-related CO_2 emissions

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are projected to occur. The production of all types of lignocellulosic energy crops results in a water deficit ranging from 327 mm/year to 1071 mm/year. In general, there is an increase in potential soil loss when marginal land is converted to lignocellulosic energy crops. The average change in soil loss varies between 4.5 t/ha year and 7.5 t/ha year.

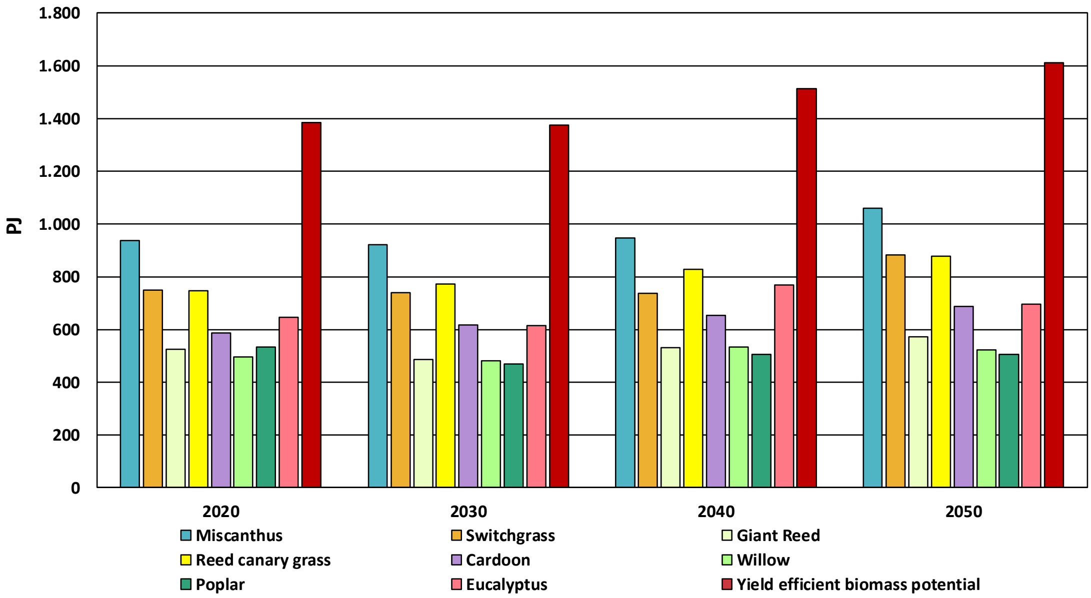

Figure 1 Biomass potentials for each lignocellulosic energy crop (i.e. all available land is allocated to one crop) and yield efficient biomass potential (for each location the crop with highest potential biomass yield is selected) in Europe for 2020, 2030, 2040 and 2050.

The biomass potentials and environmental impacts strongly depend on location specific bio-physical conditions, land use/cover prior to conversion, and feedstock type. The potential production of lignocellulosic energy crops on marginal lands can cover to some extent future bio-energy demand. However, the deployment of such potential should be done with care. Despite that it can contribute to EU GHG emissions reduction targets it can also generate considerable impacts in other areas. The implementation of lignocellulosic energy crop production on marginal land will require demanding location specific measures that promote an efficient use of water and include support practices targeted to reduce soil loss. This study shows that smart choices on location and crop type for lignocellulosic energy crop production can be made to enable sustainable biomass production in Europe under RED II sustainability criteria and overcome challenges of biomass availability.

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1. Introduction

In line with the Paris Agreement, the European Union (EU) has set ambitious targets to reduce anthropogenic greenhouse gas emissions (GHG) by substituting the use of fossil fuels with renewable energy sources. Meeting a 95% reduction in GHG emissions by 2050 (compared to pre-industrial levels) will require a substantial deployment of various renewable energy sources (UNFCCC 2015). Biomass is expected to play a vital role in the decarbonisation of the energy system, and meeting strict GHG emissions reduction targets (Rogelj et al. 2018). However, current biomass production volumes are limited and far from meeting current and future bioenergy requirements, (Junginger et al. 2019). Although a large increase in bioenergy production is projected to be required to meet GHG emission targets, there are many sustainability concerns regarding large-scale biomass deployment for bioenergy. The majority of these concerns are related with (in)direct Land Use Change (LUC) (Van Der Hilst et al. 2018), such as LUC related GHG emissions (IPCC 2006), and the impacts on water, biodiversity (Creutzig et al. 2015; Milner et al. 2016) and soils (Vogel et al. 2016).

The sustainability of the bioenergy sector has been the subject of extensive debate (Mbow et al. 2017). However, recently adopted regulatory measures include strict biomass -sustainability criteria. For example, the new EU Renewable Energy Directive on the production and promotion of energy from renewable sources (RED II) has set strict limitations regarding the blending share of biofuels at maximum 7% of final energy use in transport up to 2030. It also includes land-related sustainability criteria in regard to dedicated biomass production in the EU (European Parlament 2018). For example, it is strongly encouraged that biomass for energy production should not compete with food and feed production. In addition, unsustainable land-use practices should be avoided; e.g. biomass should not be produced on land with a high biodiversity value (European Parlament 2018).

The potential of the bioenergy sector to reduce GHG emissions without causing negative environmental impacts will rely primarily on the land availability and sustainable land use for dedicated biomass production (Haberl et al. 2010). Several studies have quantified land availability and biomass potentials under different sustainability criteria (Allen et al. 2014; Creutzig et al. 2015; Fischer et al. 2010; De Wit and Faaij 2010). However, most of these projections on land availability and biomass potentials include a limited number of sustainability issues (e.g. only estimate GHG emissions). Therefore, a more integrated approach that includes several/additional sustainability impact categories and constraints is required to estimate the sustainable biomass potential in Europe (Kluts et al. 2017). Allocating marginal lands for dedicated biomass production has been identified as a promising option for sustainable bioenergy production, especially if these are used for the production of perennial lignocellulosic energy crops

(Mehmood et al. 2017). Cultivating perennial lignocellulosic energy crops on low productive (marginal) land can derive potential advantages compared to the cultivation of first-generation energy crops on high productive agricultural land. In these conditions, there is a lower risk of competing with food production. In addition, perennial lignocellulosic energy crops have lower crop requirements and can therefore obtain higher yields than first generation energy crops in less favourable conditions. Furthermore, lignocellulosic energy crop production could contribute to carbon sequestration (biomass and soil organic carbon accumulation), land restoration, limiting soil erosion and to rural development, (Nsanganwimana et al. 2014; Richter et al. 2015; Valentine et al. 2012). Consequently, the use of marginal land for lignocellulosic energy crop production is considered a valuable strategy to produce biomass for energy purposes while minimising negative environmental impacts and potentially inducing positive ones.

With the recent ratification of the RED II, a set of land-related sustainability criteria for biomass (including lignocellulosic biomass) production for energy purposes was adopted (European Parlament 2018) . However, the potential of lignocellulosic energy crop production on European marginal lands that meet RED II sustainability criteria is not quantified. In addition, the environmental impacts of lignocellulosic energy crop production on marginal lands are unknown. Biomass potentials and LUC-related impacts depend on location specific biophysical conditions such as soil type, climate and previous land use. Therefore, potentials and environmental impacts of lignocellulosic energy crop production is spatially heterogeneous. Due to the spatial variability in biophysical conditions, the production of lignocellulosic energy crops could lead to negative environmental impacts in certain areas, despite meeting strict RED II sustainability criteria. Therefore, current and future biomass potentials and environmental impacts of lignocellulosic energy crops production should be assessed considering the heterogeneity of biophysical conditions (van der Hilst 2018).

The objective of this report is to assess the current and future potential and environmental impacts of lignocellulosic energy crops cultivated on marginal lands in Europe using a spatial explicit approach. Land-related sustainability criteria of the RED II will be applied and the potential and impacts are assessed for 2020, 2030, 2040 and 2050. Four key environmental impact categories are included: LUC-related GHG emissions, erosion risk, water depletion and biodiversity. The assessment provides insights in:

1) Land availability: the amount and location of available land that is considered marginal and fulfils land related sustainability criteria of the RED II and therefore can be allocated to biomass production.

2) Biomass potentials: the location-specific amount of lignocellulosic biomass that can be produced on the available land.

3) The potential environmental impacts of lignocellulosic energy crop cultivation at these locations.

This report consists of five chapters. Chapter two describes the methods used to assess the biomass potentials and environmental impacts and is divided in three sections. The land availability section discusses how RED II l sustainability criteria as well as the requirement of marginal land affect land availability for energy crops. The section on biomass potentials describes how the potential yields of lignocellulosic energy crops are determined. The environmental impacts section discusses the methods to estimate location specific potential LUC-related environmental impacts of lignocellulosic energy crop production. Chapter three presents the location-specific results for Europe. Chapter four discusses the robustness of the results and conclusions of this study are presented.

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2. Methods

A three-step aggregate approach was applied to determine the potential available land, biomass potentials and LUC-related environmental impacts of lignocellulosic energy crops production at marginal lands in the EU for 2020, 2030, 2040 and 2050. The assessment was conducted for several points in time to consider the time related LUC dynamics in the EU that result from economic, demographic and political drivers (Baranzelli et al. 2015b). The geographical scope of the assessment was limited to 26 EU countries[1], due to data availability. The 8 most representative second-generation feedstock types in Europe (Perpiña Castillo et al. 2015) were selected for the assessment: Miscanthus, Switchgrass, Reed canary grass, Giant reed, Cardoon, Willow, Poplar and Eucalyptus. The assessment was carried out at a spatial resolution of 1 km^2 considering the heterogeneity of biophysical conditions. The assessment was conducted within a GIS-environment and included three complementary steps that are essential to determine biomass potential and LUC-related environmental impacts. (1) Land availability for lignocellulosic energy crops production was mapped based on land marginality and RED II sustainability criteria. (2) Crop-specific biomass potentials were calculated considering the phenological requirements of each crop and location-specific biophysical conditions such as climate, soil and elevation. (3) LUC-related environmental impacts were calculated for GHG emissions, water depletion and soil erosion risk. LUC-related GHG emissions were assessed, following the methods in the IPCC guidelines (IPCC 2006), given the changes in above and below ground biomass and Soil Organic Carbon (SOC) when land use is changed to lignocellulosic energy crops. Impacts on soil erosion were quantified with the Revised Universal Soil Loss Equation (RUSLE) (Renard et al. 1997). A water balance approach (Brouwer and Heibloem 1986) was used to determine the impacts on local water quantity. Biodiversity was considered in an indirect manner and was addressed in the land availability section; high biodiverse areas such as protected areas, natural forest and natural grassland were excluded from available land for energy crops. The approach is depicted in Figure 2. The individual components of the approach are explained in the following sections.

[1] France, Lithuania, Czech Republic, Germany, Estonia, Latvia, Sweden, Finland, Luxembourg, Belgium, Spain, Denmark, Romania, Hungary, Slovakia, Poland, Ireland, United Kingdom, Greece, Austria, Italy, Netherlands, Slovenia, Croatia, Bulgaria and Portugal

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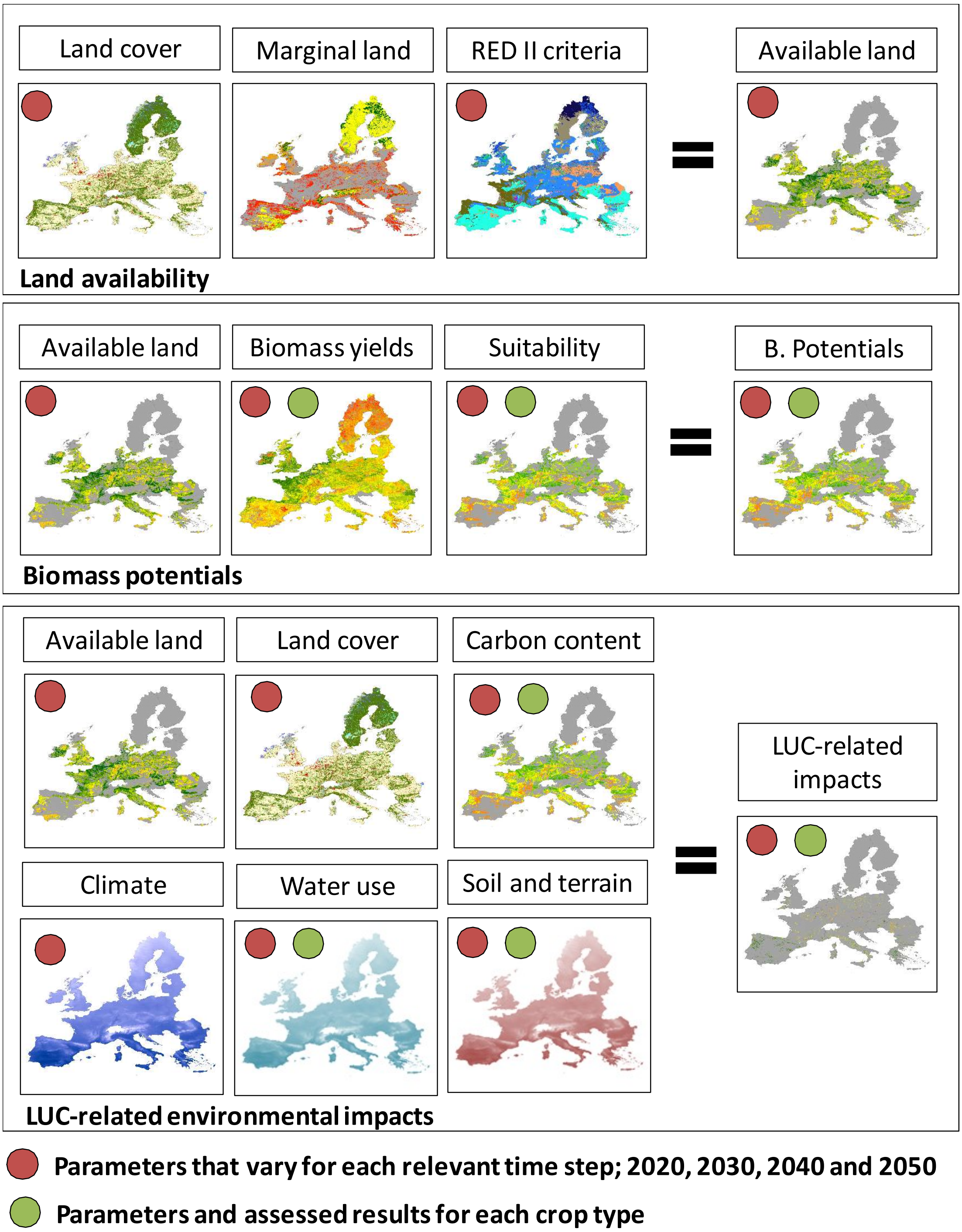

Figure 2. The three steps approach in this study to assess land availability, biomass potentials and environmental impacts of lignocellulosic energy crop production on marginal lands in Europe for the production of advanced fuels.

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2.1. Land availability

The land availability for lignocellulosic energy crops was determined for each decade up until 2050 at a spatial resolution of 1 km^2 following a two-step approach. (1) Land use/cover projections for 2020, 2030, 2040 and 2050 were processed to determine the areas that are categorized as marginal under the H2020 project MAGIC[2] definition; (2) from the marginal land selection, the land that does not meet the RED II sustainability criteria was filtered out and excluded. Therefore, only marginal land that meets RED II sustainability criteria was considered available for lignocellulosic energy crop production. In addition to the RED II sustainability criteria, it was considered that land use/cover with natural or artificial constrains such as water, urban areas and bare rock were not suitable for lignocellulosic energy crops production and are therefore also excluded from the assessment. The extent of marginal land, protected areas and High Nature Value (HNV) is assumed to remain constant over time. Consistent with *Article 29* in the RED II directive (European Parlament 2018), land with the following constraints are excluded:

Land dedicated to food, feed and fibre production [3]

- National protected areas, e.g. Natura 2000
- Land categorized as HNV farmland
- High carbon stock lands:
    - Forest
    - Peatland
    - Wetlands
- Land with a high biodiversity value:
    - Forest
    - Natural grassland

Figure 3 displays the location and extent of the criteria applied to determine land availability for lignocellulosic energy crops.

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[2] MAGIC defines marginal lands as: "*lands having limitations which in aggregate are severe for sustained application of a given use and/or are sensitive to land degradation, as a result of inappropriate human intervention, and/or have lost already part or all of their productive capacity*" (Elbersen et al., 2017)

[3] This minimizes the effect of Indirect Land Use Change (ILUC), i.e. the displacement of food, feed and fibre crops from the production of lignocellulosic energy crops

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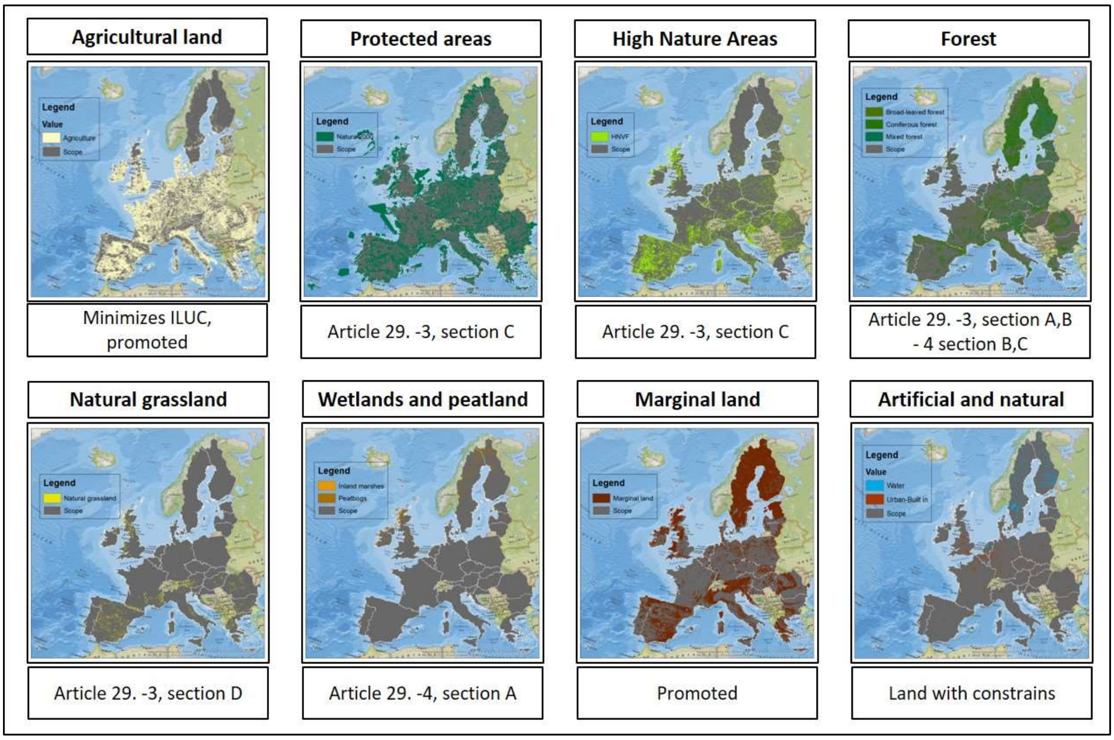

Figure 3. RED II land-related sustainability criteria and marginal land area. the extent of marginal land, protected areas and HNV is assumed to remain constant over time. The extent of the rest of the variables vary over time as a function of land use/cover change

Spatially explicit land-use projections are crucial to determine land availability and derived environmental impacts from lignocellulosic energy crop production. The amount of marginal land that meets the RED II sustainability criteria varies over time in line with LUC dynamics. Land use/cover projections were obtained from the Land-Use-based Integrated Sustainability Assessment modelling platform (LUISA) (Lavalle 2014) [4]. This dataset provides spatially explicit land use/cover projections on an European level considering economic, demographic and political drivers (Baranzelli et al. 2015b). However, the land use/cover classification[5] from the LUISA dataset can hamper an accurate estimation of land availability and environmental impacts, due to the aggregation of land use/cover categories. For example, LUISA land use/cover category '*Forest/Transitional woodland-shrubland'* integrates several lands use/covers. From this category, forest land is to be excluded in line with the RED II criteria. However, from the same land use/cover category, shrubland is assumed to be available for lignocellulosic energy crop production. In addition, GHG emissions (net carbon fluxes) due to changes in above and below ground biomass can vary considerably between forest or shrubland (IPCC 2006). Therefore, for this research several land use/cover categories from LUISA projections were disaggregated/aggregated into a new land use/cover classification to allow for a more accurate assessment of

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4 For a complete description of the LUISA land use/cover projections and land allocation please see (Baranzelli et al. 2015b; Baranzelli et al. 2015a)

5 See Table 1 of the Annex

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the land availability and environmental impacts from lignocellulosic energy crop production. The procedure for aggregation/disaggregation of land use/cover categories is covered in the next sub-section.

Land use/cover classification

The disaggregation/aggregation process of the land categories from the LUISA land use/cover projections[6] was performed using the most recent version (2018) of the Corine Land Cover (CLC) classification[7] (EEA 2018). The CLC data set was selected for this process as (1) several of LUISA land cover/use categories have a direct correspondence with the CLC classification; (2) CLC has more detailed land use/cover categories which allows for disaggregation of the LUISA classification. Based on this aggregation/disaggregation process of the LUISA classification, 11 land use/cover categories are distinguished in this report: (1) Artificial, (2) Agriculture, (3) Forest, (4) Natural grassland, (5) Established dedicated crops, (6) Wetlands, (7) Water bodies, (8) Shrublands, (9) Open space not suitable (10) Open space suitable and (11) Abandoned land. Table 1 from the Annex explains the diseggregation process of the LUISA land use/cover classification into the new land use/cover classification used in this report, making use of the CLC classification.

2.2. Biomass potentials

Biomass potentials were quantified for each lignocellulosic energy crop under a three-step approach:

(1) Water is commonly the key limiting factor for biomass production (Doorenbos and Kassam 1979). The water constrained theoretical biomass potential is the maximum amount of biomass that can be produced annually given the water use efficiency of biomass production in relation to water loss from evapotranspiration. This was calculated spatially explicitly based on the spatial variation in evapotranspiration rates of the lignocellulosic energy crops given climate conditions.

(2) However, there are other location specific biophysical conditions, such as soil characteristics and slope that affect crop growth. Therefore, crop specific suitability maps were employed to include the effect of other biophysical characteristics on potential biomass yield.

[6] For a complete description of the LUISA land use/cover categories please see (Baranzelli et al. 2015b; Baranzelli et al. 2015a)

[7] CLC 2018 identifies 44 different types of verified land use/cover categories in Europe, a complete description of each category please see (EEA 2018)

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(3) Furthermore, crop-specific harvest indices were applied to calculate the biomass that could be harvested from the total location specific biomass potential.

Due to the spatial variation in biophysical conditions and crop-specific requirements, not all available land areas are (equally) suitable for each crop. Therefore, the spatial variability in yield levels varies across the various lignocellulosic energy crops. In addition to crop-specific biomass potentials (i.e. the biomass potential given all available land would be used for a single crop), a yield efficient biomass potential was estimated. The yield-efficient biomass potential is quantified by evaluating and selecting for each location the lignocellulosic energy crop with the highest attainable yield. The crop-specific and yield-efficient biomass potentials are quantified for each point in time and expressed in PJ biomass.

2.2.1. Water-constrained biomass potential

The AquaCrop crop productivity water model developed by the FAO (Doorenbos and Kassam 1979) was used to estimate the biomass potentials for the 8 lignocellulosic energy crop types. The AquaCrop model consists of a simple equation to estimate potential biomass production and therefore it has been widely applied in various studies such as the H2020-project S2Biom on sustainable biomass deployment in Europe (Dees et al. 2017). Equation 1 is derived from AquaCrop and represents the relation between crop specific phenological characteristics and climate conditions on the one hand and the biomass potential on the other. Daily evapotranspiration was calculated spatially explicitly for various points in time (2020, 2030, 2040, 2050) using the Penman–Monteith equation (Monteith 1965). Climatic parameters were derived from the HadGEM2-ES global climatic model under the Representative Concentration Pathway 4.5 (RCP 4.5) scenario. The RCP 4.5 scenario was selected as it is the most widely applied climate scenario given that is characterized as moderate within RCP's (Panagos et al. 2017), and it includes mitigation policies (e.g. Paris agreement), in line with recent developments, to reduce GHG emissions and stabilize radiative forcing in 2100 (Thomson et al. 2011). Spatially explicit projections on temperature, precipitation, relative humidity, shortwave radiation and wind speed for the various points in time were collected from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP2b) database (Warszawski et al. 2014). Crop-specific parameters were used to estimate the length of the growing season and each crop growing stage, cumulative evapotranspiration for each crop growing stage and corresponding biomass production. These parameters (Table 1) are obtained from data from the S2Biom project (Dees et al. 2017), which was built upon an extensive literature review. Each crop specific growing season consists of 4 stages (initial, development, mid and late), with stage-specific crop evapotranspiration coefficients. The location specific reference evapotranspiration is multiplied by the crop specific stage coefficient (Kc) to obtain a crop-stage specific evapotranspiration. The location-and crop-specific cumulative evapotranspiration is multiplied by the crop-specific water use efficiency to obtain the above ground biomass potential ($AB_{potential}$), see Equation 1.

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Equation 1

$$AB_{potential,i} = \sum_j ET_j * Kc_{i,j} * WP_i$$

Where:

$AB_{potential} = Cumulative$ above ground biomass in, $t_{dry}/ha\ year$,

$i =$ Crop type,

$j =$ Crop growing stage,

$ET =$ Reference evapotranspiration, in $m^3/year$,

$Kc =$ Crop coefficient (dimensionless),

$WP =$ Water use efficiency in $t_{dry}/m^3 ha$,

Table 1 Crop specific phenological characteristics used as input for the calculation of the water constrained biomass potential, Data is derived from the S2Biom project (Dees et al. 2017)

Crop	**Length season** (days)	**Start day** (day)	**Cumulative growing season stage** (Fraction of length of season)				**Crop coefficient per growing stage** (Kc)				**Water use efficiency** (t_{dry}/m^3 ha)	**Harvest index** (%)
			Initial (i)	Development (i)	Mid (i)	Late (i)	Initial (i)	Development (i)	Mid (i)	Late (i)		
Miscanthus	210	80	0.21	0.34	0.84	1	0.48	1.05	1.41	0.95	33	0.7
Switchgrass	210	80	0.18	0.31	0.80	1	0.50	0.99	1.30	0.80	30	0.6
Giant reed	220	90	0.21	0.32	0.78	1	0.54	1.01	1.74	1.10	31	0.7
Reed canary grass	190	80	0.20	0.30	0.80	1	0.50	1.00	1.40	1.00	22	0.6
Cardoon	250	90	0.10	0.20	0.80	1	0.50	0.70	1.00	0.95	31.3	0.6
Willow	300	80	0.16	0.39	0.84	1	0.40	1.00	1.50	0.50	30	0.65
Poplar	300	80	0.16	0.39	0.84	1	0.40	1.00	1.50	0.40	29	0.6
Eucalyptus	300	90	0.16	0.39	0.84	1	0.40	1.00	1.50	0.40	27	0.65

2.2.2. Biomass potential based on agro-ecological suitability

The effect of location specific biophysical conditions on crop growth is determined using crop-specific agro-ecological suitability maps (FAO 1996). The crop-specific agro-ecological suitability maps are based on 10 biophysical parameters such as temperature, precipitation and soil type (Perpiña Castillo et al. 2015). The agro-ecological suitability is expressed as a percentage of the water constrained theoretical maximum obtainable yield, ranging from 0 (unsuitable conditions) to 100 (highly suitable conditions), see Equation 2. The suitability maps were generated for each crop and point in time following the methods from Perpiña Castillo et al. (2015)[8]. Soil pH, soil texture, soil depth, soil type, soil drainage and slope are considered to be constant in time while temperature, precipitation, Frost Free Days (FFD) and Temperature growing periods (LGPt) vary in accordance to the RCP 4.5 projections. It was assumed that $AB_{potential}$ was the

[8] For more information about the methods to calculate each crop specific suitability maps please see (Perpiña Castillo et al. 2015)

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maximum water-constrained biomass potential. The technical potential (AB_s) was obtained by multiplying the crop specific $AB_{potential}$ with the corresponding location and crop-specific suitability index.

Equation 2

$$AB_{s,i} = AB_{potential,i} * S_i$$

Where:

AB_s = Above ground biomass considering biophysical factors, $t_{dry}/ha\ year$,

i= Crop type,

$AB_{potential}$ = Above ground biomass, $t_{dry}/ha\ year$,

S = Suitability index for specific location, %,

2.2.3. Harvestable biomass yields

Crop-specific harvest indices are applied to calculate the location specific harvestable yields for each lignocellulosic energy crop (Equation 3).

Equation 3

$$Y_i = AB_{s,i} * HI_i$$

Where:

Y = Yield, $t_{dry}/ha\ year$,

i= Crop type,

AB_s = Above ground biomass considering biophysical factors, $t_{dry}/ha\ year$,

HI = Harvest index, %,

Biomass potentials are calculated with RCP 4,5 projections for the various points in time. Besides a 1% annual yield increase of the theoretical water constrained biomass potential was considered for all energy crops. The yield increase was considered to reflect yield improvements from crop management practices in line with Baranzelli et al. (2015a,b);

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2.3. LUC-related environmental impacts

2.3.1. LUC-related GHG emissions

LUC-related GHG emissions are the result of carbon stock changes in biomass, dead organic matter, litter, harvested wood products and soils (IPCC 2006). Carbon stocks are potentially altered when land use is changed. The IPCC Guidelines for National Greenhouse Gas Inventories Volume 4 (IPCC 2006) were applied to assess the potential GHG emissions from the production of lignocellulosic energy crops on the available marginal land. Dead organic matter, litter and harvested wood products are primarily relevant when land is converted to/from forest (IPCC 2006). Therefore, in this assessment only the biomass and Soil Organic Carbon (SOC) pools are considered. The change in carbon stocks when land is converted to lignocellulosic energy crops was assessed with the stock difference method using the Tier 2 approach for the biomass carbon pool (given the level of detail in country specific data) and the Tier 1 approach for the SOC pool. Equation 4 presents the stock difference method. C_1 corresponds to the carbon stock of the available marginal land in each reference year (2020, 2030, 2040 and 2050) and C2 corresponds to the potential carbon stock if lignocellulosic energy crops would be produced on that land. In line with the IPCC guidelines, an amortization period of 20 years is assumed for carbon pools to reach equilibrium (i.e. it will take 20 years to increase/decrease from SOC at time 0 to SOC at time 1). Therefore, effects on the carbon pools from the change in land use towards lignocellulosic energy crops are calculated over a 20-year time horizon and are presented on an annual basis. The CO_2 emissions are calculated based on ΔC, and the ratio of molecular weights (C * 44/12). The LUC-related GHG emissions are expressed t CO_2/ha year. The change in carbon stock and subsequent GHG emissions are calculated for each energy crop. In addition, a maximum carbon sequestration potential was estimated. The maximum carbon sequestration potential was estimated by evaluating and selecting for each location the crop with the lowest LUC-related CO_2 emissions / highest carbon sequestration.

Equation 4

$$GHG_{LUC,i} = \frac{C_{2i} - C_1}{T} \cdot 44/12$$

Where:

$GHG_{LUC,i}$ = LUC related GHG emissions for energy crop i, $t\ CO_2/ha\ year$,

C_1 = Carbon stock on marginal land, $t\ C/ha$,

C_{2i} = potential carbon stock if marginal land is used for production of energy crop i, $t\ C/ha$,

T = amortization period, years,

$44/12$ = conversion factor to convert C to CO2,

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Biomass carbon stocks

To determine the GHG emissions from changes in biomass carbon spatially explicitly, the spatially explicit biomass carbon stock was calculated for each lignocellulosic energy crop and for land the cover/use of the available marginal land. The method to assess the above ground biomass potentials of lignocellulosic energy crops was already described in the section on the biomass potentials. The total amount of biomass for each lignocellulosic energy crop was calculated using the crop-specific root-to-shoot ratios obtained from a literature review (Table 2). In addition, the harvest period (numbers of years before harvest) was considered for all lignocellulosic energy crops. Willow Poplar and Eucalyptus are not harvested annually. For these crops it is assumed that the average biomass carbon accumulates for 3 to 7 years (Dees et al. 2017). For the land cover of available marginal land prior to conversion, the spatially explicit above and below ground biomass was calculated with a similar method as for the energy crops. The above ground biomass of available marginal land was quantified making use of the land-use and climate-zone specific default values of the IPCC on maximum amount of above ground biomass and the spatially explicit data on soil productivity (the degree to which the soil carries out its biomass production service)[9] (Tóth et al. 2013). The productivity index of the soil productivity maps ranges from 0 (unproductive conditions) to 10 (excellent productivity conditions). Below ground biomass was estimated as a function of above ground biomass using the climate-dependent root to shoot ratios of the IPCC (IPCC (2006). The carbon fractions (0.47 for grassy biomass and 0.50 for woody biomass) were employed to obtain crop specific biomass carbon stock. For a more detailed description of the spatially explicit calculation of biomass volumes of each land use/cover category please see Table 2 from the annex.

Table 2 Crops specific root-to-shoot ratios

Crop	**Root-to-shoot ratio** (BG_r)
Miscanthus	0.49[A]
Switchgrass	0.48[B]
Giant reed	0.56[C]
Reed canary grass	0.48[D]
Cardoon	0.80[E]
Willow	0.48[F]
Poplar	0.30[G]
Eucalyptus	For $AB_s < 50$, then BG_r 0.44. For $AB_s > 50$, then BG_r 0.28[H]

[A] (Dohleman et al. 2012; Kahle et al. 2001; MIGUEZ et al. 2009; Strullu et al. 2011)
[B](Bolinder et al. 2002; Bowden et al. 2010; Dohleman et al. 2012; Frank et al. 2004)
[C](Nassi o Di Nasso et al. 2013; NASSO et al. 2009; Proietti et al. 2017)
[D](Kätterer and Andrén 1999)
[E](Marin et al. 2002; Raccuia and Melilli 2004)

[9] For a complete description of the soil productivity map please see (Tóth et al. 2013)

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[F](Dias et al. 2017; Dušek and Květ 2006; Heller et al. 2003; Pacaldo et al. 2013) [G](Heilman et al. 1994; Oliveira et al. 2018) [H](IPCC 2006)

Equation 5

$$TB_i = \left(AB_{s,i} * BG_{r,i}\right) + AB_{s,i}$$

Where:

$TB =$ Total biomass production considering biophysical factors, $t_{dry}/ha\ year$,

$i=$ Crop type,

$AB_s =$ Above ground biomass considering biophysical factors, $t_{dry}/ha\ year$,

$BG_r =$ Above to below ground biomass ratio,

Soil organic carbon stocks

The changes in soil organic carbon were assessed by comparing the SOC levels of the land cover/use category of the available marginal land with the potential SOC levels of the lignocellulosic energy crops. The IPCC default values for reference SOC levels for mineral soils were assigned to each land cover/use category while considering soil type and climate zones stratification. IPCC SOC stock change factors were employed to consider the effect of land use, management regime and input of organic amendments (Equation 6). These factors are applied for each land use/cover category based on the description in the IPCC guidelines. The description of the assigned stock change factors for each category are presented in Table 3 from the annex.

Equation 6

$$SOC_{x\ or\ i} = SOC_{ref} * F_{LU} * F_{MG} * F_I$$

Where:

$SOC_{x\ or\ i}=$ Soil organic carbon stock for marginal land under land use/cover type x or soil organic carbon stock if marginal land is used for production of energy crop i, $t\ C/ha$,

$SOC_{ref}=$ The reference carbon stock, $t\ C/ha$,

$F_{LU} =$ Stock change factor for land use system,

$F_{MG} =$ Stock change factor for management regime,

$F_I =$ Stock change factor for input of organic matter,

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2.3.2. Water depletion

Water availability is strongly linked with LUC dynamics. These dynamics, mainly through changes in evapotranspiration rates, can affect directly the water balance of a region (Sterling et al. 2012). In addition, water supply for irrigation can induce additional disturbances in the water cycle and result in water scarcity (Abrahão et al. 2015). The water balance approach from Brouwer and Heibloem (1986) was used to determine the water requirements of each feedstock type and the potential local water deficits given the spatial heterogeneity in climatic conditions. Despite that this method lacks a direct indicator to determine the potential water depletion in the crop production area, it provides an adequate estimate of the amount of additional water (irrigation) each feedstock type requires to obtain the estimated potential biomass yields. Equation 7 represents the water balance approach in which crop Water Shortage (WS) is determined for each crop by comparing crop evapotranspiration rates during the length of its growing cycle with the effective precipitation during the same period. Effective precipitation is the share of precipitation that is stored in the soil and is available for the crop and is derived from actual precipitation (Equation 8) (Brouwer and Heibloem 1986). The method to determine daily evapotranspiration from lignocellulosic energy crops was already covered in the section on biomass potentials. In addition to each crop water shortage, a least-water-deficit potential was estimated. The least water deficit potential is quantified by evaluating and selecting for each location the lignocellulosic energy crop with the least water deficit (regardless of other parameters such as yield). Water shortage is expressed in mm/year (growing cycle).

Equation 7

$$WS_i = \sum_{GC} ET_0 * Kc_{i,j} - \sum_{GC} EP$$

Where:

WS = Water shortage, $mm/year$,
GC= Grow cycle,

i= Crop type,

j= Crop growing stage,

ET_0 = Evapotranspiration, mm/day,

Kc = Crop coefficient,

EP = Effective precipitation, mm/day,

Equation 8

$$EP = P * \left(\frac{125 - 0.2 * P}{125}\right) \; for \; P_{month} < 250 \, mm$$

Or

$$EP = 125 + 0.1 * P \; for \; P_{month} > 250 \, mm$$

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Where:
EP = Effective precipitation, mm/day,
P= Precipitation, mm/day,

2.3.3. Soil erosion risk

LUC dynamics can alter the physical and chemical properties of the soil and can potentially result in soil degradation (Smith et al. 2016). Soil erosion, which is considered the main driver of soil degradation, reduces SOC and limits the soil's capacity to sustain plant growth (Paul 2014). The Revised Universal Soil Loss Equation (RUSLE) (Renard et al. 1997) was applied to determine the change in potential soil loss when land is converted to lignocellulosic energy crops. The RUSLE method (Equation 9) considers 5 major factors: rainfall erosivity, soil erodibility, topography, cover management practices, and soil prevention management practices. The rainfall erosivity factor (R) is defined as the aggressiveness of the rain to generate erosion (Wischmeier and Smith 1978). The soil erodibility factor (K) is related to the susceptibility of the soil to erode and it is defined by soil physical properties (Panagos et al. 2014). The combined topography factors (LS) are determined by the effect of slope length (L) and influence of slope gradient on erosion (S) (Panagos et al. 2015a). The cover management factor (C) quantifies the effect of land cover on soil loss (Kinnell 2010) and the conservation support practice factor (P) reflects the effect of management practices to prevent soil erosion (mainly applicable to arable land). For each point in time for all available marginal land, the potential soil loss of cultivating lignocellulosic energy crops is compared to potential soil loss of the reference land use. The change in potential soil loss is expressed in t/ ha year.

Equation 9

$$A = R * K * LS * C * P$$

Where:

A = Soil loss for each land use/cover, $t/ha\ year$,
R = Rainfall-runoff erosivity factor, $MJ\ mm/ha\ h\ year$,
K = Soil erodibility factor, $t\ ha\ h\ /ha\ MJ\ mm$,
L = Slope-length factor,
S = Slope steepness factor,
C = Cover management factor,
P = Conservation support practice factor,

The R factor is generally calculated by adding for each rainstorm the product of total storm energy and the maximum 30-min intensity (Wischmeier and Smith 1978). However, this method requires precipitation data with a high temporal resolution which is not available for future climate projections. Other studies approximate R values with equations based on monthly data. These equations are suitable for local/regional conditions but less accurate for large scale assessments (Panagos et al. 2017). To estimate the R factor for several points in time, data from Panagos et al. (2017) was used. Panagos et al. (2017) projected the R factor for Europe in 2050 spatially explicitly. For these projections the RCP 4.5 scenario is considered, and data is collected from the HadGEM2-ES global climate model (in line with this report). The R factors are also assessed for 2010, and the difference in R-factor between 2010 and 2050 projections was quantified. A linear change between the location specific R values of 2010 and 2050 was considered. Following this approach, the R factors were estimated for 2020, 2030 and 2040. The K and LS factors for Europe were obtained from the European Soil Data Centre (ESDAC). The Cover-management factor is assigned to each land use /cover category based on Panagos et al (2015b) (Table 3). The C factor values are time dependent e.g. it changes during the growing stages of the lignocellulosic energy crops. However, in this report it is assumed that these values remain constant over time. The P (the conservation support) factor is not considered in this assessment given that P factor values (1) are highly uncertain (Morgan and Nearing 2016), (2) can be commonly ignored in soil erosion studies (Benavidez et al. 2018), and (3) are difficult to quantify on large scale areas (Benavidez et al. 2018) . The R factor varies over space and time according to changes in precipitation conditions. The C factor are constant in time for each land use/cover category and vary according to land use dynamics. The K and LS factors are constant in time and vary spatially according to soil type and morphology. In addition to the change in potential soil loss for each crop a least soil loss potential was estimated. The least soil loss potential is quantified by evaluating and selecting for each location the lignocellulosic energy crop with the least potential soil loss (regardless of other parameters such as yield). The change in potential Soil loss is expressed in t/ha year.

Table 3 Cover management factor for the relevant land use/cover categories and lignocellulosic energy crops based on Panagos et al (2015b)

Land use/cover	C factor
5. Established dedicated crops	-[A]
8. Shrublands	0.0219[B]
10. Open space suitable	0.1058[C]
11. Abandoned land	0.5[D]
Lignocellulosic energy crops (grasses)	0.0903[E]
Lignocellulosic energy crops (woody)	0.0881[F]

[A] No soil loss is assumed when land is covered with already established dedicated crops
[B] Value from category "Transitional woodland-shrub" is assumed.
[C] Average value from categories "Moors and heathland", "Sclerophyllous vegetation", "Sparsely vegetated areas" and "Burnt areas" (Panagos et al. 2015b)(Panagos et al. 2015b)(Panagos et al. 2015b)
[D] Value assumed from category "fallow land"
[E] Value assumed from category "pastures"
[F] Value assumed from category "agroforestry"

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3. Results

3.1. Land availability

Figure 4 displays the amount of marginal land available for lignocellulosic energy crops in Europe that meets RED II sustainability criteria for various points in time. Available marginal land for lignocellulosic energy crops varies from approximately 208 thousand km^2 in 2020 to 210 thousand km^2 in 2050. There is little variation in the total amount of available land over time, with the lowest amount of available land projected for 2030 (205 thousand km^2). The largest share of available land corresponds to shrubland followed by the land category 'Open space suitable'. The available area of shrubland reduces by approximately 5.6 thousand km^2 between 2020 and 2030 and remains roughly constant between 2030 and 2050. Conversely, the amount of available land from the 'Established dedicated crops' land use/cover category increases over time, starting from (close to) zero in 2020 and reaching approximately 14 thousand km^2 in 2050. The small variation over time in land availability for lignocellulosic energy crops is party attributed to the boundary imposed by land marginality which remains equal over time: i.e, the projections of LUC dynamics, and related land availability for lignocellulosic energy is always limited to the location of marginal areas.

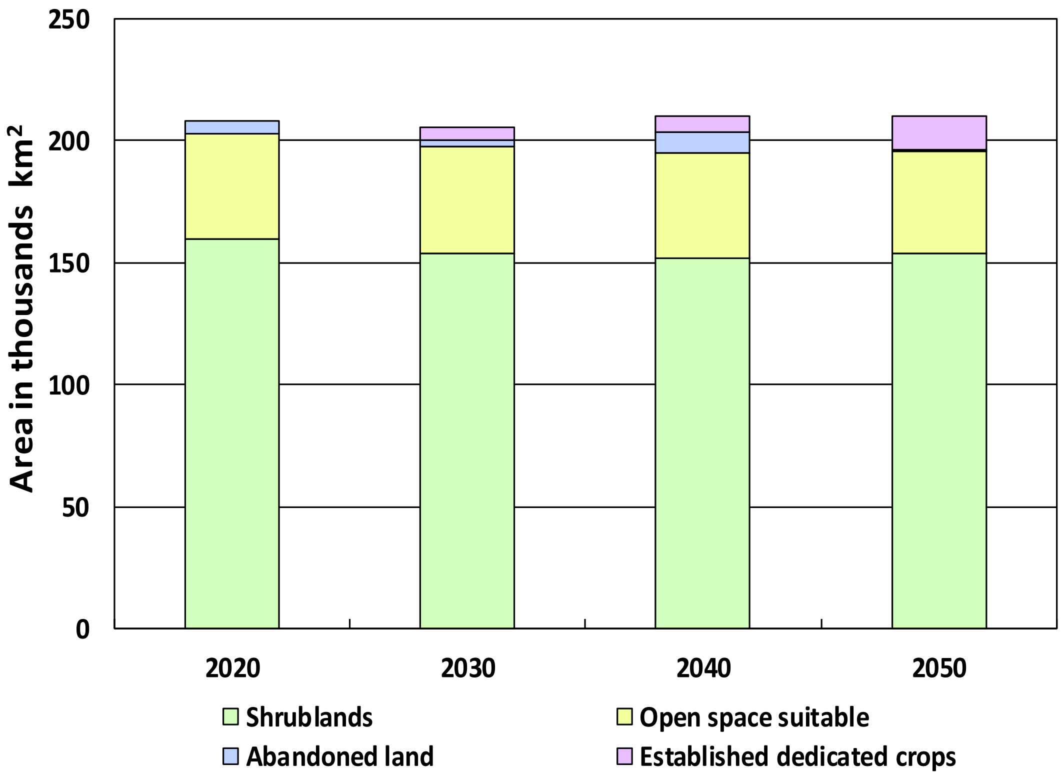

Figure 4. Available marginal land for lignocellulosic energy crops in Europe under RED II sustainability criteria for 2020, 2030, 2040 and 2050

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Figure 5 shows the spatial distribution of available land for lignocellulosic energy crop production in 2050. There is a strong variability between and within countries in the categories of available land. For example, in the Iberian Peninsula there are several areas of available land especially in the north and northeast that are categorized as ‘Shrubland’, while in the centre and south ‘Open space suitable’ and ‘Established dedicated crops’ prevail. In countries such as Spain, France, Germany and Romania there is strong spatial variation in land use/cover categories of the available land for lignocellulosic energy crops: all land use/cover types are found in relatively small areas distributed over the country. Little available land can be seen in areas with natural constrains such as the Alps and the Pyrenees. For countries such as Sweden and Finland, most of the land is categorised as marginal. In addition, most of the marginal land in Sweden and Finland are covered by forest and to a lesser extent by shrubland. Therefore, these two countries have a considerable amount of marginal land that meets RED II criteria (without considering the land dedicated for forest). Other countries such as France have less available land for the potential production of lignocellulosic energy crops. Little land is available in France given that most of the land is already dedicated to agriculture. For several countries located in Eastern Europe such as Poland and Hungary, there are extensive marginal land areas that in 2040 are projected to be used for agricultural production, and in 2050 are projected to be available under RED II criteria. In the Iberian Peninsula, there are several areas, mainly in the north east region that are considered marginal but fail to meet RED II sustainability criteria

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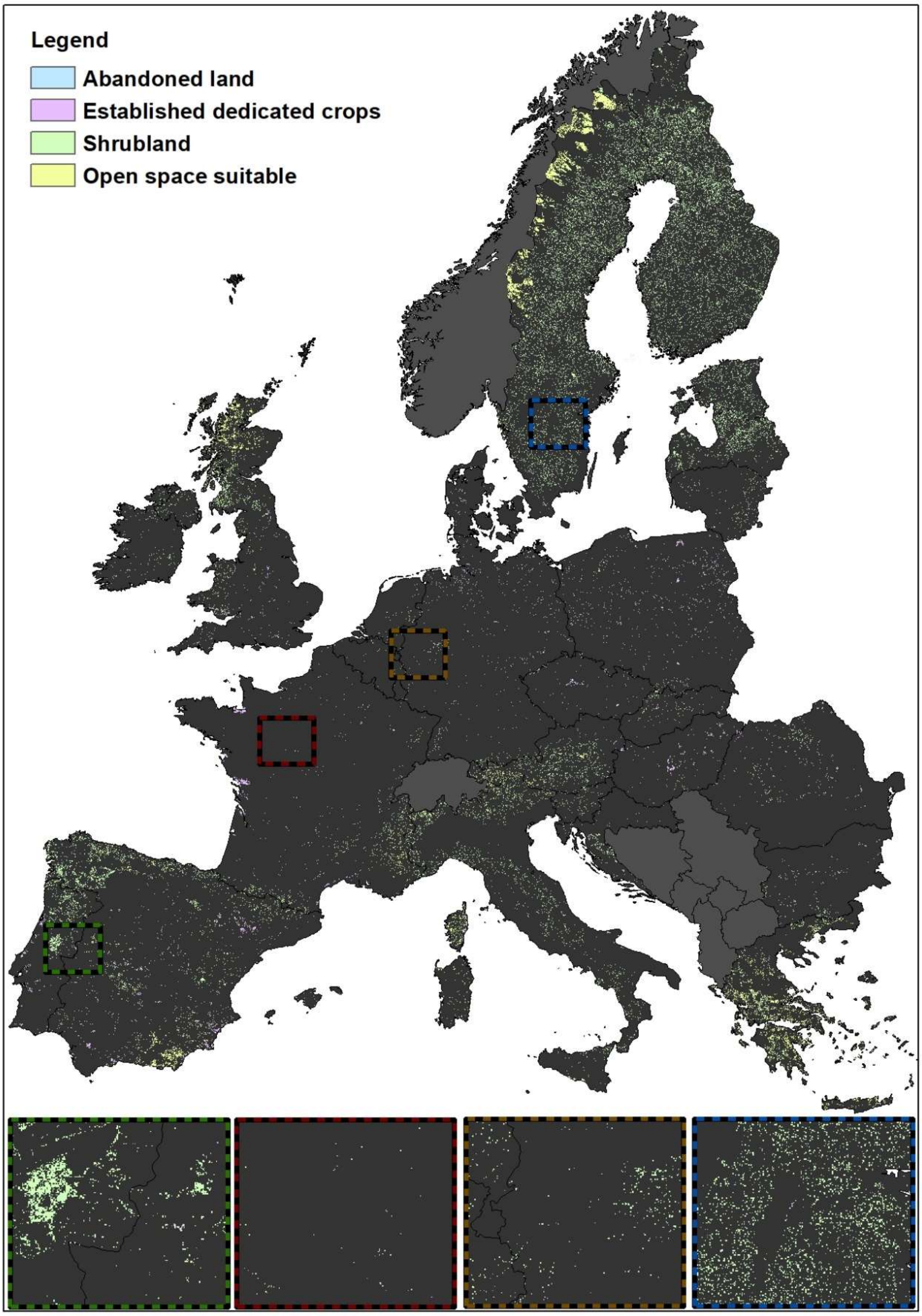

Figure 5. Availability of marginal land for energy crops in Europe for 2050 under RED II sustainability criteria.

3.2. Biomass potentials

Figure 6 shows the development in biomass potentials for the 8 lignocellulosic energy crops and the yield efficient biomass potential (i.e. selecting the highest yielding lignocellulosic energy crop (in MJ/ha) for each location of available land) over time. The biomass potentials have a similar pattern for each point in time. The yield efficient biomass potential shows an increment of 225 PJ over time; increasing from 1385 PJ in 2020 to 1610 PJ in 2050. The highest biomass potentials are projected for Miscanthus, Reed canary grass and Switchgrass, followed by Eucalyptus and Cardoon. The higher potential of these crops is the result of relatively high potential yield as well as relative high suitability for various biophysical conditions. Reed canary grass has one of the lowest potential yields. However, the high tolerance of Reed canary grass allows for the production of this feedstock in locations that are not suitable for any other lignocellulosic crop. Giant reed, Willow and Poplar show the lowest biomass potential. Despite that Giant Reed has the highest potential yield among all lignocellulosic energy crops, the biophysical characteristics required for Giant Reed production are limited to a few areas in Europe. Willow and Poplar report similar biomass potentials: while Willow has a higher potential yield, most of the available marginal land is more suitable for Poplar.

Biomass potentials are projected to increase over time as a result of LUC dynamics, variation in climate conditions and the assumed 1% annual yield increase. The LUC dynamics determine the availability of marginal land under RED II sustainability criteria. Climate variations, mainly temperature and precipitation, dictate the extent to which a crop is constrained to grow in a specific location. For example, the increment in Eucalyptus biomass potential between 2030 and 2040 is attributed largely by the increase in frost free days. Such climatic changes allow for the production of Eucalyptus in locations that were unsuitable before. This also applies to Giant reed: the projected increase in biomass potentials of Giant Reed between 2040 and 2050 is due to an increase in projected annual precipitation in the south of Europe.

As shown in Figure 7 ,the main contribution to the yield efficient biomass potential comes from Miscanthus and Giant reed followed by Reed canary grass, Eucalyptus and Willow. Despite that Reed canary grass has one of the highest potential yields among the selected lignocellulosic energy crops, higher yields are obtained by other feedstock types for several of the locations where Reed canary grass can potentially be cultivated, due to the different tolerance for biophysical conditions. Therefore, the contribution of Reed canary grass to the yield efficient biomass potential is limited to areas that are not suitable for other feedstock types. Giant reed and Miscanthus share the highest water use efficiency ratios. In addition, Giant reed delivers more biomass per hectare than any other feedstock type under the mid and late growing stages. These characteristics results in higher biomass yields for Giant reed and therefore, Giant reed is

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selected over any other feedstock for the locations where different lignocellulosic energy crops can potentially be produced. The contribution of Switchgrass, Cardoon and Poplar to the yield efficient biomass potential is insignificant. Switchgrass and Miscanthus share similar phenological characteristics. However, as Miscanthus has higher potential yields, Miscanthus is selected over Switchgrass when considering the most efficient feedstock. The same applies to Willow and Poplar; at several locations, Willow is preferred over Poplar because it has slightly higher potential yields. Eucalyptus is one of the feedstock types better adapted to dry conditions and can potentially be produced in several areas that are less suitable for other crops.

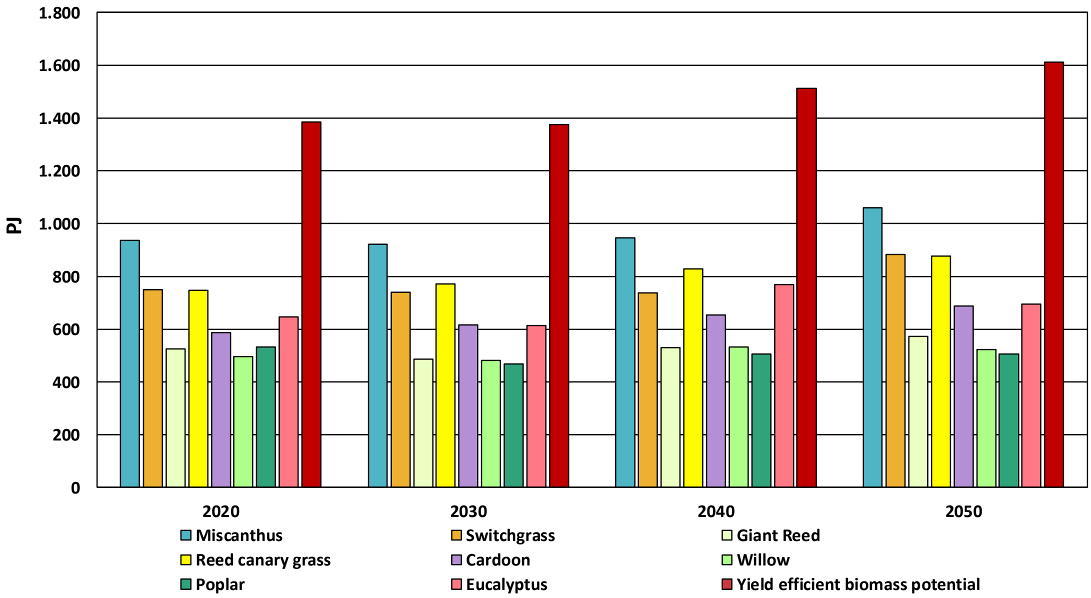

Figure 6 Biomass potentials for each lignocellulosic energy crop (i.e. all available land is allocated to one crop) and yield efficient biomass potential (for each location the crop with highest potential biomass yield is selected) in Europe for 2020, 2030, 2040 and 2050.

Figure 8 shows the spatial variation of the feedstock types contributing to the yield efficient biomass potential in Europe in 2050. There is substantial spatial variation in the selection of crops for the yield efficient biomass potential. The difference in phenological characteristic of the 8 lignocellulosic energy crops and the spatial heterogeneity of biophysical conditions across Europe determine the regional crop variability. In the northern areas of Europe such as in the Scandinavian countries and the Baltic states, the yield efficient biomass potential is mainly dominated by Willow, Miscanthus and Reed canary grass. These feedstock types are better adapted to these regions' biophysical conditions in comparison to other feedstock types. In the Iberian Peninsula there is a large variation in the most suitable feedstock types. The north is dominated by Reed canary grass and Miscanthus, while in the center and south Giant Reed and Eucalyptus prevail. In the centre of the Iberian Peninsula there are small areas where Cardoon shows the highest potential; and in the south Eucalyptus and Reed canary grass are most suitable. In the UK, the yield efficient biomass potential comes mainly from Miscanthus and Giant Reed and to a lesser extent from Willow. There are countries, such as Poland, where the potential is dominated mainly by only one crop (i.e. Miscanthus). In the south of France, Germany, Italy and Austria various feedstock types contribute to the yield efficient biomass potential.

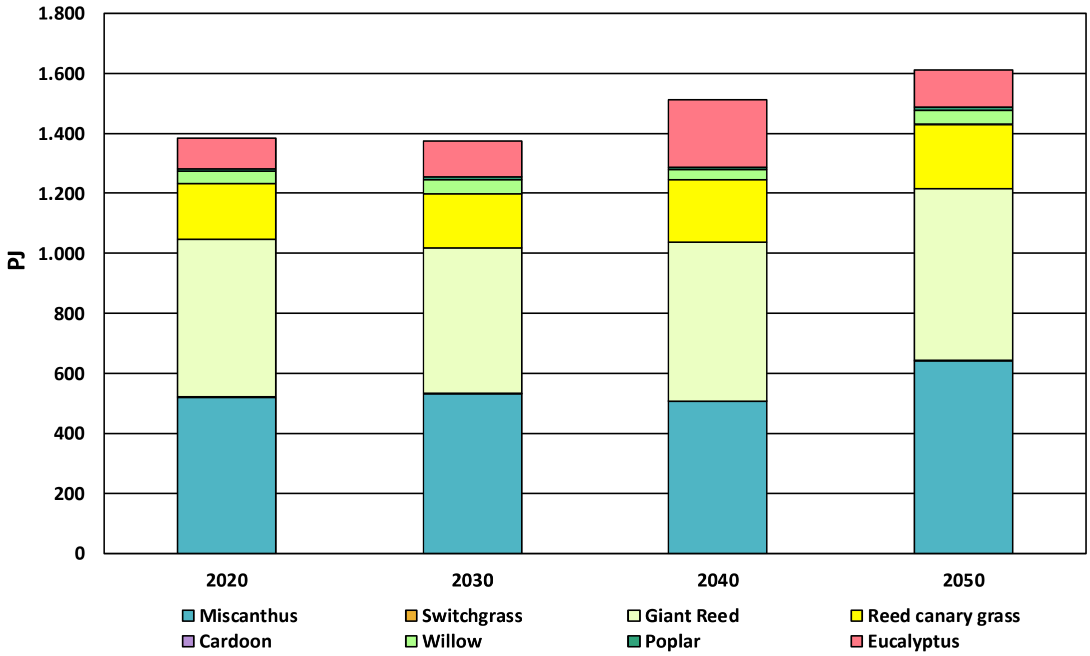

Figure 7: Crop composition of the yield efficient biomass potential (at each location of available land, the crop with the highest attainable biomass yield is selected) in Europe for 2020, 2030, 2040 and 2050

As shown in Figure 9, the lowest biomass yields (GJ/ha year) are in the most northern parts of Europe (Sweden and Finland), the north of the Iberian peninsula and areas located in the vicinity of the Alps. The biophysical conditions in these areas limit biomass production to a large extent and allows only for the potential production of Reed canary grass (the feedstock type with a high tolerance for various biophysical conditions but with lowest potential yield). Therefore, on average, many of those areas can only potentially deliver 0 - 100 GJ/ha year. In the south of Europe, especially the Iberian Peninsula and Greece are characterized by high temperatures and relatively low precipitation; these biophysical conditions limit the biomass production from several feedstock types. However, Giant reed and Eucalyptus are adapted to such conditions and can potentially deliver relatively high yields in these locations (200 -350 GJ/ha year). Although some lignocellulosic energy crop types can grow in high northern latitude areas, the extreme biophysical conditions in these regions limits biomass production, i.e. yields are generally < 100 GJ/ha year. The areas with the highest biomass potentials are in some areas of Spain, Greece and Hungary. These areas feature favourable biophysical conditions for Giant Reed production, which result in potential biomass yields of 350-450 GJ/ha year. In Germany, Central and Eastern Europe, biomass yields range on average between 200 to 300 GJ/ha year. For whole Europe, the average yield is reported to be 212 GJ/ha year, this corresponds to approximately 11 t/ha year.

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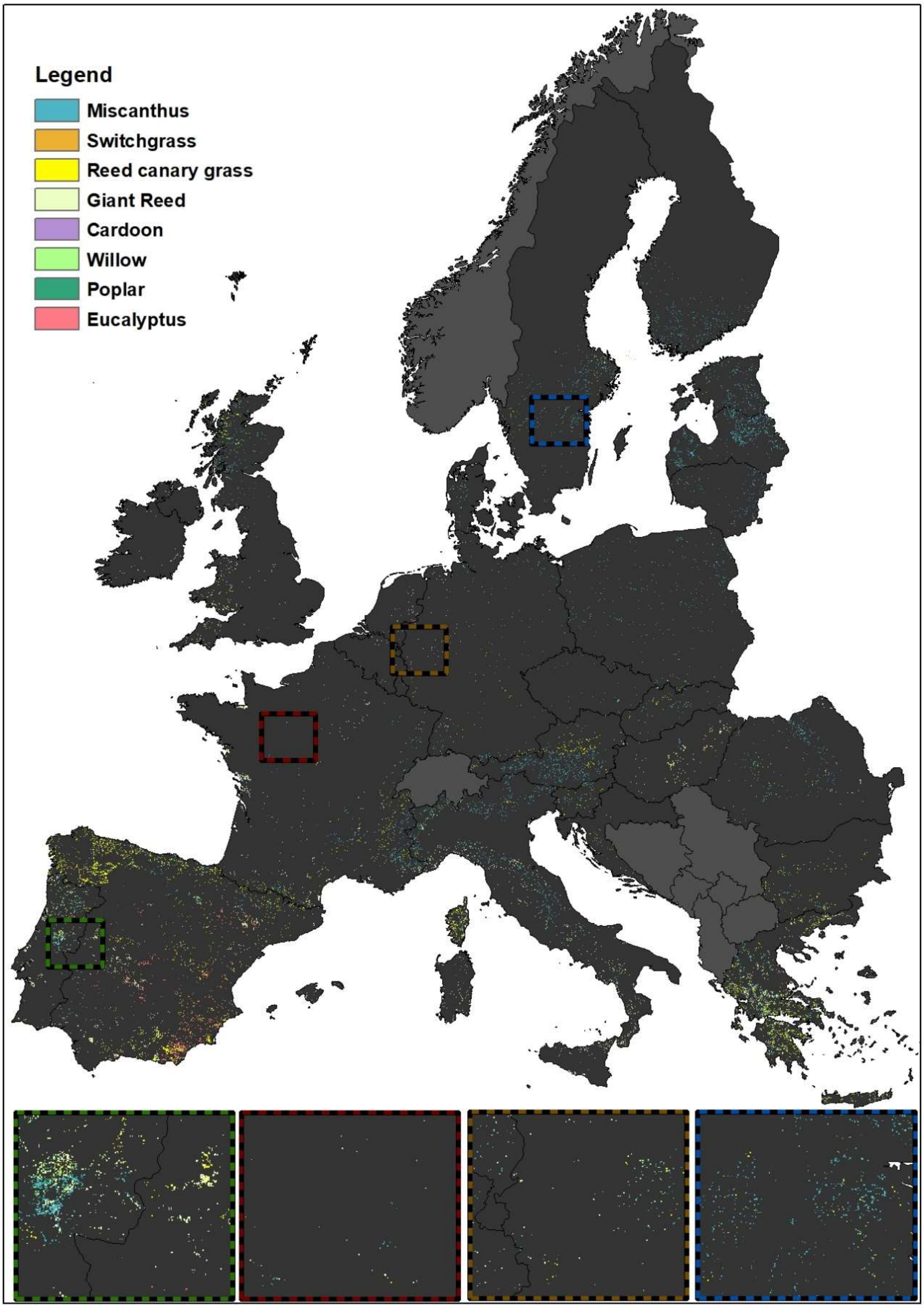

Figure 8 Crops composition of the yield efficient biomass potential (for each location, the crop with the highest potential biomass yield is selected) in Europe for 2050

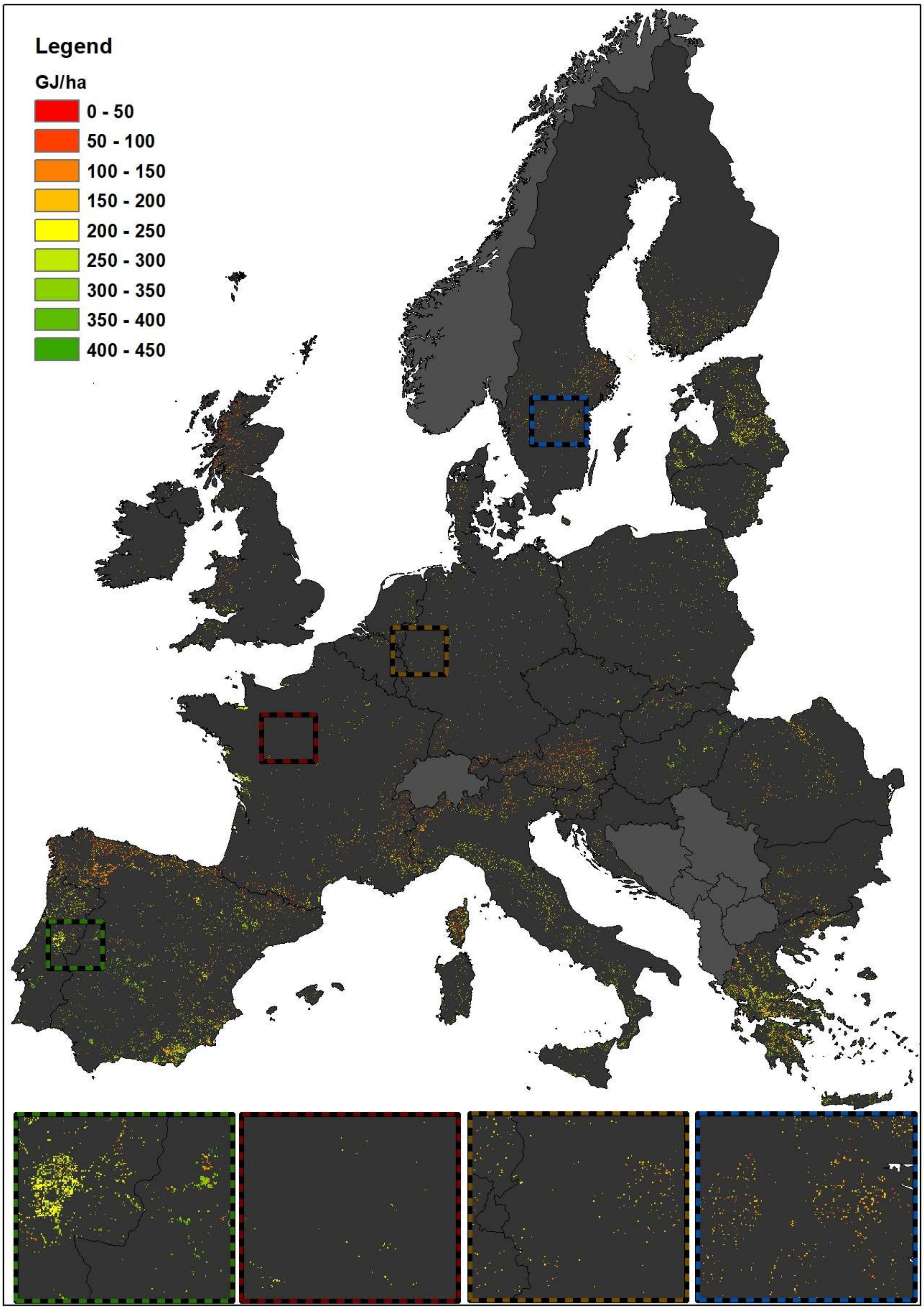

Figure 9 Yield efficient biomass potential (at each location of available land, the crop with the highest attainable biomass yield is selected) in Europe for 2050

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3.3. Environmental impacts

3.3.1. LUC-related GHG emissions

As shown in Figure 10, the cultivation of all feedstock types results on average in carbon sequestration for all points in time. CO_2 emissions vary on average between -0.23 t CO_2/ha year for Reed canary grass in 2030 to – 7.1 t CO_2/ha year for Eucalyptus in 2040. The changes in carbon stocks are mostly the result of changes in biomass carbon and to a lesser extent of changes in the SOC. Generally, the conversion of land to grassy lignocellulosic energy crops results in the loss of soil organic carbon. Conversely, the change of land towards woody lignocellulosic energy crops results in carbon accumulation in the soil. For all the feedstock types, most of the carbon accumulation occurs in the above ground biomass. However, a large share of this carbon is contained in the harvestable section of the plant. Despite that all feedstock types result in (average) carbon sequestration, there are locations where the production of some of the lignocellulosic energy crops results in LUC-related CO_2 emissions. For example, there are location where the production of Reed canary grass can result in a potential release of 3.1 t CO_2/ha year as a result of carbon losses from LUC. The same occurs occur for other lignocellulosic energy crops such as Miscanthus, Switchgrass and Cardoon. The CO_2 emissions related from LUC occurs mainly in areas with low potential lignocellulosic energy crops yields when compared to the biomass volumes of the land use/cover type prior to conversion. The production of woody lignocellulosic energy crops results generally in the sequestration of carbon given that these crop types can store more carbon (in the biomass and SOC pools) in comparison to grassy lignocellulosic energy crops and in comparison to the land prior to conversion.

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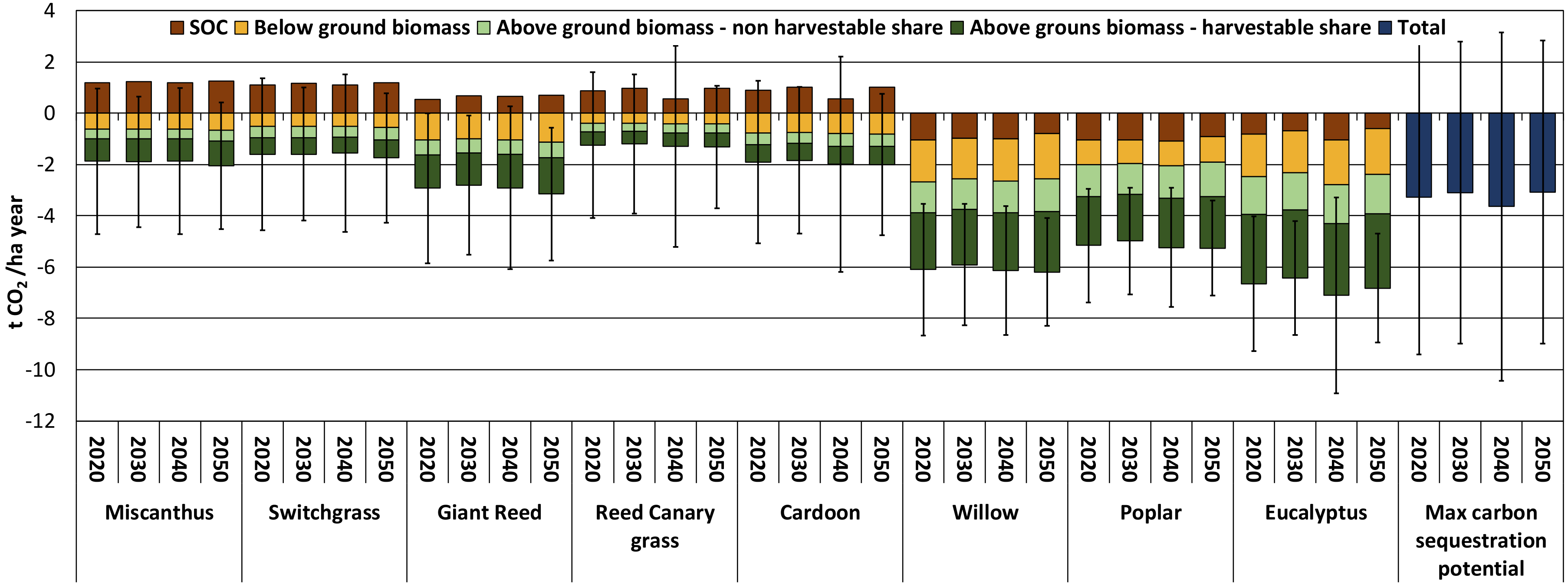

Figure 10 Average LUC related GHG emissions with two standard deviations for the cultivation of each lignocellulosic energy crops on marginal land t in Europe for 2020, 2030, 2040 and 2050 and for the max carbon sequestration potential. The ranges indicate the spatial variability of LUC GHG emissions due to the heterogeneity in biophysical conditions

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Eucalyptus shows the lowest average CO_2 emissions for all points in time. The high carbon sequestration capacity from Eucalyptus in comparison to other feedstock types is attributed mainly to high yields and the carbon accumulation capacity that occurs for several years in the above and below ground biomass. This also occurs with Willow and Poplar. In some locations, the production of Eucalyptus result in the storage of approximately 10 t CO_2/ha year. From the grassy lignocellulosic energy crops, Giant reed shows the highest average carbon sequestration. Giant reed has higher yields and stores more carbon in the below ground biomass than other grassy feedstock types. Conversely, Reed canary grass shows the lowest average carbon sequestration. Reed canary grass biomass production is largely spread in areas where yields are highly constrained by biophysical conditions. As a result, the above ground biomass of reed canary grass is on average slightly above the volumes of biomass of the land use/cover of the available marginal land. Some feedstock types such as Cardoon, which has low yields, show similar CO_2 emissions results to feedstock types that deliver high yields (Miscanthus). Cardoon has the highest above to below ground biomass ratio and therefore, accumulates more carbon in below ground biomass.

Almost all feedstock types show a similar trend over time, with a slight decrease in average CO_2 sequestration between 2020 and 2030, followed by a slight increase between 2030-2040, and finally another slight increase between 2040 and 2050. The trend in average CO_2 emissions is partly driven by the amount of abandoned land that becomes available. The production of lignocellulosic energy crops on abandoned land often results in high CO_2 sequestration. Therefore, the increase in average CO_2 sequestration for almost all feedstock types coincides with the years (2020 and 2040) that show the highest amount of abandoned land becoming available. Yield increase and other land use/cover types becoming available over time also influences land related CO_2 emissions. Yield increase reduces the range in CO_2 emissions that can occur on a specific location over time.

Besides the differences in the harvest index that determines the share of CO_2 accumulated in the harvestable section, the differences in below ground biomass of the energy crops also affect the LUC related CO_2 emissions. Among woody energy crops, Willow generally has higher yields than Poplar. In addition, the ratios of above-to-below ground biomass are larger for Willow and Eucalyptus than for Poplar. Therefore, like Cardoon, Willow can accumulate larger amounts of carbon in the below ground biomass per unit of above ground biomass. Accordingly, Willow shows on average a higher carbon sequestration potential than Poplar. At some locations, Willow can store up to -6 t CO_2/ha year. Also, the biophysical conditions that are favourable for relative high yields for energy crops are also favourable for biomass production from other land

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use/cover categories such as Shrubland. Similarly, areas with less favourable biophysical conditions for energy crop production are also less favourable for biomass production of other land use/cover categories.

As shown in Figure 11, the main share of the max carbon sequestration potential consists mainly to of Eucalyptus and Miscanthus, followed by Reed canary grass and to a lesser extent by Cardoon and Willow. The contribution of Poplar is minor and the of Switchgrass, Cardoon and Giant Reed is negligible. Different from the yield efficient biomass potential, Eucalyptus is widely more considered for the max carbon sequestration potential as it can store more carbon when compared to other feedstock types. Despite that Giant reed can store on average more carbon then the other grassy lignocellulosic energy crops, it has a similar suitability extent as Eucalyptus. Both crops are suitable for the conditions in south Europe. Therefore, for those locations, Eucalyptus is always preferred over Giant reed. The same occurs for Willow. Despite that Reed canary grass has on average the lowest carbon sequestration potential of all energy crops, it contributes approximately to 20-25% of the share from the max carbon sequestration potential. This is because Reed canary grass can potentially be grown in locations that are not suitable for other feedstock types.

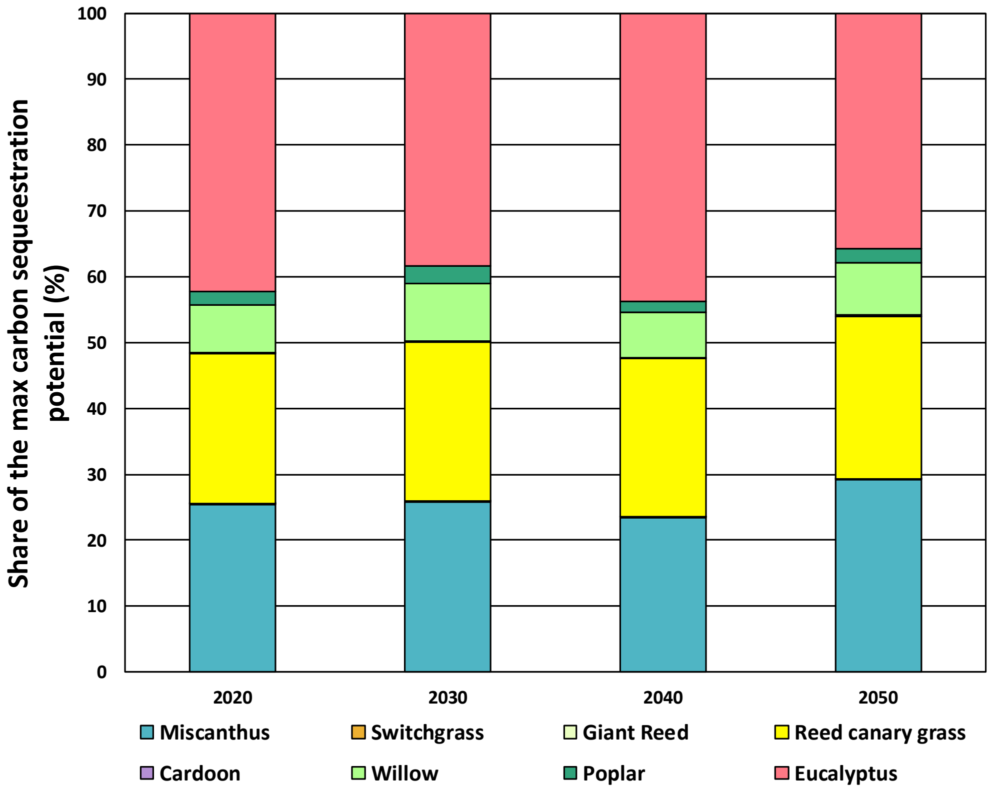

Figure 11. Crop composition of the max carbon sequestration potential (for each location of available land, the energy crop with the highest carbon sequestration potential is selected)) in Europe for 2020, 2030, 2040 and 2050

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Figure 12 displays the spatial variation of the different feedstock types across Europe for the max carbon sequestration potential in 2050. There is a considerable spatial variation in crops allocation across Europe. In the north of Europe, Willow and Miscanthus are chosen for several locations. In Greece, the carbon sequestration is mainly covered by Eucalyptus and Reed canary grass. In addition, there is a small area in the north of the country dominated by Willow. In the north of Italy, Willow and Miscanthus are preferred over any other feedstock type while in the centre and south Willow and Eucalyptus are preferred. Similar to the yield efficient biomass potential, the sequestration of carbon in some countries such as Poland is dominated by a single crop (Miscanthus). For France, mainly in the south, Reed canary grass, Miscanthus and Eucalyptus are the crops that can potentially sequester most carbon. In the Iberian Peninsula various feedstock types contribute to the max carbon sequestration potential. Similar to the yield efficient biomass potential, the north is dominated by Reed canary grass. However, the areas that were dedicated to Miscanthus production in the yield efficient biomass potential (north of the Iberian Peninsula) are selected for Willow and Eucalyptus in the max carbon sequestration potential. These feedstock types accumulate more carbon than Miscanthus for the mentioned locations. A similar trend is reported in the north of Portugal, where Willow is preferred over other feedstock types. In the centre and south of the Iberian Peninsula there are extensive areas where Eucalyptus shows the highest carbon sequestration. However, there are also some areas of the Iberian Peninsula where the potential production of Reed canary grass shows the highest carbon sequestration.

Figure 13 shows the spatial variation in the max carbon sequestration potential from the production of lignocellulosic energy crops in Europe. There is a strong variability in CO_2 emissions across Europe, with almost all locations showing carbon sequestration. On average, -3.1 t CO_2/ha year is sequestrated. There are few locations that report CO_2 emissions, mainly in the north of the UK. The CO_2 emissions in these areas are associated to the production of Reed canary grass. Reed canary grass has on average the lowest yields. Therefore, the conversion to Reed canary grass in such extreme locations can result in CO_2 emissions as high as 4 t CO_2/ha year. Similarly, areas in Austria, France, Germany and Scandinavia that show CO_2 emissions between 0 and 2 t CO_2/ha year are related to potential production of Reed canary grass and to a lesser extent of Miscanthus. For Spain, Italy, Greece, the south of France, the south of Portugal and Hungary the highest carbon sequestration is projected, on average between -8 and -4 t CO_2/ha year; mainly from the potential production of Eucalyptus. A similar trend is also reported in areas with Willow such as the North of Portugal. In these locations, CO_2 sequestration ranges from -6 to – 4 t CO_2/ha year

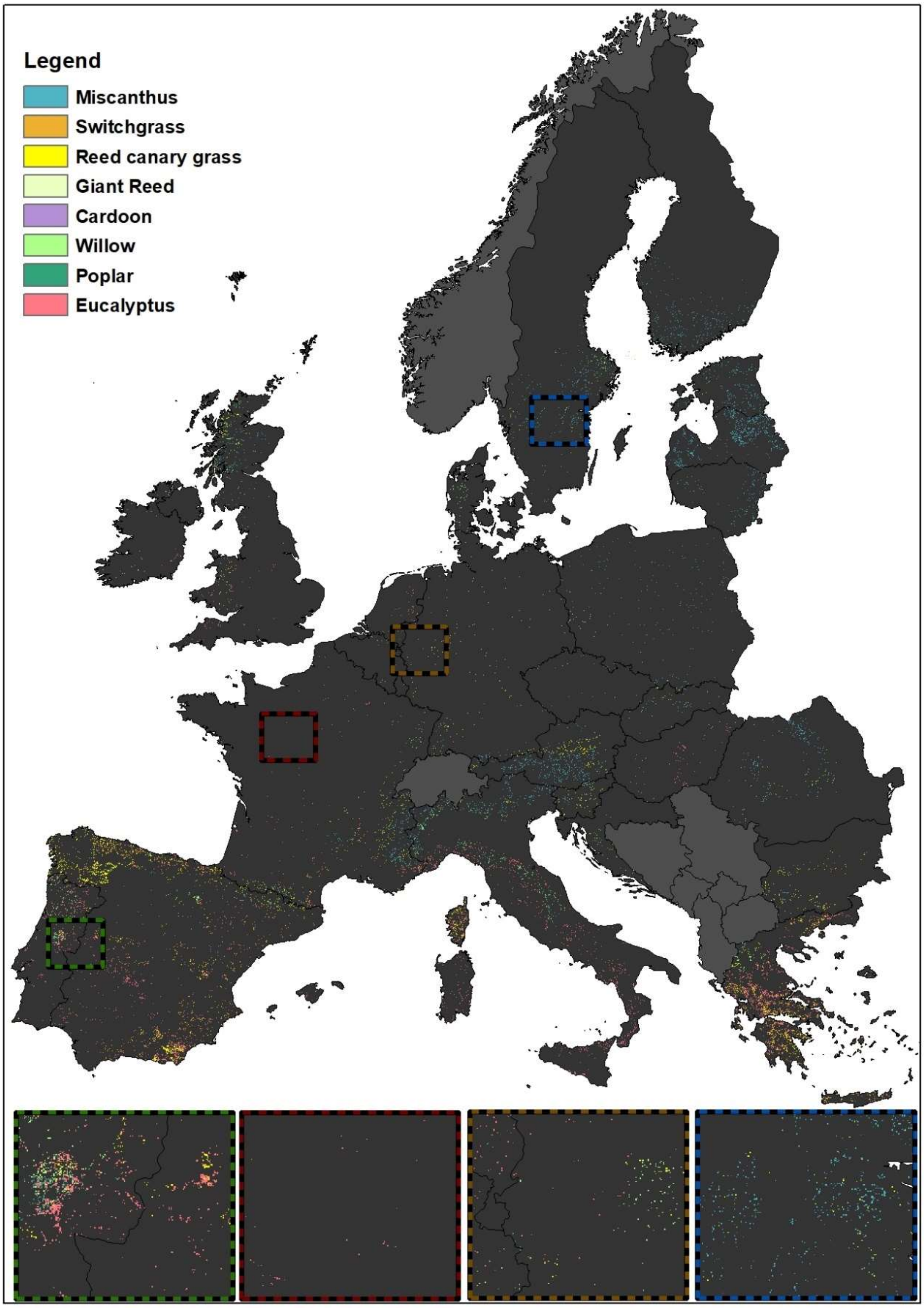

Figure 12 Crop composition of the max carbon sequestration (lowest CO_2 emissions per hectare) in Europe for 2050

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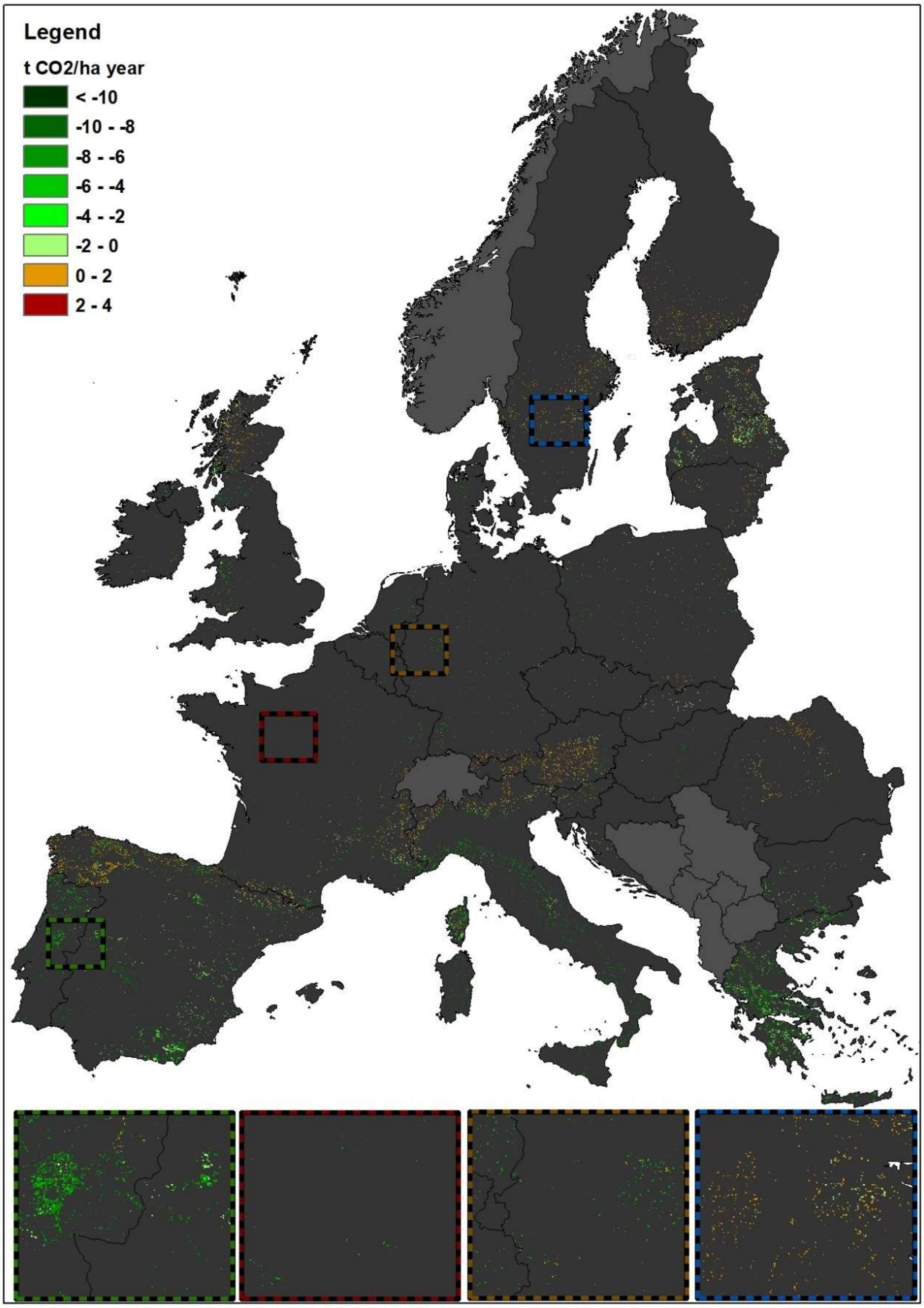

Figure 13 Spatial variation of max carbon sequestration potential (for each available location, the crop with highest carbon sequestration potential is selected)) in Europe for 2050

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3.3.2. Water depletion

Figure 14 shows the average water deficit from the production of lignocellulosic energy crops in Europe for different points in time and the least water deficit potential per unit of area dedicated to production. On average, the water deficit varies from 327 mm/year for Cardoon in 2020 to 1072 mm/year for Giant Reed in 2050. This signifies that on average, an additional 3270 m^3 of water per hectare for Cardoon and 10720 m^3 of water per hectare for Giant Reed are required during the crop growing cycle to deliver the estimated biomass potentials and obtain the projected yields. The projected water deficit from the lignocellulosic energy crops indicates that on average for all crops additional water is required. The supply of such water volumes can disturb water tables and result in potential local water depletion. Still, for almost all feedstock types, there are locations where the precipitation conditions supply suffcient water to produce biomass an obtined the estimated yields in previus sections without the need of additional water inputs. In this case, negative values for water deficit are reported. The large water deficit from Giant reed is caused by the high water requirmenst of Giant reed during the growing season; especially during the mid-season growth stage, Giant reed requires considerable more water than any other feedstock type. Cardoon has the lowest water requirements during the growing season. Consequently, the lowest average water deficit is projected for Cardoon. The trend in projected water deficits over time is similar for the various crops. The increase in water deficit is ascribed to the changes in climate conditions, mainly in precipitation and temperature. Over time, annual precipitation decreases while annual average temperature increases. Despite that Willow, Poplar and Eucalyptus have similar water requirements during the crop growth stages, Eucalyptus shows on average a considerable higher water deficit. Eucalyptus can potentially be produced in southern Europe such as Spain and Greece. These are commonly dry regions and are projected to get dryer over time.

Crops types such as Miscanthus, Willow and Poplar that deliver relative high yields in comparison to Cardoon or Reed canary grass report similar results in water deficits over time. The crop characteristics of these crop types prevents them to grow in areas that are characterized by low precipitation. As a result, these feedstock types show a lower water deficit than crops such as Eucalyptus, Giant reed and Reed canary grass that can still potentially be produced to some extent in low precipitation conditions. Similarly, Cardoon can potentially be produced to some extent in low precipitation conditions. However, the water demand of the potential production of Cardoon is considerably lower when compared to other crops. Reed canary grass shows one if the highest water deficits. The suitability of Reed canary grass allows for the potential production of this crop in climate conditions that are not suitable for any other crop type. The production of Reed canary grass in such conditions leads to low yields and high water deficits.

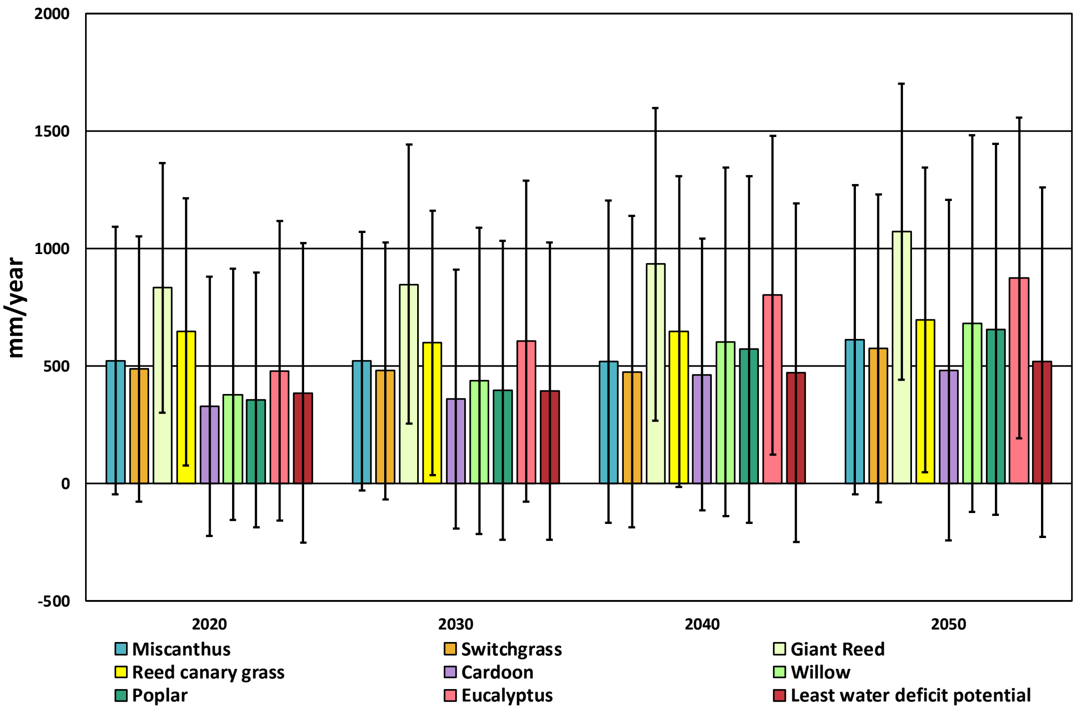

Figure 14 Average water shortage with two standard deviations for the cultivation of lignocellulosic energy crops on marginal land in Europe for 2020, 2030, 2040 and 2050 and for the least water deficit potential. The ranges indicate the spatial variability of water shortage due to the heterogeneity in biophysical conditions.

The least water deficit potential was calcualted by selecting the crop with the lowest water deficit for each loaction of available marginal land. The least water deficit potential increases from 385 mm in 2020 to 517 mm in 2050. As shown in Figure 15, the main share of the least water deficit potential is composed of Cardoon, followed by Reed canary grass, Switchgrass and to a considerably lesser extent by Eucalyptus and Poplar. Miscanthus, Willow and Giant reed don't contribute to the least water deficit potential. Despite that Switchgrass and Miscanthus share similar characteristics, Switchgrass is selected over Miscanthus given that Switchgrass requires less water per unit of area (but less biomass is produced). This characteristic leads to the opposite result as for the yield efficient biomass potential, as for the yield efficient biomass potential, Miscanthus is most often selected over Switchgrass as it delivers higher yields. The same applies to Poplar and Willow. The least water deficit potential is mainly composed of crops that achieve low yields, Cardoon, Reed canary grass and Switchgrass. The water requirements of Cardoon are considerably lower than of other feedstock types. Although Reed canary grass generally leads to high water deficits, it is part of the least water deficit potential as it is selected at locations that are not suitable for any other crop. The decrease in contribution from Eucalyptus over time is caused by the projected changes in climate conditions that allow for potential production of Cardoon in the areas that were previously not suitable for Cardoon. As

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a result, at several locations in Spain and France where Eucalyptus was the crop with least water deficit in 2020, Cardoon became the crop with least water deficit for the later points in time.

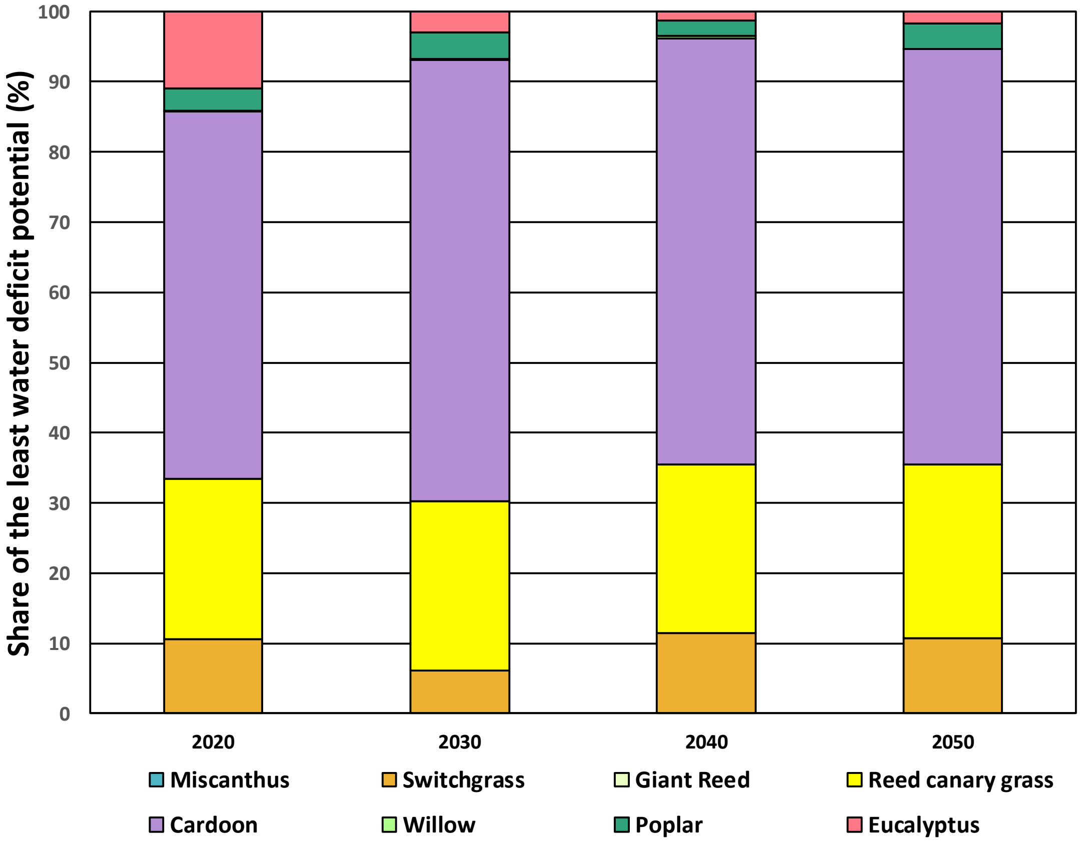

Figure 15. Crop composition of the least water deficit potential (for each location the crop with the lowest water deficit is selected) in Europe for 2020, 2030, 2040 and 2050

As shown in Figure 16, there is considerably less variation of feedstock types across Europe for the least water deficit potential when compared to the yield efficient biomass potentials or max carbon sequestration potentials. For several countries such as Italy, Poland and Czech Republic, the least water deficit potential is mainly composed of Cardoon. Switchgrass is preferred in areas such as the north of the Baltic States, Sweden and Finland. Germany is one the countries with more variation in feedstock types contributing to the least water deficit. In the north and the south of the country, Cardoon is often the crop with the lowest water deficit, while in the centre, Poplar and Reed canary grass cause the lowest water deficits. Close to the border with France, there is a small area where eucalyptus causes the lowest water deficit. In the Iberian Peninsula, the least water deficit potential is dominated by Cardoon and Reed canary grass. However, there are also areas in the north of Portugal where the production of Poplar results in lower water deficits.

Figure 17 shows the spatial variation in crops contributing to the least water deficit potential in Europe for 2050. Despite that on average there is a water deficit of 520 mm/year for each plot

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of lignocellulosic energy crop cultivation, there are areas that have negative values. i.e, in these locations the precipitation is sufficient for the crop biomass production and therefore, no additonal water is required. This occurs in areas such as the North of the UK, Austria and Germany. The North of the UK is characterized by a high precipitation. This region is one of the wettest in Europe and annual precipitation is projected to reach more than 2400 mm in 2050. For this region, the potential water deficit of mainly Poplar Cardoon and Switchgrass production is negative (between -20 to - 400 mm/year). The same applies to western Austria. In west Austria, where precipitation levels (which are even if lower than in the North of the UK), are adequate to produce Swhticgrass and Cardoon without the need of additional water. The highest water deficit of lignocellolusic energy crop production is projected to occur in the South of Spain, Italy and Greece. These regions exhibit the driest conditions for Europe. In some of these locations, to obttain the estimated potential yields, more than 1000 mm/year of additional water is required for the production of Cardoon and Reed canary grass.

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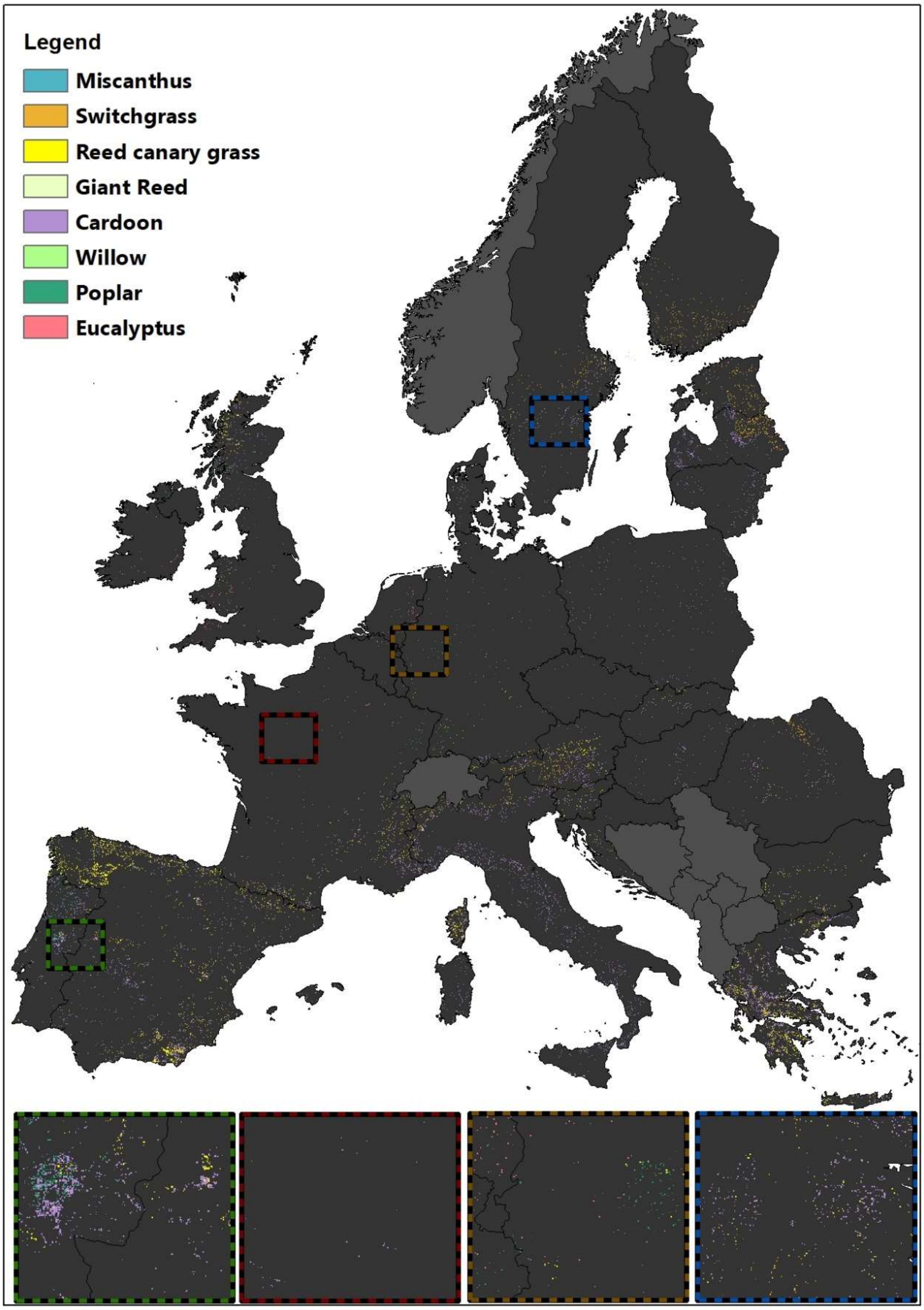

Figure 16 Crop composition of the least water deficit potential (for each location of available land, the crop with the lowest water deficit per unit of space is selected) in Europe for 2050

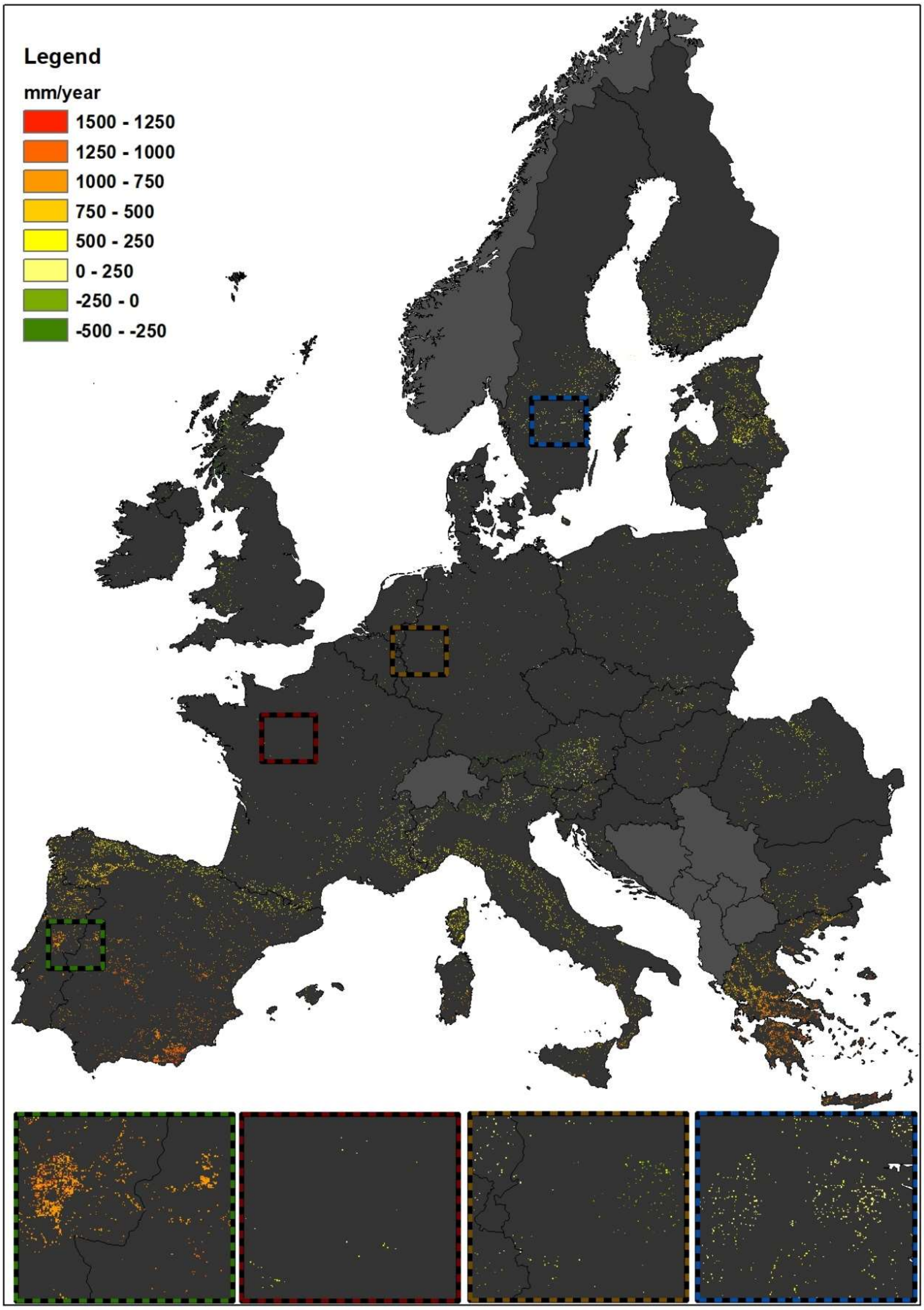

Figure 17. Spatial variation of the least water deficit potential (*for each location of available land, the crop with the lowest water deficit per unit of space is selected) in Europe for 2050*

3.3.3. Soil erosion risk

As shown in Figure 18, on average the production of all feedstock types is projected to result in an increase in potential soil loss compared to the potential soil loss of the land use/cover of the marginal land. There is little difference in soil loss between the different feedstock types. Average increases in potential soil loss varies between 4.5 t/ha year for Eucalyptus in 2040 to 7.5 t/ha year for Poplar in 2050. A large increase in soil erosion risk occurs when shrubland is converted to lignocellulosic energy crops, as shrubland provides a better year-round cover against rain impact. The change from 'abandoned land' and 'open space suitable' to lignocellulosic energy crops results in negatives scores; i.e. the conversion to energy crops results in a decrease in erosion risk. However, most of the projected available land for lignocellulosic energy crop production is categorised as shrubland. The large ranges in changes in soil loss for all feedstock types is caused by the high spatial heterogeneity in biophysical conditions, mainly terrain conditions. The trend in soil loss over time is to some extent caused by the amount of abandoned land that is projected to become available for feedstock production. In 2020 and 2040 the largest amount of abandoned land becomes available. Therefore, on average, slightly lower soil losses are projected for almost all lignocellulosic energy crops in those years. Of all feedstock types, Poplar is projected to result in the highest soil losses. This is because the land suitable for Poplar production contains a larger share of shrubland in comparison to the other feedstock types.

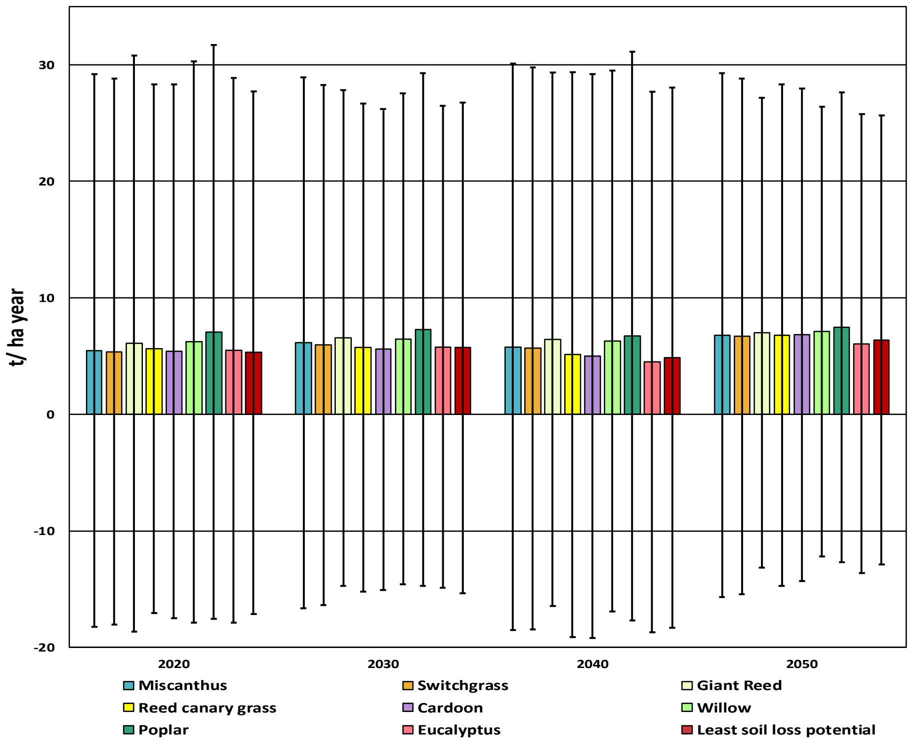

Figure 18 Average change in potential soil loss with two standard deviations for the cultivation of each lignocellulosic energy crops on marginal land in Europe for 2020, 2030, 2040 and 2050. The ranges indicate the spatial variability of LUC soil loss due to the heterogeneity in biophysical conditions the least soil loss potential is the biomass potential when for each location the energy crop with the lowest erosion risk is selected.

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There is a strong spatial variability in the change in potential soil loss from the potential production of lignocellulosic energy crops across Europe in 2050 (Figure 19). The areas that shows the highest potential LUC-related soil loss from lignocellulosic energy crop production are the ones located in mountainous or hilly terrain. For example, in the Alps region, lignocellulosic crop production can lead to the loss of 40 t of soil per hectare. The high soils loss in this type of region is caused by the relative high slope-length and slope-steepness. These conditions can severely enhance soil loss. These high soil losses are projected to occur mainly when shrubland located in high slope-length and slope-steepness areas is changed to lignocellulosic energy crops. The opposite effect is projected for the same slope-length and slope-steepness conditions when 'open space suitable' is converted to lignocellulosic energy crops. The production of lignocellulosic energy crops in such areas results in less soil loss than of the land prior to conversion (i.e. negative scores for change in soil erosion).

In all countries, there is a strong spatial variation in the change in potential soil loss which is caused by the variation in land use/cover of marginal land available for lignocellulosic energy crop production. In the Iberian Peninsula, the northern region shows medium to high potential soil loss from lignocellulosic energy crop production. Most of this area is characterized as mountainous and most of the available marginal land is shrubland. In the south, there are several regions for which a reduction as large as 10 t/ha year in soil erosion is projected when land is converted from 'open space suitable' to energy crops. In Greece, despite that several regions are characterized with high slope-length and slope-steepness, most of the available land is categorized as 'open space suitable'. Therefore, the potential change to lignocellulosic energy crops results in lower soil loss when compared to the land prior to conversion. The same occurs in the north of the UK and south of France. The highest reduction in potential soil loss (up to -30 t/ha year) is reported for few regions in the middle of Germany and Italy when abandoned land is converted to lignocellulosic energy crops.

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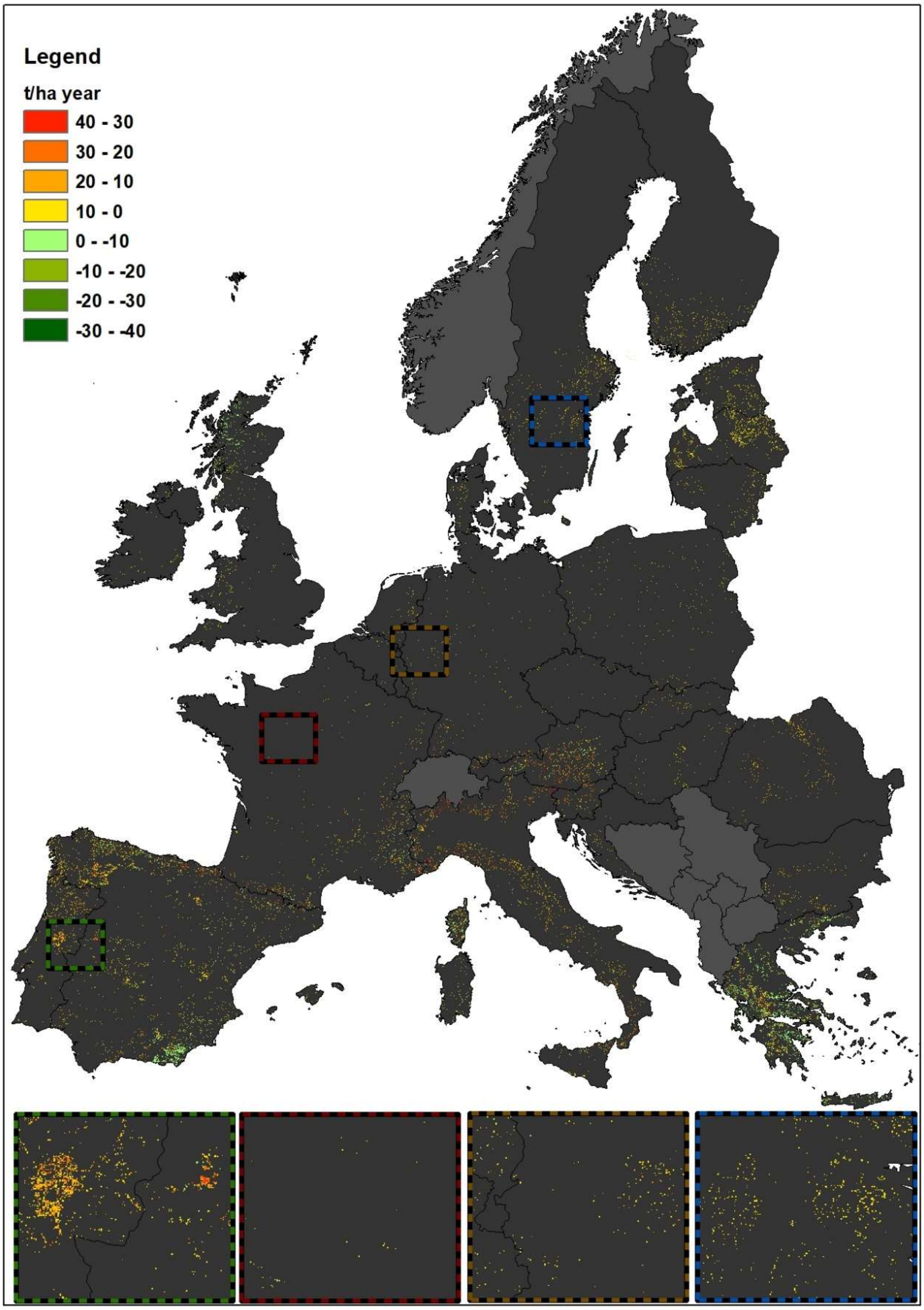

Figure 19. Spatial variation of the least soil loss potential (for each location, the crop with the *least soil loss in comparison to land prior to conversion is selected) in Europe for 2050.*

4. Discussion and Conclusion

In this study, land availability, biomass potentials and LUC-related environmental impacts from lignocellulosic energy crops production on marginal lands in EU-26 under RED II sustainability constrains were assessed spatially explicitly. A large variability in magnitude and direction (i.e. positive and negative) was found for all LUC related environmental impacts of lignocellulosic energy crop production at different points in time. The biomass potentials and environmental impacts strongly depend on location specific biophysical conditions, land use/cover prior to conversion, and feedstock type.

4.1. Land availability

Total available marginal land that meets RED II sustainability criteria is projected to vary between 208 thousand km^2 in 2020 to 210 thousand km^2 in 2050. However, a large share of the available land is not suitable for lignocellulosic energy crops production. Approximately one third, ± 75 thousand km^2, of land area is projected to be suitable. The area of available marginal land under RED II sustainability criteria that can potentially be dedicated to lignocellulosic energy crops production is considerably smaller than current and future projected agricultural area in EU-26, which is estimated to decline from 2029 thousand km^2 in 2020 to 1940 thousand km^2 in 2050 (Lavalle 2014). Other studies on land availability for lignocellulosic energy crops with similar restrictive scenarios, estimate larger amounts of available land. For example, the low scenario from the JRC-EU-TIMES model (Ruiz et al. 2015) projects land availability for lignocellulosic energy crops production between 150 thousand km^2 in 2020 to 130 thousand km^2 in 2050 In contrast to this study, the land availability was not limited for energy crops was not limited to marginal land.

The results of this report should be interpreted with care as there are many uncertainties regarding projections on future land availability. The location of marginal lands was assumed to be constant over time. However, some parameters related with climate conditions (temperature, precipitation and humidity) that define to some extent land marginality (Elbersen et al. 2017) are not constant. Including the temporal variation in climate conditions in line with the RCP 4.5 projections in the identification of marginal land would affect the extent of land that is projected to become available for lignocellulosic energy production and consequently affect biomass potentials. In addition, for the disaggregation/aggregation of land use/cover categories it assumed that some land use cover categories, such as forest, remain constant over time. However, in practice forest area is likely to change. This assumption affects the amount of shrubland projected to be available for energy crops.

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In LUISA, land is allocated and aggregated based on a supply-demand module that considers agricultural markets, demographic and macroeconomic trends. However, when compared to other land use projections, large differences were found (Alexander et al. 2017).

4.2. Biomass potentials

When all available land is allocated to a single type of crop, the highest biomass potential is projected for Miscanthus with a potential of 1058 PJ/year by 2050. If for each plot of available land, the crop with the highest yield would be selected, the total biomass potential varies from 1385 PJ/year in 2020 to 1610 PJ/year in 2050. Current (for EU-28) gross domestic bioenergy consumption is 5700 PJ (EUROSTAT 2018),

The differences in scope and considered parameters limits the comparison of the projected biomass potentials with other studies. The most conservative projections estimate a domestic biomass potential in the EU-28 of 4800 PJ in 2020 and increasing to 8160 PJ in 2050 (Hoefnagels and Germer 2020). The yield efficient biomass potentials are 70% to 80% less respectively if marginal lands under RED II sustainability criteria are used. Still, other biomass potentials include additional biomass types such as residues. When considering only lignocellulosic energy crops, the low scenario of the JRC-EU-TIMES model (Ruiz et al. 2015), in which similar constrains are considered (Eucalyptus potential is not assessed), projects a biomass potential of 1515 PJ in 2050. The medium and high scenario, in which less sustainability constraints are considered project biomass potentials of 2063 PJ and 3369 PJ in 2050. In S2Biom (Dees et al. 2017) , in which similar methods and sustainability constraints are applied as in this study, a biomass potential of 2661 PJ is projected for 2030. However, they include more EU countries and the production of lignocellulosic energy crops is not strictly limited to marginal lands. There is a considerable difference with biomass potentials projected in other studies such as BioSustain, which found a biomass potential of 4731 PJ for 2030 (Bogaert et al. 2017). However, in BioSustain the use of agricultural land for the production of lignocellulosic energy crops is assumed.

The selection of a crop to obtain the highest biomass potential for a specific location depends entirely on the crop phenological characteristics and the local biophysical conditions. This emphasises the importance of considering location specific biophysical conditions for the assessment of biomass potentials and LUC related environmental impacts. Three key factors dictate the increase in biomass potentials over time. (1) LUC dynamics determine the availability of marginal land that meets RED II sustainability criteria for different points in time. (2) Variations in climate conditions, mainly temperature and precipitation result in an increase in suitable land for lignocellulosic energy crop production. (3) The 1 % annual yield increase assumed for improvement in crops management over time.

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The climate projections from the HadGEM2-ES RCP 4.5 scenario were used as key input to determine biomass potentials and LUC related impacts. The results of this report would likely change for different RCP's. However, no big differences are expected, as in the short term there is no large variation between scenarios (Collins et al. 2013). At longer times scales, i.e. after 2050, the differences between scenario projections become considerable and could lead to strong differences in biomass potentials and potential LUC-related environmental impacts of lignocellulosic energy crop production.

In addition, the accessibility to certain areas was not considered. For example, some areas that are considered suitable for the potential production of lignocellulosic energy crop are difficult to access. The potential production in such areas can be unsuitably given accessibility conditions and not suitability conditions. The inaccessibility of production areas could also result in a reduction of biomass potentials. Furthermore, it must be considered that the potentially available biomass disregards the readability to supply to end-use-markets. The supply of large biomass volumes to the markets will require a considerable amount of time to scale up logistics and processing capacity.

4.3. Environmental impacts

On average, the potential production of lignocellulosic energy crops on marginal lands under RED II sustainability constrains results in net carbon sequestration. However, there are also locations where LUC-related CO_2 emissions are projected to occur. The average carbon sequestration varies between -7.1 t CO_2/ha year and -0.23 t CO_2/ha depending on the crop type. Generally, woody crops store more carbon in the biomass and SOC pools than grassy crops. Woody crops accumulate carbon for several years given their harvest cycle. It is projected that the potential production of lignocellulosic energy crops in EU-26 can contribute to mitigate between 20 to 26 million t CO_2/year by carbon sequestration in biomass and soils. In 2018, the total GHG emissions from Europe were 4473 million t CO_2 (EEA 2019a). When considering the total savings projected for 2020 (20 million t CO_2/year), the potential production of lignocellulosic energy crops could reduce in less than 1 % the European GHG emissions from 2018. Despite that this reduction seems minimal, GHG emissions in Europe fell only by 2 % from 2017 to 2018 (EEA 2019a). However, it must be highlighted that the GHG savings from the potential production of lignocellulosic energy crops is considering only the carbon sequestration in biomass and soils, most of the GHG savings will potentially come from the replacement of fossil fuels with advance fuels.

In the calculation of LUC-related carbon emissions from lignocellulosic energy crop production, fertilizer-induced N_2O emissions were not considered as the scope of the study was strictly

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limited to LUC-related impacts. However, the use of fertilizers for crop production can lead to considerable GHG emissions (Dias and Arroja 2012; IPCC 2006; Morales et al. 2015; Murphy et al. 2013; Porsö and Hansson 2014). Including the impact of fertilizer application in the greenhouse gas emissions, could partly offset the LUC related carbon sequestration. However, fertilizer requirements of lignocellulosic energy crops are generally relatively low. Linking the spatially explicit analysis of LUC-related GHG emissions to a lifecycle assessment including all emissions of the supply chain (cultivation, transport and storage and conversion), would allow for the quantification overall GHG mitigation potential of advance fuels of lignocellulosic energy crops.

The production of all types of lignocellulosic energy crops results in a water deficit during the crop growth season, i.e. additional water is required to obtain potential yields. Still, in some areas precipitation levels are sufficient. The average water deficit varies between 327 mm/year and 1071 mm/year depending on the crop. For the least water deficit potential, Cardoon is mostly preferred over other crops types. However, Cardoon is one of the crops with the lowest average yield. In Europe, 65,000 million m^3 of water is used in agriculture; this corresponds to 59% of the total fresh water use (EEA 2019b). Most of the water is used for irrigation, while irrigated areas cover only about 8% of the agricultural land (10.2 million ha in 2017) (EEA 2019b). Abound 80% of the irrigated land is located in southern Europe which is characterized by dry conditions. Accordingly, approximately 6300 m^3/ha year of water are allocated for irrigation in Europe. The potential production of lignocellulosic energy crop could require on average between 5170 m^3/ha year (depending of relevant point in time). A portion of this water demand would need to cover by irrigation; this could potentially increase the total European water demand allocated for irrigation. The high-water requirements for the potential production of lignocellulosic energy crops is partly driven by the high land availability for energy crops in southern Europe.

Water deficit was estimated as a function of the potential production of lignocellulosic energy crop on available marginal land and was not quantified as the change compared to the water consumption of the land use/cover prior to conversion, as done for the other impacts. The water deficit is a good proxy to determine the additional water needed for crop growth but lacks a direct indicator to understand the impacts on local ground water tables and discharge as a consequence of the additional water use.

In general, there is an increase in potential soil loss when marginal land is converted to lignocellulosic energy crops. Still, there are locations where higher potential soil losses are reported for the original land use/cover of marginal land. The average change in soil loss varies between 4.5 t/ha year and 7.5 t/ha year depending on the crop type. The change in potential soil loss is largely affected by the type of land use/cover prior to conversion. The conversion of shrublands

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to lignocellulosic energy crops generally results in an increase in potential soils loss. The most recent estimates in Europe for soil loss report an average loss of 2.46 t/ha year for arable lands and 9.47 t/ha year for permanent crops such as vineyards and olive trees (Panagos et al. 2015c). In addition, more than 4 million ha of arable lands report soil losses of >5 t/ha year which is considered unsustainable (Panagos et al. 2015c). The potential increase in soil loss of lignocellulosic energy crop production is on average close or slightly above the considered threshold of unsustainable soil loss (> 5 t/ha year)

For the calculation of potential soil loss, the C (cover management) factor of the RUSLE equation was assigned to each lignocellulosic energy crop based on similar land uses considered in Panagos et al (2015b). This resulted in a single C actor for all grassy lignocellulosic energy crops and one for all woody lignocellulosic energy crops. However, there is difference in cover between the crops that could potentially results in differences in potential soil losses. In addition, no support practices were considered (P factor). Including support practices could reduce potential soil loss of lignocellulosic energy crop production on marginal lands.

4.4. Further research

The yield efficient biomass potential is higher than the maximum carbon biomass potential, the least water efficient biomass potential, or the lowest erosion risk biomass potential. Also, depending on the criterion, a different crop is selected for each location. This means that there will be trade-offs between the biomass potentials and the various environmental impacts. Quantifying these impacts and quantifying the synergies and trade-offs between those impacts will contribute to informed decision making on the sustainable land use for lignocellulosic energy crops. Combining this spatially explicit assessment on environmental impacts with a lifecycle approach on advance fuel production could help to identify the environmental impacts of the total lifecycle and the GHG mitigation potentials of advanced fuels compared to fossil fuels and to other renewable alternatives.

The cost of production for different crops types was not considered. The biomass production cost and the competitiveness of the different crop types will vary and will affect what crops are selected by a farmer to be produced. Combining spatially explicit cost assessment of biomass production with a techno-economic analysis of advanced biofuel supply chains, could contribute to identify hotspots for viable advanced biofuel production.

The potential production of lignocellulosic energy crops on marginal lands can cover to some extent future bioenergy demand. However, the deployment of such production should be done with care. Despite that it can contribute towards EU GHG emissions reduction targets it can also

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generate considerable impacts in other areas. The implementation of lignocellulosic energy crops production in marginal land will require demanding location specific measures that promote an efficient use of water and include support practices targeted to reduce soil loss. In addition, considerable support from the government would be required to support farmers and implement location specific measures to reduce potential environmental impacts. This study shows that smart choices on location and crop type for lignocellulosic energy crop production can be made to enable sustainable biomass production in Europe under RED II sustainability criteria

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N.º764799.

5. References

Abrahão R, García-Garizábal I, Merchán D, Causapé J. Climate change and the water cycle in newly irrigated areas. Environ. Monit. Assess. [Internet]. 2015;187(2):22. Available from: https://doi.org/10.1007/s10661-014-4260-1

Alexander P, Prestele R, Verburg PH, Arneth A, Baranzelli C, Batista e Silva F, et al. Assessing uncertainties in land cover projections. Glob. Chang. Biol. [Internet]. John Wiley & Sons, Ltd; 2017 Feb 1;23(2):767–81. Available from: https://doi.org/10.1111/gcb.13447

Allen B, Kretschmer B, Baldock D. Space for energy crops–assessing the potential contribution to Europe's energy future. LinkServID= F6E6DA60-5056-B741-DBD250D05D441B53. 2014;
Baranzelli C, Jacobs-Crisioni C, e Silva FB, Castillo CP, Barbosa A, Torres JA, et al. The Reference scenario in the LUISA platform–Updated configuration 2014. 2015a;.

Baranzelli C, Perpiña Castillo C, Lavalle C, Pilli R, Fiorese G. Evaluation of the land demands for the production of food, feed and energy in the updated Reference Configuration 2014 of the LUISA modelling platform. Methodol. Framew. Prelim. considerations.. EUR. 2015b;27018.

Benavidez R, Jackson B, Maxwell D, Norton K. A review of the (Revised) Universal Soil Loss Equation ((R) USLE): with a view to increasing its global applicability and improving soil loss estimates. Hydrol. Earth Syst. Sci. Copernicus GmbH; 2018;22(11):6059–86.

Bogaert S, Pelkmans L, van den Heuvel E, Devriendt N, De Regel S, Hoefnagels R, et al. Sustainable and optimal use of biomass for energy in the EU beyond 2020-Final Report To EC Directorate General for Energy Directorate C1–Renewables and CCS policy.

PricewaterhouseCoopers EU Serv. EESV's consortium, Brussels. 2017;

Bolinder MA, Angers DA, Bélanger G, Michaud R, Laverdière MR. Root biomass and shoot to root ratios of perennial forage crops in eastern Canada. Can. J. Plant Sci. NRC Research Press; 2002;82(4):731–7.

Bowden R, Wayman S, Ernst CL, Mitchell R. Aboveground and belowground biomass and nitrogen retranslocation in switchgrass (panicum virgatum). Proc. ASA, CSSA SSSA. 2010;
Brouwer C, Heibloem M. Irrigation water management: irrigation water needs. Train. Man. 1986;3.

Collins M, Knutti R, Arblaster J, Dufresne J-L, Fichefet T, Friedlingstein P, et al. Long-term climate change: projections, commitments and irreversibility. Clim. Chang. 2013-The Phys. Sci. Basis Contrib. Work. Gr. I to Fifth Assess. Rep. Intergov. Panel Clim. Chang. Cambridge University Press; 2013. p. 1029–136.

Creutzig F, Ravindranath NH, Berndes G, Bolwig S, Bright R, Cherubini F, et al. Bioenergy and climate change mitigation: an assessment. GCB Bioenergy [Internet]. John Wiley & Sons, Ltd (10.1111); 2015 Sep 1;7(5):916–44. Available from: https://doi.org/10.1111/gcbb.12205
Dees M, Elbersen B, Fitzgerald J, Vis M, Anttila P, Forsell N, et al. A spatial data base on sustainable biomass cost-supply of lignocellulosic biomass in Europe-methods & data

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N.°764799.

sources. University of Freiburg; 2017;

Dias AC, Arroja L. Environmental impacts of eucalypt and maritime pine wood production in Portugal. J. Clean. Prod. Elsevier; 2012;37:368–76.

Dias GM, Ayer NW, Kariyapperuma K, Thevathasan N, Gordon A, Sidders D, et al. Life cycle assessment of thermal energy production from short-rotation willow biomass in Southern Ontario, Canada. Appl. Energy [Internet]. Elsevier; 2017 Oct 15 [cited 2019 Aug 6];204:343–52. Available from: https://www.sciencedirect.com/science/article/pii/S0306261917309261

Dohleman FG, Heaton EA, Arundale RA, Long SP. Seasonal dynamics of above- and below-ground biomass and nitrogen partitioning in Miscanthus × giganteus and Panicum virgatum across three growing seasons. GCB Bioenergy [Internet]. John Wiley & Sons, Ltd (10.1111); 2012 Sep 1;4(5):534–44. Available from: https://doi.org/10.1111/j.1757-1707.2011.01153.x

Doorenbos J, Kassam AH. Yield response to water. Irrig. Drain. Pap. 1979;33:257.

Dušek J, Květ J. Seasonal dynamics of dry weight, growth rate and root/shoot ratio in different aged seedlings of Salix caprea. Biologia (Bratisl). [Internet]. 2006;61(4):441. Available from: https://doi.org/10.2478/s11756-006-0074-0

EEA. CLC 2018 [Internet]. 2018 [cited 2019 Jun 27]. Available from: https://land.copernicus.eu/pan-european/corine-land-cover/clc2018?tab=download

EEA. Total greenhouse gas emission trends and projections in Europe. 2019a;. Available from: https://www.eea.europa.eu/downloads/6f120fbcec964495b3c693f5f0a635c0/1576746405/assessment-3.pdf

EEA. Use of freshwater resources in Europe. 2019b;. Available from: https://www.eea.europa.eu/downloads/fc19dd26f36c4b1aae9a887fe4b3f8e3/1578392729/assessment-4.pdf

Elbersen B, Eupen van E, Mantel S, Verzandvoort S, Boogaard H, Mucher S, et al. Deliverable 2.6 Methodological approaches to identify and map marginal land suitable for industrial crops in Europe. 2017.

European Parlament. Directive (EU) 2018/2001 of the European parliament and of the council of 11 December 2018 on the promotion of the use of energy from renewable sources. Off. J. Eur. Union [Internet]. 2018;128. Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L2001&from=EN

FAO. Agro-ecological zoning: Guidelines. Food & Agriculture Org.; 1996.

Fischer G, Prieler S, van Velthuizen H, Berndes G, Faaij A, de Wit M. Biofuel production potentials in Europe: Sustainable use of cultivated land and pastures, Part II: Land use scenarios. Biomass and Bioenergy [Internet]. Pergamon; 2010 Feb 1 [cited 2019 Dec 4];34(2):173–87. Available from: https://www.sciencedirect.com/science/article/pii/S0961953409001470

Frank AB, Berdahl JD, Hanson JD, Liebig MA, Johnson HA. Biomass and carbon partitioning in switchgrass. Crop Sci. Crop Science Society of America; 2004;44(4):1391–6.
Haberl H, Beringer T, Bhattacharya SC, Erb K-H, Hoogwijk M. The global technical potential of bio-energy in 2050 considering sustainability constraints. Curr. Opin. Environ. Sustain. [Internet]. Elsevier; 2010 Dec 1 [cited 2019 Dec 9];2(5–6):394–403. Available from: https://www.sciencedirect.com/science/article/pii/S1877343510001132

Heilman PE, Ekuan G, Fogle D. Above-and below-ground biomass and fine roots of 4-year-old hybrids of Populus trichocarpa× Populus deltoides and parental species in short-rotation culture. Can. J. For. Res. NRC Research Press; 1994;24(6):1186–92.

Heller MC, Keoleian GA, Volk TA. Life cycle assessment of a willow bioenergy cropping system. Biomass and Bioenergy [Internet]. Pergamon; 2003 Aug 1 [cited 2019 Aug 6];25(2):147–65. Available from: https://www.sciencedirect.com/science/article/pii/S0961953402001903
van der Hilst F. Location, location, location. Nat. Energy [Internet]. 2018;3(3):164–5. Available from: https://doi.org/10.1038/s41560-018-0094-3

Hoefnagels R, Germer S. Supply potential, suitability and status of lignocellulosic feedstocks for advanced biofuels. 2020;

IPCC. 2006 IPCC guidelines for national greenhouse gas inventories [Internet]. 2006. Available from: https://www.ipcc-nggip.iges.or.jp/public/2006gl/

Junginger HM, Mai-Moulin T, Daioglou V, Fritsche U, Guisson R, Hennig C, et al. The future of biomass and bioenergy deployment and trade: a synthesis of 15 years IEA Bioenergy Task 40 on sustainable bioenergy trade. Biofuels, Bioprod. Biorefining. John Wiley & Sons, Ltd; 2019 Mar;13(2):247–66.

Kahle P, Beuch S, Boelcke B, Leinweber P, Schulten H-R. Cropping of Miscanthus in Central Europe: biomass production and influence on nutrients and soil organic matter. Eur. J. Agron. [Internet]. Elsevier; 2001 Nov 1 [cited 2019 Jul 22];15(3):171–84. Available from: https://www.sciencedirect.com/science/article/pii/S1161030101001022#TBL2

Kätterer T, Andrén O. Growth dynamics of reed canarygrass (Phalaris arundinacea L.) and its allocation of biomass and nitrogen below ground in a field receiving daily irrigation and fertilisation. Nutr. Cycl. Agroecosystems [Internet]. 1999;54(1):21–9. Available from: https://doi.org/10.1023/A:1009701422394

Kinnell PIA. Event soil loss, runoff and the Universal Soil Loss Equation family of models: A review. J. Hydrol. Elsevier; 2010;385(1–4):384–97.

Kluts I, Wicke B, Leemans R, Faaij A. Sustainability constraints in determining European bioenergy potential: A review of existing studies and steps forward. Renew. Sustain. Energy Rev. [Internet]. Pergamon; 2017 Mar 1 [cited 2019 Dec 9];69:719–34. Available from: https://www.sciencedirect.com/science/article/pii/S1364032116307638#bib29

Lavalle C. OUTPUT - Land-use/cover maps (LUISA Platform REF2014) [Internet]. European Commission, Joint Research Centre (JRC); 2014. Available from: http://data.europa.eu/89h/jrc-luisa-land-use-ref-2014

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N.°764799.

Marin M, Ybarra M, Fé A, García-Férriz L. Effect of arbuscular mycorrhizal fungi and pesticides on Cynara cardunculus growth. MTT Agrifood Research Finland; 2002;

Mbow H-OP, Reisinger A, Canadell J, O'Brien P. Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems (SR2). 2017;

Mehmood MA, Ibrahim M, Rashid U, Nawaz M, Ali S, Hussain A, et al. Biomass production for bioenergy using marginal lands. Sustain. Prod. Consum. [Internet]. Elsevier; 2017 Jan 1 [cited 2020 Jan 2];9:3–21. Available from: https://www.sciencedirect.com/science/article/pii/S2352550916300197

MIGUEZ FE, ZHU X, HUMPHRIES S, BOLLERO GA, LONG SP. A semimechanistic model predicting the growth and production of the bioenergy crop Miscanthus×giganteus: description, parameterization and validation. GCB Bioenergy [Internet]. John Wiley & Sons, Ltd (10.1111); 2009 Aug 1;1(4):282–96. Available from: https://doi.org/10.1111/j.1757-1707.2009.01019.x

Milner S, Holland RA, Lovett A, Sunnenberg G, Hastings A, Smith P, et al. Potential impacts on ecosystem services of land use transitions to second-generation bioenergy crops in GB. GCB Bioenergy [Internet]. John Wiley & Sons, Ltd (10.1111); 2016 Mar 1;8(2):317–33. Available from: https://doi.org/10.1111/gcbb.12263

Monteith JL. Evaporation and environment. Symp. Soc. Exp. Biol. Cambridge University Press (CUP) Cambridge; 1965. p. 205–34.

Morales M, Aroca G, Rubilar R, Acuna E, Mola-Yudego B, González-García S. Cradle-to-gate life cycle assessment of Eucalyptus globulus short rotation plantations in Chile. J. Clean. Prod. Elsevier; 2015;99:239–49.

Morgan RPC, Nearing M. Handbook of erosion modelling. John Wiley & Sons; 2016.

Murphy F, Devlin G, McDonnell K. Miscanthus production and processing in Ireland: An analysis of energy requirements and environmental impacts. Renew. Sustain. Energy Rev. Elsevier; 2013;23:412–20.

Nassi o Di Nasso N, Roncucci N, Bonari E. Seasonal Dynamics of Aboveground and Belowground Biomass and Nutrient Accumulation and Remobilization in Giant Reed (Arundo donax L.): A Three-Year Study on Marginal Land. BioEnergy Res. [Internet]. 2013;6(2):725–36. Available from: https://doi.org/10.1007/s12155-012-9289-9

NASSO DI, NASSI O, Angelini LG, Bonari E. Improving energy crop cultivation in the Mediterranean region: nutrient content, uptake and nutrient use efficiency in giant reed (Arundo donax L.). 16th Nitrogen Work. Differ. scales nitrogen use Agric. Fiordo Tip. srl; 2009. p. 321–2.

Nsanganwimana F, Pourrut B, Mench M, Douay F. Suitability of Miscanthus species for managing inorganic and organic contaminated land and restoring ecosystem services. A review. J. Environ. Manage. [Internet]. Academic Press; 2014 Oct 1 [cited 2020 Feb 3];143:123–34. Available from: https://www.sciencedirect.com/science/article/pii/S0301479714002163

Oliveira N, Rodríguez-Soalleiro R, Pérez-Cruzado C, Cañellas I, Sixto H, Ceulemans R. Above- and below-ground carbon accumulation and biomass allocation in poplar short rotation plantations under Mediterranean conditions. For. Ecol. Manage. [Internet]. Elsevier; 2018 Nov 15 [cited 2019 Aug 7];428:57–65. Available from: https://www.sciencedirect.com/science/article/pii/S0378112718308892

Pacaldo RS, Volk TA, Briggs RD. Greenhouse Gas Potentials of Shrub Willow Biomass Crops Based on Below- and Aboveground Biomass Inventory Along a 19-Year Chronosequence. BioEnergy Res. [Internet]. 2013;6(1):252–62. Available from: https://doi.org/10.1007/s12155-012-9250-y

Panagos P, Ballabio C, Meusburger K, Spinoni J, Alewell C, Borrelli P. Towards estimates of future rainfall erosivity in Europe based on REDES and WorldClim datasets. J. Hydrol. [Internet]. Elsevier; 2017 May 1 [cited 2020 Mar 17];548:251–62. Available from: https://www.sciencedirect.com/science/article/pii/S0022169417301439

Panagos P, Borrelli P, Meusburger K. A new European slope length and steepness factor (LS-Factor) for modeling soil erosion by water. Geosciences. Multidisciplinary Digital Publishing Institute; 2015a;5(2):117–26.

Panagos P, Borrelli P, Meusburger K, Alewell C, Lugato E, Montanarella L. Estimating the soil erosion cover-management factor at the European scale. Land use policy [Internet].

Pergamon; 2015b Nov 1 [cited 2020 Mar 17];48:38–50. Available from: https://www.sciencedirect.com/science/article/pii/S0264837715001611#sec0070

Panagos P, Borrelli P, Poesen J, Ballabio C, Lugato E, Meusburger K, et al. The new assessment of soil loss by water erosion in Europe. Environ. Sci. Policy [Internet]. Elsevier; 2015c Dec 1 [cited 2020 Apr 7];54:438–47. Available from: https://www.sciencedirect.com/science/article/pii/S1462901115300654

Panagos P, Meusburger K, Ballabio C, Borrelli P, Alewell C. Soil erodibility in Europe: A high-resolution dataset based on LUCAS. Sci. Total Environ. Elsevier; 2014;479:189–200.

Paul E. Soil microbiology, ecology and biochemistry. Fourth edi. Academic Press; 2014.

Perpiña Castillo C, Lavalle C, Baranzelli C, Mubareka S. Modelling the spatial allocation of second-generation feedstock (lignocellulosic crops) in Europe. Int. J. Geogr. Inf. Sci. [Internet]. Taylor & Francis; 2015 Oct 3;29(10):1807–25. Available from: https://doi.org/10.1080/13658816.2015.1051486

Porsö C, Hansson P-A. Time-dependent climate impact of heat production from Swedish willow and poplar pellets – In a life cycle perspective. Biomass and Bioenergy [Internet].

Pergamon; 2014 Nov 1 [cited 2020 Mar 28];70:287–301. Available from: https://www.sciencedirect.com/science/article/pii/S0961953414004140#fig6

Proietti S, Moscatello S, Fagnano M, Fiorentino N, Impagliazzo A, Battistelli A. Chemical composition and yield of rhizome biomass of Arundo donax L. grown for biorefinery in the Mediterranean environment. Biomass and Bioenergy [Internet]. Pergamon; 2017 Dec 1 [cited

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N.°764799.

2019 Aug 7];107:191–7. Available from: https://www.sciencedirect.com/science/article/pii/S0961953417303197#bib19

Raccuia SA, Melilli MG. Cynara cardunculus L., a potential source of inulin in the Mediterranean environment: screening of genetic variability. Aust. J. Agric. Res. CSIRO; 2004;55(6):693–8.

Renard KG, Foster GR, Weesies GA, McCool DK, Yoder DC. Predicting soil erosion by water: a guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE). United States Department of Agriculture Washington, DC; 1997.

Richter GM, Agostini F, Redmile-Gordon M, White R, Goulding KWT. Sequestration of C in soils under Miscanthus can be marginal and is affected by genotype-specific root distribution. Agric. Ecosyst. Environ. [Internet]. Elsevier; 2015 Feb 1 [cited 2019 Oct 31];200:169–77. Available from: https://www.sciencedirect.com/science/article/pii/S016788091400512X?via%3Dihub

Rogelj J, Shindell D, Jiang K, Fifita S, Forster P, Ginzburg V, et al. Mitigation pathways compatible with 1.5 C in the context of sustainable development. Intergovernmental Panel on Climate Change; 2018;

Ruiz P, Sgobbi A, Nijs W, Thiel C, Dalla Longa F, Kober T, et al. The JRC-EU-TIMES model. Bioenergy potentials for EU and neighbouring countries. JRC Sci. Policy Report, Eur. Comm. 2015;

Smith P, House JI, Bustamante M, Sobocká J, Harper R, Pan G, et al. Global change pressures on soils from land use and management. Glob. Chang. Biol. [Internet]. John Wiley & Sons, Ltd (10.1111); 2016 Mar 1;22(3):1008–28. Available from: https://doi.org/10.1111/gcb.13068

Sterling SM, Ducharne A, Polcher J. The impact of global land-cover change on the terrestrial water cycle. Nat. Clim. Chang. [Internet]. Nature Publishing Group; 2012 Oct 14;3:385. Available from: https://doi.org/10.1038/nclimate1690

Strullu L, Cadoux S, Preudhomme M, Jeuffroy M-H, Beaudoin N. Biomass production and nitrogen accumulation and remobilisation by Miscanthus × giganteus as influenced by nitrogen stocks in belowground organs. F. Crop. Res. [Internet]. Elsevier; 2011 Apr 3 [cited 2019 Jul 22];121(3):381–91. Available from: https://www.sciencedirect.com/science/article/pii/S0378429011000256

Thomson AM, Calvin K V, Smith SJ, Kyle GP, Volke A, Patel P, et al. RCP4.5: a pathway for stabilization of radiative forcing by 2100. Clim. Change [Internet]. 2011;109(1):77. Available from: https://doi.org/10.1007/s10584-011-0151-4

Tóth G, Gardi C, Bódis K, Ivits É, Aksoy E, Jones A, et al. Continental-scale assessment of provisioning soil functions in Europe. Ecol. Process. [Internet]. 2013;2(1):32. Available from: https://doi.org/10.1186/2192-1709-2-32

UNFCCC. ADOPTION OF THE PARIS AGREEMENT [Internet]. 2015. Available from: https://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf

Valentine J, Clifton-Brown J, Hastings A, Robson P, Allison G, Smith P. Food vs. fuel: the use of land for lignocellulosic 'next generation' energy crops that minimize competition with primary food production. GCB Bioenergy [Internet]. John Wiley & Sons, Ltd (10.1111); 2012 Jan 1;4(1):1–19. Available from: https://doi.org/10.1111/j.1757-1707.2011.01111.x

Van Der Hilst F, Hoefnagels R, Londo M. Biomass Provision and Use: Sustainability Aspects: A Volume in the Encyclopedia of Sustainability Science and Technology, Second Edition Alternative Jet Fuels View project S2Biom View project. 2018;

Vogel E, Deumlich D, Kaupenjohann M. Bioenergy maize and soil erosion — Risk assessment and erosion control concepts. Geoderma [Internet]. Elsevier; 2016 Jan 1 [cited 2019 Dec 13];261:80–92. Available from:
https://www.sciencedirect.com/science/article/pii/S0016706115300070
Warszawski L, Frieler K, Huber V, Piontek F, Serdeczny O, Schewe J. The inter-sectoral impact model intercomparison project (ISI–MIP): project framework. Proc. Natl. Acad. Sci. National Acad Sciences; 2014;111(9):3228–32.

Wischmeier WH, Smith DD. Predicting rainfall erosion losses - a guide to conservation planning. Hyattsville, Maryland: USDA, Science and Education Administration; 1978.
De Wit M, Faaij A. European biomass resource potential and costs. Biomass and bioenergy. Elsevier; 2010;34(2):188–202.

Annex

Land use/cover classification

Table 1 Description of the Land use/cover categories distinguished in this report and the disaggregation/aggregation process with LUISA and CLC land use/cover categories

Land use/cover categories classification for this report	LUISA land use/cover categories	Corine land cover land use/cover categories	Description of aggregation/disaggregation process
1. Artificial	• 1. Urban • 2.Industry, Commercial and Services • 7. Infrastructures • 10. Urban green leisure	Not included for the aggregation/disaggregation process	Aggregation of LUISA categories: "1. Urban", "2. Industry, Commercial and Services", "7. Infrastructures" and "10. Urban green leisure"
2. Agriculture	• 3. Agriculture	Not included for the aggregation/disaggregation process	Corresponds with LUISA category: "3. Agriculture"
3. Forest	• 4.Forest/Transitional woodland-shrubland	• 3.1.1 Broad leaved forest • 3.1.2 Coniferous forest	Category "3. Forest" is disaggregated from LUISA category "4. Forest/Transitional woodland-shrubland". By implementing a layover analysis, it was assumed that land under the forest classification in

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		• 3.1.3 Mixed forest	CLC 2018 (categories 3.1.1, 3.1.2 and 3.1.3) is kept constant over time, towards 2050. Therefore, all area classified as forest in CLC 2018 that overlaps with category "4. Forest/Transitional woodland-shrubland" in LUISA 2020, 2030, 2040, and 2050 is considered category "3. Forest". The remaining area classified as "4. Forest/Transitional woodland-shrubland" that does not overlap with the forest category from CLC 2018 is considered category "8. shrubland"
4.Natural grassland	• 6. Natural land	• 3.2.1 Natural grassland • 3.2.2 Moors and heathland • 3.2.3 Sclerophyllous vegetation • 3.3.1 Beaches-	Category "4. Natural grasslands" (valid for this report) is disaggregated from LUISA category: "6. Natural land"; this category aggregates "3.2.1 Natural grasslands", " 3.2.2 Moors and heathland", "3.2.3 Sclerophyllous vegetation", "3.3.1 Beaches-dunes-sands", " 3.3.2 Bare rocks", "3.3.3 Sparsely vegetated areas", " 3.3.4 Burnt areas" and "3.3.5 Glaciers and perpetual snow" from the CLC 2018 classification.

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		dunes-sands • 3.3.2 Bare rocks" • 3.3.3 Sparsely vegetated areas • 3.3.4 Burnt areas • 3.3.5 Glaciers and perpetual snow"	First, CLC 2018 categories "3.3.1 Beaches-dunes-sands", "3.3.2 Bare rocks" and "3.3.5 Glaciers and perpetual snow" that overlap with category "6. Natural land" in LUISA 2020, 2030, 2040, and 2050 are defined for this report as category "9. Open space not suitable" (land with physical constrain that not allows for ligno-cellulosic energy crops production). Second, a similar assumption is considered for categories " 3.2.2 Moors and heathland", "3.2.3 Sclerophyllous vegetation", " 3.3.3 Sparsely vegetated areas" and "3.3.4 Burnt areas". The land under the mentioned categories classification that overlaps with category "6. Natural land" in LUISA 2020, 2030, 2040, and 2050 are defined for this report as category "10. Open space suitable" (land with no-physical constrain that allows for lignocellulosic energy crops production. Finally, it was considered that the newly aggre-

			gated categories for this report, "9. Open space not suitable" and "10. Open space suitable", are kept constant over time, towards 2050. The remaining area classified as "6. Natural land" that does not overlap with the newly aggregated categories ("9. Open space not suitable" and "10. Open space suitable") is considered category "4. Natural grassland"
5. Established dedicated crops[10]	• 5. New energy crops	Not included for the aggregation/disaggregation process	Category "5. New energy crops" from the LUISA data set corresponds to land dedicated to produce energy crops in accordance to the resources supply-demand modules in the LUISA model (Baranzelli, Perpiña Castillo, et al., 2015). However, despite that this land can be allocated for such production in LUISA, it can fail to meet this assessment marginality requirements and RED II sustainability criteria. Therefore, the LUC dynamics for this category

10 It is important to note that the breakdown of this category between abandoned land, other categories and energy crops has a minimal repercussion on the total amount of land that can be dedicated for lignocellulosic energy crops. According to LUISA projections, most of the land that is transformed towards the "New energy crops" category corresponds to agricultural land (here reported as abandoned land). Therefore, if such breakdown was not implemented the total reported land availability in the results section would not vary considerably. However, the breakdown is required to assess on higher accuracy the LUC-related environmental impacts, mainly LUC-related GHG emissions from lignocellulosic energy crops production (for more information see the LUC-related GHG emissions section)

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			were tracked retrospectively on time to identify the type of land use/cover that changed into category "5. New energy crops" and assure that RED II sustainability and marginality criteria were fulfilled. It was assumed that the formerly dedicated land for agriculture on a previous time step that changed in use towards "5. New energy crops" in the next time step, was denominated as agricultural abandoned land and is considered and reported as category "11. Abandoned land". When land remains in use for category "5. New energy crops" between time steps, then is considered category 5 Established dedicated crops (classification valid for this report). The rest of categories that change into category "5. New energy crops" over time in LUISA projections and lack of meeting RED II sustainability, marginality and/or land related constrains criteria were considered to remain in the use/cover of the time step

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			prior to conversion. For example, if land designated as forest in 2020 changes in use towards "5. New energy crops" in 2030 (according to LUISA projections), this land was assumed to remain as forest in 2030 as it not fulfils RED II sustainability criteria and reported as category "3. Forest" (valid for this report.
6. Wetlands	• 9. Wetlands	Not included for the aggregation/disaggregation process	Corresponds with LUISA category: "9. Wetlands"
7. Water bodies	• 10. Water	Not included for the aggregation/disaggregation process	Corresponds with LUISA category: "10. Water"
8. Shrublands	Please see category "3. Forest" description"		
9. Open space not suitable	Please see category "4. Natural grassland" description"		
10. Open space suitable	Please see category "4. Natural grassland" description"		
11. Abandoned land	Please see category "5. Established dedicated crops" description"		

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Biomass carbon stocks

Table 2. Spatially explicit calculation of biomass volumes of each land use/cover category

Land use/cover categories	Availability for production	Above ground biomass	Above to below ground biomass ratios	Carbon fraction
5. Established dedicated crops	Yes	Established spatially explicit dependent on land use prior to conversion[A]	Dependent on land use prior to conversion[A]	
8. Shrublands	Yes	Established spatially explicit[B]	2.8[C]	0.5[C]
10. Open space suitable	Yes	Established Spatially explicit[D]	Boreal/Cold temperate/Warm temperate – Wet = 4.0[C]	0.47[C]
			Cold temperate/Warm temperate/Tropical – Dry = 2.8[C]	
11. Abandoned land	Yes	Abandoned land: This land is assumed to be abandoned agricultural land from annual cropland and therefore to be allocated to energy crops recently after harvest. Therefore, it was assumed that little biomass was present in this category prior to conversion and the biomass carbon stock pool can be assumed as 0[C]		-

[A] See annex GHG emissions Established dedicated crops biomass

[B] See annex GHG emissions, Shrublands biomass

[C] (IPCC 2006)

[D] See annex GHG emissions, Open space suitable biomass

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SOC

Table 3 Relative SOC stock change factors valid for each land use/cover category, derived from (IPCC 2006)

Land use/cover categories	Climate region	Relative stock change factors in accordance to IPCC		
		F_{LU}	F_{MG}	F_{I}
8. Shrublands [A]		1[B]	1[C]	1[D]
10. Open space suitable [E]	Temperate/Boreal climates	1[B]	0.95[F]	1[D]
	Tropical		0.97 [F]	
11. Abandoned land [G]	Temperate/Boreal dry	0.80[H]	1[I]	1.04[J]
	Temperate/Boreal moist / tropical wet	0.69[H]		1.11[J]
	Tropical dry	0.58 [H]		1.04 [J]
Lignocellulosic energy crops (grasses)	Temperate/Boreal dry	0.93[k]	1.02[L]	1[M]
	Temperate/Boreal and tropical wet	0.82[k]	1.08[L]	
	Tropical dry	0.93[k]	1.09[L]	
Lignocellulosic energy crops (woody)	Temperate/Boreal dry	1[N]	1.02[L]	1[M]
	Temperate/Boreal wet		1.08[L]	
	Tropical dry		1.09[L]	

[A] All stock change factors for Shrubland are assigned from IPCC chapter 6 Grasslands given that there are no specific values for Shrubland

[B] Value for all permanent grasslands

[C] Value for non-degraded without significant management improvements

[D] Value for grasslands where no additional management inputs have been used

[E] All stock change factors for Open space suitable are assigned from IPCC chapter 6 Grasslands given that this land use/cover definition includes a like habitat such as moors or and heathland

[F] This category includes burnt areas and areas where grazing has occurred. Therefore, the value for moderately degraded grassland was applied. The Climate zone tropical is very limited to a few areas in the south of Europe.

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[G] This category is assumed to be abandoned agricultural land that has been under the use of annual cropland (for long term) and to be available for energy crops allocation recently after harvest. Therefore, stock change factors for this category are assigned based on IPCC annual cropland default values.
[H] Values for areas that have been continuously managed to predominantly annual crops
[I] Tillage practices are assumed to take place to produce annual crops
[J] Given the difficulty to cover the different annual crops types and used inputs for each of them. It was assumed a high input factor.
[K] Value for perennial grasses
[L] Given these crops managements characteristics full till is not needed (Perpiña Castillo et al. 2015) and therefore, reduce till with little soils disturbance is considered
[M] It was considered that after harvesting the residues are left on the field and no additional organic matter is needed (in line with the biomass section). Value for crops with medium input
[N] Value for Long-term perennial tree crops

GHG emissions

Established dedicated crops

The biomass for this category was assigned in relation to the land/use cover prior to conversion following the same assumptions described in the land availability section:

- Established dedicated crops: It can be assumed that land remaining over time under the same category has a biomass net balance of 0 (IPCC 2006)
- Shrubland: See annex GHG emissions, Shrublands biomass
- Open space suitable: See annex GHG emissions, Open space suitable biomass

Shrubland biomass

The grasslands soil productivity map and IPCC default biomass stocks present on grasslands coefficients (climate zone dependent) were used as a proxy indicator to estimate spatially explicit above ground biomass for the shrubland category. This approach was employed given the lack of biomass spatially explicit shrubland detail data. With an overlay assessment and based on proximity, soil productivity values were assigned to each shrubland area from the grassland soil productivity map. Then, considering IPCC climatic zones, the maximum soil productivity values for each climatic zone were identified. These values were assumed to be correlated with the IPCC climate zone specific peak above ground biomass coefficients. The shrubland above ground biomass was determined from each location specific soil productivity value by considering the established link between maximum soil productivity and peak biomass coefficients. Total biomass was obtained by applying a 2.8 ratio from below to above ground biomass ratio (IPCC 2006).

Open space suitable

Given the definition for this category (see available land section), the grasslands soil productivity map and IPCC default biomass stocks present on grasslands coefficients (climate zone dependent) were used as a proxy indicator to estimate spatially explicit above ground biomass for this

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category. The same approach as the one taken for the shrubland category was applied. Different from the approach taken for the shrubland category, the above to below ground biomass ratios for this category are climate dependent (IPCC 2006) .

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