Marginal lands for Growing Industrial Crops

D.5.2 – High Resolution Maps of Potential Biomass Supply from Marginal Lands around a Biorefinery

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Responsible Author

S. Njakou Djomo	INRAE	sylvestre.njakou-djomo@inrae.fr	Telephone
B. Gabrielle	AgroParisTech	benoit.gabrielle@agroparistech.fr	Telephone
I. Staritsky	WUR	igor.staritsky@wur.nl	Telephone
B. Elbersen	WUR	berien.elbersen@wur.nl	Telephone
B. Annevelink	WUR	bert.annevelink@wur.nl	Telephone

Additional Authors

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Publishable executive summary

This report presents the intermediate results of the "MAGIC" project regarding the modelling of supply chain logistics in the context of three demand-driven case-studies in France, Spain and Romania, respectively. These cases correspond to the three agro-ecological zones delineated in MAGIC across Europe, and involve two target value-chains: the pyrolysis of lignocellulosic feedstocks and the conversion of plant oil to a range of bio-based polymers. This report focuses on assessing the potential marginal lands along with the potential yields of energy crops grown on these lands. It also quantifies the amount of residues available in these agro-ecological zones for the supply of additional biomass to a biorefinery project. The objectives of this report are: *(i)* to identify and estimate potential marginal lands suitable for energy crops production at regional scale in three agro-ecological zones in Europe; *(ii)* to simulate the yields and to map the distribution of suitable energy crops on these lands; *(iii)* to quantify and to map agricultural and forest residues that could serve as additional biomass sources in each region.

To reach these objectives three cases studies were chosen across three EU countries for investigating and demonstrating the practical applicability of bioenergy production on marginal lands, which in this context are defined as lands not used for agricultural production, residential and other purposes. These cases were applied to fours contrasting energy crops (miscanthus, tall wheatgrass, Siberian elm, and castor bean) and two types of residues (from agriculture and forestry). The French case (case study #1) focuses on the production of miscanthus on marginal lands in Brittany, and on the assessment of agricultural residues available for biorefinery in the region. The Spanish case (case study #2) deals with the production of tall wheatgrass and/or Siberian elm on marginal lands in Soria, it also assesses the agricultural and forest residues available for biorefinery in Soria. Finally, the Romania case (case study #3) addresses the production of castor bean on marginal lands around the city of Cluj for the production of biomaterials. The three case studies represent the different types of marginal lands as well as different climate regimes across Europe.

The French case focuses on quantifying the biomass potential from marginal lands and the amount of agricultural residues that could supply a pyrolysis plant in Brittany. Brittany has limited land resources; therefore, the region must rely on agricultural residues and energy crops from marginal lands for the the development of its biorefinery industries. The objectives of this case study were: *(a)* to estimate the potential marginal land in Brittany, *(b)* to assess the yields of miscanthus on these lands, *(c)* to quantify the additional biomass from agricultural residues that can complement miscanthus in Brittany. We first identified, quantify and mapped the potential marginal lands in Brittany using land cover and land use history, biophysical attributes, and the geographical information system. We then used the agro-ecosystem model CERES-EGC to simulate the yields of miscanthus on these marginal lands. After validation of this model with different climatic condition in Western Europe, it was used to simulate miscanthus yields on marginal lands in Brittany. The amount of agricultural residues (theoretical) from the three main crops (wheat, corn, and rapeseed) in Brittany was quantified considering: (*i*) types of crop and the area of crop production, (*ii*) yields of crops, (*iii*) residue-to-grain ratios. Thereafter a set of environmental and socio-economic constraints, as well as the competing uses limiting the availability of these residues were applied to the theorethical potential in order to derive the available agricultural residues bioenergy. Data on crop production originated from the national agricultural statistics. These data were supplemented with data on residue-to-grain ratio, residues removal rates, and the competing uses data collected from the literature. Finally, detailed spatial distribution maps of both miscanthus and agricultural residues in Brittany were made using ArcGis software.

Results show that about 57,744 ha marginal lands are available in Brittany. This represents about 3% of the total utilizable agricultural area in the region. Most of these lands are located in the Ile-et-Vilaine department with 32695 ha while the Côte d' Amor is the department with little marginal lands (3448 ha) in Brittany. Crop rooting constraint arising from low rootable soil volume or unfavorable soil texture was the dominant limiting factor, followed by chemical limitations, mainly salinity. Miscanthus yields on these lands range from 2-10 ton dry matter (DM) $ha^{-1}yr^{-1}$, with an average of 6.2 ton $ha^{-1}yr^{-1}$. Total miscanthus biomass from marginal lands in Brittany amount to 351 kton yr^{-1}, sufficient to supply up to 10 pyrolysis plants with a demand of 25 kton DM yr^{-1}. Unlike maginal lands that are concentrated in one department, agricultural residues were fairly distributed in Brittany with comparable volumes in each department. The potential supply residues totalled 9,293 kton DM yr^{-1}, however when sustainability constraints were considered, this total potential dropped to 5,627 kton yr^{-1} by 40%. Corn stover was the prominent source of residues followed by wheat straw; together these two residues source represented 99% of the available residues in Brittany. Overall, our analysis showed that Brittany has sufficient biomass potential for biorefinery development in the region. It also pointed out that the ideal location of biorefinery plant could be the department of Ile-et-Vilaine because of it larges biomass concentration. The development of a biorefinery plant such as Empyro in Brittany should have a positive impact for farmers, as it will bring additional income. Howver, consistent biomass supply volumes and feedstock prices are required for the development and expansion of biorefineries in Brittany.

The Spanish case assesses the biomass potential from marginal lands as well as from agricultural and forest residues for biorefinery development in Soria. Similar to the French case, the purpose of this case study were *(a)* to estimate the potential marginal lands in Soria, *(b)* to assess the productivity and yields of tall wheatgrass and Siberian elm on these lands, *(c)* to estimate forest and agricultural residues that can complement tall wheatgrass in Soria. Using land cover and land use history, biophysical factors and the ArcGIS software, we identified and mapped marginal land in the province of Soria. Then the CERES-EGC model was used to predict the yields of tall wheatgrass as well as those of Siberian elm on these marginal lands. ArcGIS was used to maps the yields distribution of these energy crops on marginal lands in Soria. Agricultural residues in Soria were quantified and mapped using similar approach as in the French case study. Data on crops production in Soria originated from the annual agricultural statistics published by the Spanish ministry of agriculture, whereas data on product-to-residue ratios and recoverable residues were collected from the literature. To compute and map the theoretical and available forest residues, we first classified the forest cover within Soria, and then estimated the theoretical forest residue potential at regional level. In a third step, we applied to the theoretical amount of residues a series of economic, management, and environmental factors which limit the availability of forest residues to quantify the available forest residues. Finally, we applied the ArcGIS tool to distribute spatially the theoretical and available biomass in Soria. Data for forest estimates and marketable wood were derived from the Spanish National Forest Inventory. Data for wood-to-residue-ratio, and the net wood increaments were taken from the literature.

Results showed that there are about 376,500 ha (3765 km^2) marginal lands potentially suitable for energy crops cultivation in the province of Soria. This represents about 37% of the total croplands in this region. Here also, rooting was the most dominant marginality factors followed by fertility and climate, which occurred in combination with rooting limitations. All together, these factors contributed more than 98% to the marginality limitations in Soria. Unlike in the Brittany case, salinity has little to no influence in Soria. The biomass yields of tall wheatgrass on these lands ranged from 3.1 to 4.3 tons DM ha^{-1}yr^{-1} with a mean yield of 3.8 tons ha^{-1}yr^{-1}. When Siberian elm was cultivated on these lands (instead of tall wsheatgrass), the biomass yields varied between 2.8 and 6.7 tons ha^{-1}yr^{-1}, with a mean yield of 4.2 tons ha^{-1}yr^{-1}. Consequently, between 1431 and 1582 kton yr^{-1} biomass could be produced each year on these lands depending on the adopted energy crop. Additonal available residues for bioenergy in this region was estimated at 549 kton yr^{-1}, of which 95% come from agricultural residues and the remaining fraction (5%) from forest residues. Cereal straw was the main agricultural residues in Soria whereas residues from coniferous forests were the major source of forest biomass in Soria. Overall, our assessment showed that Soria has limited residues potential, but its high marginal lands position this region as one of the main candidate for development and implementation of biorefinery in near future. The quantification of agricultural and forest residues as well as biomass from marginal lands provides grounds for the development of industrial crops in Brittany and Soria without relying too much on first generation crops. Policy towards second generation crops and energy prices will have significant impact on the amounts of agricultural/forest residues and biomass from marginal lands produced for second-generation bioenergy purpose. Since different biomass utilization concepts oppose each other, policy should promote the most efficient and advantageous biomass utilization concepts.

Regarding the third MAGIC case study in Romania, we could not quantify and map the marginal lands potential in Cluj (target area), nor model the productivity of castor bean on these lands as initially planned. However, works are underway to overcome the hurdles arising from the lack of data on land cover and land use transitions in this region. Mapping post-socialist land use/land cover changes based on satellite images is a solution in such case, and primitive map layers well suited for this purpose. Once maps of marginal land in Cluj have been made, they will serve as support for modelling the productivity of castor beans on marginal lands based on biophysical constraints. Contacts have been made with a local farmers' cooperative developing castor bean, and data were obtained in the summer of 2019 on the yield of native and modern, hybrid castor breeds.

1 Introduction

1.1 Background

Energy security and climate change are challenges faced by many countries around the world. Responding to these challenges the European Union (EU) has committed itself to increase the share of renewable energy in its energy supply mix. The RED II (2018) sets targets of 32% of energy from renewable sources across the EU by 2030. The corresponding greenhouse gas (GHG) emissions reduction target is 40% (with respect to 1990 levels), from 20% in 2020. Currently the EU is evaluating its 2050 decarbonization target to ensure that EU climate policy is in line with the Paris Agreement on climate change. Renewable energy sources provide a sustainable and clean energy sources, and improve the security and diversity of supply. Beside the ambitions for an increase in the share of renewable energy sources including biofuels, the EC bioeconomy strategy also specifies the EU ambition to build a carbon neutral future. This can be achieved by reducing the dependence on non-renewable energy (e.g. coal, oil, gas) and by using renewable feedstock such as biomass.This implies that the demand for biomass in orther sectors than the energy sector will also increase.

Among renewables, bioenergy is seen as the resource with the highest potential especially in the transport sector where the potential of other renewable energy sources such as sun and wind is more limited. Bioresources are evenly distributed around the globe than other renewable energy sources and thus offer more potential to reduce the dependency on energy import from a small number of countries and to increase local production of bioenergy. Bioenergy whether fuels, heat or power can generate additional income and employment and thus contribute to reducing poverty in rural areas (Bekunda et al. 2009). It has been argued that the large scale deployment of bioenergy combined with carbon capture and storage might be an option to achieve negative CO_2 emissions required to limit the global warming to 2 ºC until 2100 (Smith et al. 2016, Popp et al. 2014).

The decision to invest in bioenergy technologies requires a detailed knowledge of locally available biomass feedstock as well as its temporal variability. Biomass feedstock for bioenergy and biobased materials production includes food crops, residues, and energy crops. However, bioenergy (especially biofuels) is currently produced from food crops grown on croplands. This use of foodcrops for bioenergy production can increase the costs of food commodities (Johansson et al. 2007), or can result to the loss of natural ecosystems worldwide (Kim and Dale, 2004, Kluts et al. 2017). It has been shown that greater demands for energy crops result in increasing prices for other crops that must compete for the same land. Diverting food crops to bioenergy production has been blamed to cause deforestation around the world. To circumvent tension between food and energy production, the European Commission has proposed to use forest and agricultural residues for bioenergy, and to limit wherever possible, energy crops production on marginal lands.

Forest and agricultural residues are ideal bioresources that can contribute a significant fraction to the EU's bioenergy supply (Harrison et al. 2004, Panoutsou et al. 2017). Forest residues are non-merchantable woody biomass found in forests, wood waste from logging practices, while agricultural residues are the part of the plant that is left in the field after harvest, varying greatly in properties and decomposition rates (Lal, 2005). The production of both forest and agricultural residues does not compete with food production because they are co-production of wood and food-crop production (Townsend et al. 2017), and high level of wood and grain production do not have any negative effects in the utilization of these residues as bioresources. Forest and agricultural residues play a critical role in regulating market prices for agricultural crops that otherwise are not used for bioenergy. Their relative abundance and low costs particularly in forest and agriculture rich areas reduce the total production costs (Aleman-Nava et al. 2015, Ruiz et al. 2016). Leaving residues in the forests or in the farms cause significant GHG emissions because of decomposition, while fossil fuels are still being used (Gabrielle et al. 2015). Removal of these residues for bioenergy production would clearly prevent GHG emissions from residues decomposition while eliminating those from fossil fuels (Gan & Smith, 2007, Eriksson 2008, Hammar et al. 2015, Kilpolainen et al. 2016). The extraction of forest and agricultural residues does not threaten endangered species, biodiversity or soil nutrient balances, provided it is done in sustainable manner (Dahlberg et al. 2011). Removal of agricultural residues can also be beneficial for some crops as it may help to control pests and diseases and increase soil temperature in the sprint, thus facilitating seed germination (Anders, 2006).

To alleviate the dependency and pressures on forest and agricultural residues, marginal lands have been advocated and promoted as viable land resources for the cultivation of energy crops to supplement these residues. Indeed, the cultivation of marginal land is inevitable because of the shortage of prime agricultural lands in Europe and other parts of the world. Moreover, importing bioenergy feedstocks will not decrease energy dependence, and a large amount of arable land cannot be moved from food production to bioenergy production without endangering the food independency. Consequently, diversifying feedstock resources for bioenergy is necessary. Globally, ~1.3 billion hectares of marginal lands are theoretically available. For the EU28 the marginal land area has been mapped in Work Package 2 of the MAGIC project. It was estimated that around 29% of the agricultural land can be regarded as marginal which equals to about 69 million hectares (Elbersen et al. (2018). Part of these lands remain unused and may be used for biomass production. Even if only part of these lands can be used without competing with food production and other ecosystem services, it will offer a high potential for biomass production to meet the EU target of bioenergy.

Marginal lands refer to lands where biophysical, environmental, and socio-economic constraints hinder the cultivation of food/feed crops (Gopalakrishnan et al., 2011; Wiegmann et al., 2008). This includes idle/fallow croplands, abandoned/degraded lands, abandoned pastureland, and polluted lands (Cai et al., 2011; Gopalakrishnan et al., 2011). The definition of marginal lands in the literature is controversial and subject to a wide range of opinions and contexts. In this report marginal land is defined 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 as result of inappropriate human intervention'* (Elbersen et al. 2018). This definition was also followed when mapping the marginal lands in Work Package 2 of this project. Compared to croplands, marginal lands have lower yields due to its less fertile soils and often less favorable water, undesired topology, and other environmental conditions. Growing energy crops on these lands could sequester soil organic carbon, improve soil quality, reduce rates of erosion, increase agricultural productivity, and could help to restore the production potential of these lands (Lal 2009, Fischer 2010). Such a restoration would contribute to unlock the increased production of food and bioenergy feedstock from lands (Kidd et al. 2015). Moreover, the utilization of marginal lands for energy crop production is believed to reduce the indirect land use change (Tilman et al. 2008).

Extracting forest and agriculture residues also carries some risks such as soil erosion, ground damage, threats to biodiversity and impact on nutrient balance in soil (Anon 2010, Bjorheden 2010). It is thus essential to extract these residues in a manner that maintains forest and environmental values. On the other hand, limited research that focuses on identifying and quantifying the potential marginal lands, and the potential yields of energy crops on these lands in different regions exist in the literature (Gelfand et al. 2013), because of the high uncertainty associated with the spatial extent of these lands and the potential production on these lands.

Several assessment studies on the potential forest and agricultural residues at global, European, regional, and national scales have concluded that forest and agricultural production are the most important sources of residues (Dees et al. 2018, Simon et al. 2010). However, the divergent estimates of available residues among these studies are the indication of the differences in methodology used, working definition, difference in assumptions on actual yields, residue-to-crop ration, ecological constraints, as well as the lack of comprehensive evaluation of residue generation, and competing uses (Searle & Malins 2014). Some of the studies assessed only wheat straw and corn stover (Bentsen et al.2014, Daioglu et al. 2016, Dewit et al. 2010, Scarlat et al. 2010), while other included pruning residues (Elbersen et al. 2013; Pudelko et al. 2013). Moreover, there is little understanding on how the availability of forest/agricultural resources is related to the intensity of agriculture and forestry operation and how it may be limited by current alternative uses such as feed for livestock or use as biomaterial (Chum et al. 2011). Estimates of available residues need to account for ecological constraints and the competing uses of the total potential in order to reduce these uncertainties (IEA 2010, Scarlat et al. 2010). Furthermore, studies on regional residue generation potential are carried out for a limited number of counrties in the EU. Comparison of residues generation potential at regional scale across borders of different countries is thus missing.

Numerous studies also exist on the assessment of potential marginal lands for different regions and scales (global, regional, and national).As in the residues assessment studies above, results of assessments of potential marginal lands vary widely among studies. Considerable divergence in working definition, including input criteria, modelling framework, datasets used explain the large variation noted in these investigations (Breuning-Madsen et al. 1990, Cai et al. 2001). Another differentiating factor is the inclusion/exclusion of polluted or contaminated lands in the assessment of potential marginal lands. A land may become marginal when excess pollutions from human activities are generated on it (Fahd et al. 2012). Despite the wide variation in their estimates, these studies commonly agree that marginal lands offer a large potential for producing energy crops while storing carbon and reducing soil erosion and other environmental impacts (Davis et al. 2010, Gelfand et al. 2011). Most existing studies only assess marginal lands potential and do not provide data on types of crops and their potential yields of these crops on those marginal lands.

1.2 Objectives and target groups

The objectives of this work are:

(i) To identify and estimate marginal lands suitable for energy crops production in some EU regions
(ii) To identify appropriate cellulosic energy crops that could be cultivated on these marginal lands and to determine their potential biomass yields.
(iii) To quantify and map agricultural and forest residues biomass that could complement cellulosic energy crops production in the selected EU regions.

The analysis was conducted for three cases that represent the three agro-ecological zones (AEZ) selected in the MAGIC project. The target audience for this report is internal and external stakeholders as well as the public. Internal stakeholders are project members that have to be informed about the progress of the work package activities (e.g., project coordination’s team, work package leaders, and work package collaborating partners). The collaborating partners for this report are WUR, BTG and ARKEMA. External stakeholders are institutions or person that could benefits from outcomes of the work package or project such as all participating countries on European level, research institutions, local and national institutions, and local industry such as Deshyouest etc.

1.3 Scope and case description

The geographical scope of this assessment is Europe, which was divided into three agro-ecological zones (AEZ): Mediterranean (AEZ_1), Atlantic (AEZ_2), Continental and Boreal (AEZ_3) based on the climate, slope and soil texture. Three AEZs are studied in three European countries France (Brittany), Spain (Soria), Romania (Cluj) (Figure 1). The selection of a case study in each of these countries is based on the area of the AEZ and the economic importance of agriculture/forestry in the AEZ. Four energy crops are studied in this report on the basis of their suitability to grow in a given region, which were derived from literature as specified in Von Cossel et al. (2019). The selected energy crops are miscanthus in Brittany (France), tall wheat grass and Siberian elm in Soria (Spain) and castor bean in Cluj (Romania).

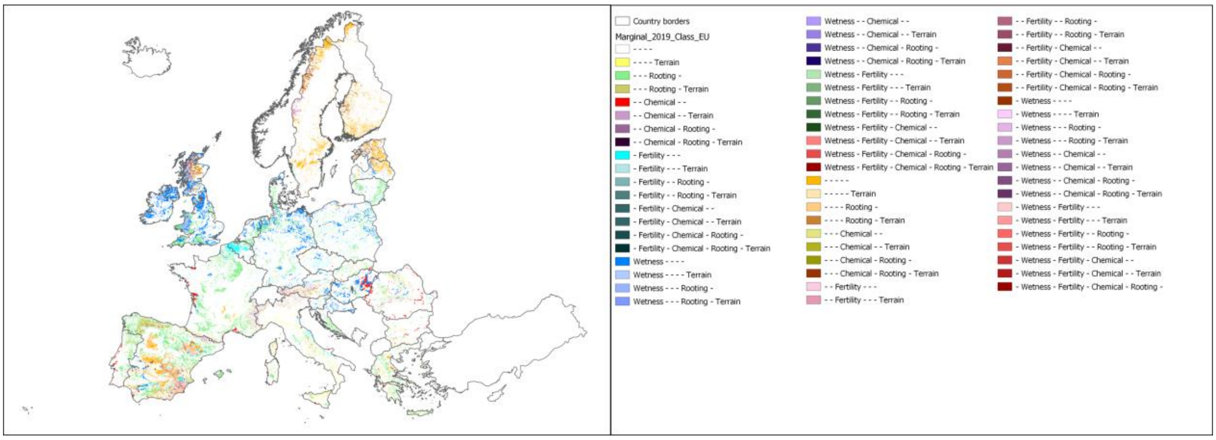

Figure 1: Marginal lands in different agro ecological zones in Europe.

1.4 Contribution of project partners and link to other activities in Magic project

The report is written by the INRAE and WUR, the contribution of WUR is related to the identification, quantification and the mapping of marginal lands, whereas the contribution of INRAE is related to the simulation of yields of energy crops of these marginal lands, and the quantification of agricultural/forest residues in the selected regions under assessment. This deliverable is connected to other work packages and tasks of the magic project. Specially, the work done by WUR to determine the biophysical constraints needed for identifying and mapping marginal lands resources in Europe (D.2.1).

1.5 Structure of this report

This report of five chapters contains the high-resolution maps of biomass potential for biorefinery in selected agro ecological zones. The remainder of this report is organized as follows: chapter 2 presents the general approaches used to quantify potential biomass for bioenergy and to map marginal land suitable for biomass production in three agro ecological zones. It discusses advantages and drawbacks of each approach and presents the methods used to estimate agricultural and forestry residues around a biorefinery plant. An overview of the required data as well as the assumptions considered in mapping marginal lands and simulating biomass production on these lands are also given. Chapter 3 covers the Brittany case in France. It provides rationale for choosing miscanthus as the suitable energy crop in Brittany. It also maps the marginal lands in Brittany, provides the biomass yields and distribution of miscanthus on these lands. In addition, it estimates and maps the available agricultural residues in Brittany. A discussion the results and some limitations related to this case study are presented. Chapter 4 deals with mapping energy crops and biomass residues in Soria (Spain). As in the Brittany case, a rationale for selecting tall wheatgrass and Siberian elm as suitable energy crops in Soria are given followed by mapping of marginal lands available for the cultivation of both tall wheat grass and Siberian elm in Soria. It then estimates and maps the distribution of agricultural and forest residues in Soria, followed by the simulation of biomass yields and the distribution of these energy crops in this province. A short discussion of the results and some limitations related to the case study are also presented. Finally, Chapter 5 discusses the overall findings, limitations, and deviations from the description of work (DoW) are presented, followed by the presentation of future work and the links between the outputs of this work and other magic work packages.

2 General methodology and approaches

This chapter presents the methodology used to reach the objectives stated in the introduction section. It starts with a short description of the LocaGIStic model, which will be used, in a later stage of the MAGIC project to simulate biomass supply chains in the 3 case-studies. The biomass resources maps presented in this report will be used as inputs to LocaGIStics.

2.1 LocaGIStics model and steps to run case studies

LocaGIStic is a regional biomass supply chain assessment tool that simulates the biomass supply from fields to bioenergy plant. The tool consists of a network several modules that can be connected to form a complete supply chain. Each module represents an operation or process (e.g. transport, harvesting, and processing) and is independently constructed with a set of inputs and outputs. The calculation of costs, energy use, and GHG emissions common to all operations and processes are gathered into individual modules as well. Biomass moves from one module to the next one through connector. The strength of the LocaGIStics model is its flexibility and ability to model multiple types of feedstock and conversion processes and its attention for discrete logistic process details. Its geospatial feature allows it to assess the biomass used and the transport distance required based on the biomass availability maps. The tool can properly handle both a single as well as a multi-mode of transport. The tool can help the users to design and analyze optimal delivery chains and networks at regional level. The LocaGIStics model described here is used for locating the biomass around the bioenergy plant.

2.2 Current Approach used to estimate agricultural and forest residues

Different methodologies for assessment of forest and agricultural residues are reported in the literature. These methodologies include statistical analysis, spatially explicit analysis, integrated assessment analysis, remote sensing etc. Each of these methods has its own advantages and limitations. Statistical analysis method uses statistical data on land use and forest/agricultural production to determine the global, regional, and national availability of forest and agricultural residues. Statistical analysis methods are transparent and reproducible; they capture well the competing use of forest/agricultural residues, the environmental constraints as well as the technological development. This report combines the statistical analysis method and geographic information systems to quantify and map the theoretical and available agricultural and forest residues in the different regions under the assessment.

2.3 Approaches used to identify and to map marginal lands

Several definitions and approaches have been used to identify, characterise, quantify and map marginal lands at local, regional, and global scale (Breuning-Madsen et al. 1990, Cia et al. 2011). These approaches can be grouped into five broad categories: expert opinion, satellite derived net primary productivity, biophysical models, and socio-economic approaches. Each of these approaches has its own advantages and disadvantages, and help better understanding the issues of marginal lands. However, none of these approaches captures or addresses all issues related to marginal lands. In the MAGIC project, a biophysical approach is adopted because it capture well the physical and productive properties (i.e. levels of soil suitability and restrictions) of the soils which agronomists and soil scientists rely on for land use planning. An extensive description of the approach used to identify and map marginal lands in the case studies of this report are given in D.2.1 of the MAGIC project.

2.4 Models for simulation of crop yields

Accurate estimations of yields of energy crops are important for stakeholders involved in bioenergy and can be obtained using crop growth models and machine learning models. Crop growth models are tools that help to represent crop growth, development, and estimate crop yields through mathematical equations as a function of climate, weather, soil conditions, environmental conditions, and management practices (Hoogenboom et al. 2002). The strength of crop growth models is their ability to extrapolate the temporal patterns of crop growth and yields beyond a simple experimental site. Several crop growth models have been developed in recent years, and they can be grouped into statistical models and process models. Statistical models use observational data and regression equations to compute crop yields. Often tailored for specific crops and/or specific regions, these models provide insights into crop yields but lack information on the mechanisms that control the outputs (Phakamas et al. 2013). Process models are fundamental crop yield models. They incorporate knowledge of specific physiological characteristic of plants and a number of environmental variables such as soil properties. In such models, the processes are separately quantified, and then integrated into the entire system (Hoogenboom, 1994). Such models are useful because they are based on known principles that determine the productivity of crops, and can explain how each affects crop yields. Examples of such models include the CERES model (Hodges et al. 1987, El Akkari et al. 2020), CROPGRO model (Jagtap et al. 2002) GAEZ model, and SALUS model (Dzotsi et al. 2013). A major difference between crop statistical models and process models is the reduction of time interval involved, e.g., from a growing season to a day or less. Most crop models employ a daily time steps to estimate growth and development, a few models require hourly time steps to execute the more detailed process that can only be described with solutions that are more precise. The CERES-EGC model is used in this report to simulate yields of miscanthus on marginal lands. To the best of our knowledge no model exists for crops such as castor bean, Siberian elm, or tall wheatgrass. We thus explored alternatives to full-blown crop models: simpler agro-meteorological models, meta-analyses comparing the yield of various biomass crops (Laurent et al., 2015), local field trials (in house data of project partners), and expert knowledge on the effect of marginality factors on crop yield potentials (Magic Crops Data Base, D1.4). The implementation of these various approaches will be detailed in the corresponding case-studies in the next sections. For instance, the yield of tall wheatgrass (a candidate feedstock in Soria) was scaled from that of switchgrass, as simulated with a crop model, using the yield ratio derived by Laurent et al. (2015) in their meta-analysis. Some marginality constraints

Table 1: Overview of the growth characteristics and yield potentials of the crops selected in the WP5 case studies. Source: Magic crops database (Deliverable 1.4 and www.magic-h2020.eu)

Energy crops	**AEZ**	**GSI**	**Life cycle**	**Growth cycle (days)**	**Photosynthesis pathways**	**Potential yields (tdm $ha^{-1}yr^{-1}$)**
Miscanthus	AEZ_1		Perennial	119-267	C_4	15-19
Tall wheatgrass	AEZ_2		Perennial	102 - 280	C_3	3 -11
Siberian elm	AEZ_2		Perennial	121 - 291	C_3	3 -15
Castor bean	AEZ_2		Annual	120 - 180	C_3	1 -2 (oil)

GSI = growth suitability index, AEZ = agro ecological zone

that were not simulated by the crop model (e.g. acidic pH) were approached with a fixed reduction factor, related to the tolerance score estimated in the Magic Crops tool (D1.4).

2.5 Approach to select suitable energy crops

Several plant species have shown potential to be used as energy crops, depending on the available land and climatic conditions (Li et al. 2008). A number of candidate energy crops are being tested around the world, among them many lignocellulosic, starchy and oil crops. The selected energy crops for the case studies of this report include herbaceous crops like miscanthus (M*iscanthus giganteus*) and tall wheat grass (*Thino pyrumponticum*), lignocellulosic tree species such as Siberian elm (*Ulmus pumila*), as well as oil bearing shrubs like castor bean (*Ricinus communis*) as shown in Table 1. These energy crops were chosen based on their growth suitability indices. This index combines biophysical and environmental information of a given crop to determine the most suitable location for its successful development. The growth suitability index for a given crop in this report was derived from the literature. Further information on selected crops used in this report as well as the full list of suitable crops for marginal land can be found in D.1.1 and in Von Cossel et al. (2019).

2.6 General chain design for use cases

The most suitable crops above were used in the three case studies of this report. Early project meeting held by the WP leaders and partners of Task 5.4 lead to the design of three case studies in the agro ecological zones of MAGIC. All these case studies focused on demand driven approach. The French and the Spanish cases studies deal with the conversion of lignocellulosic crops (miscanthus, tall wheatgrass and Siberian elm) into pyrolysis oil, based on the BTG Empyro plant, whereas the Romanian case study focuses on the production of castor oil from the castor beans for chemical industries such as ARKEMA.

3 Residues and Miscanthus for Pyrolysis Oil production in Brittany

3.1 Background

Brittany is one of the province of France, situated in the northwest corner of France, and covering 27200 km^2. This NUTS2[1] region is composed of four NUTS3 regions '*the departments*' namely Côtes d'Armor, Finistère, Ille-et-Vilaine and Morbihan (Figure 2). The climate of Brittany is oceanic with annual rainfall varying from 700-800 mm and average annual temperature of about 15°C. The majority of soils in Brittany are deep silty clay loams and most of these soils are exposed to erosion as evidenced by the high concentration of phosphorus in water reservoir. Agriculture is one of the dominant economic activities in the region. It occupies 1.73 Mha (63% of the region total area) lands in 2013 and accounts for 4.2% of the total employment in Brittany. Livestock breeding is a primary activity in the region and the animal feed production centres on wheat, corn, and rapeseed. Residues (i.e. wheat straw, corn stover, and rapeseed stalk) from these crops can be used to produce bioenergy and bio-based products in a more carbon-positive way. Besides the agricultural residues mentioned above, energy crops such as miscanthus, switchgrass and short rotation woody crops are also produced in the region as biomass resources for both domestic and industrial purposes. However, these energy crops represent only a minor fraction of the total biomass production in the region.

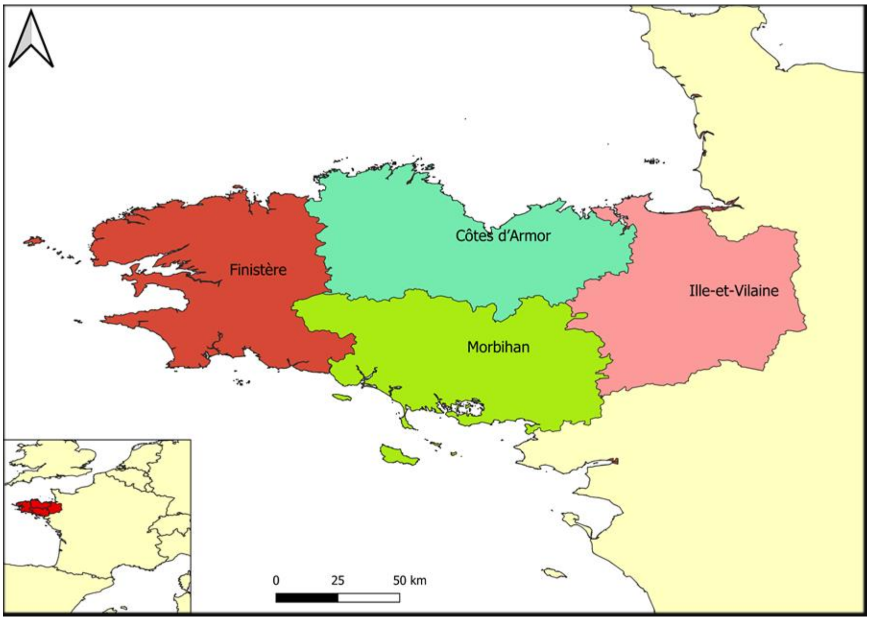

Figure 2: Brittany region and its four departments

Brittany is also the home of the Deshyouest Cooperative, one of the largest feed drying companies in France. Deshyouest possesses 800 ha of miscanthus dedicated to the production of chips used as fuel for feed drying or as feedstock for the production of miscanthus pellets sold on local market as renewable

[1] Nomenclature des unites territoriales statistiques

fuel. However, these miscanthus fields are established on croplands and can contribute to land use competition, reduction in food supply, and increase in food prices. Deshyouest is also a key player in the supply of solid biofuels in the region and the company intends to increase its production of pellets in the near future. Currently, bioenergy accounts for half of the total renewable energy production in Brittany. Bioenergy has grown substantially since 2010 and reached 2300 GWh of energy in 2014. With the objectives of transition to a low carbon economy, the region's goal is to produce 3800 GWh bioenergy in 2030. However, considerable efforts are needed to reach Brittany's 2030 bioenergy targets. Indeed future expansion of bioenergy resources will require large amount of marginal lands not currently used for food/feed or for bioenergy production to supplement agricultural residues and already established energy crops. This requires inventories with high spatial resolutions of agricultural residues and of marginal lands on which energy crops can be cultivated without risks to food security and other ecological impacts.

Several studies provide agricultural residues assessment potentials at the different geographical scales (IRENA 2014, Dees et al. 2017, Huppman et al. 2018). Quantifying and geolocalising marginal lands suitable for bioenergy crops is critical to the successful planning of the local bioenergy systems. Unlike studies conducted at national, regional or global levels, local-scale bottom-up studies are capable of incorporating parcel-level ownership and assessment records, riparian boundaries and socioeconomic considerations that are relevant for the local authorities. An important benefit of using marginal lands at local scale is that it does not diminish agricultural production or the productive lands, therefore can avoid impacts due to indirect land use change (Chin et al. 2013). Given the ambitious bioenergy goal of Brittany, its residues generation potential, and the large extent of unused or eroded lands in this region, the present case study focuses on the potential of residues and marginal lands for bioenergy production in Brittany. The objectives of this case study are: *a)* to quantify and map agricultural residues in Brittany; *b)* to identify and estimate marginal lands suitable for energy crops that could supplement agricultural residues in Brittany; *c)* to simulate the yields and distribution of miscanthus on marginal lands in Brittany.

3.2 Residues considered in the Brittany case

Cereals (e.g. wheat, corn) and oilseeds (rapeseed) are the primary feedstock used to produce most of the animal feed in Brittany. Cereal and non-cereal cropping generate lot of residues that are potential feedstocks for bioenergy, owing to their high-energy content. Major agricultural residues for bioenergy production in Brittany are wheat/barley straw, corn stover, and rapeseed stalk. These three crops were selected because they represent large sources of field biomass for which supply is contiguous over large areas. Other lignocellulosic crop residues are not included because of their low volumes. Likewise, secondary residues (manures, food/feed processing residues) as well as residues of non-cellulosic crops such as sugar beet and potatoes are excluded from this analysis not only because they are difficult and expensive to collect but also because the MAGIC project focuses on industrial crops. Similarly, forest residues are not assessed in this case study because Brittany is the least-wooded region of France with very low forest stands.

3.3 Approach used to assess potential residue generation in Brittany

Estimates of available agricultural residues that can be used for bioenergy were computed considering the type of crops, crop production areas, crop yields, residue-to-grain ratios, environmental constraints, and competing uses (Edwards et al. 2005). The theoretical crop residues production was first estimate based on the agricultural production levels (at the required spatial production levels) and residue-to-grain ratio according to the equation 1

$$\boldsymbol{P_t} = \sum_j \sum_{i=1}^{nj} \boldsymbol{\varphi_{i,j} \cdot G_{i,j} \cdot A_{i,j}} \qquad \textbf{Equation 1}$$

Where P_t is the theoretical residue yields (t/year), $\varphi_{i,j}$ is the residue-to-grain ratio for i^{th} crop in the j^{th} department; $G_{i,j}$ is the crop yield in the i^{th} crop in a year (t/year) in the j^{th} department. $A_{i,j}$ is the area (ha) under crop i in department j; and n_j is the total number of crops in department j. To determine the available agricultural residues for energy production, we factored in the equation 1 some sustainability criteria (e.g.; collectable residues, competing uses, other constraints) that limit residues availability. Collectable residues include environmental constraints imposed to protect soil against erosion as well as management practices such as tillage and recovery equipment. Competing uses of agricultural residues include their use for fibre, fuel and fertiliser as shown in the expression below:

$$\boldsymbol{P_A} = \sum_j \sum_{i=1}^{nj} \boldsymbol{\eta_{i,j} \cdot \lambda_{i,j} \cdot \varphi_{i,j} \cdot G_{i,j} \cdot A_{i,j}} \qquad \textbf{Equation 2}$$

In this expression, P_A is the available agricultural residue yields (t/year), $\eta_{i,j}$ is the collectable residues coefficient for the crop i^{th} in the j^{th} department, $\lambda_{i,j}$ is the competing use for the crop i^{th} in the j^{th} department, $\varphi_{i,j}$ is the residue-to-grain ratio for i^{th} crop in the j^{th} department. $G^{i,j}$ is the crop yield in the i^{th} crop in a year (t/year) in the j^{th} department, $A_{i,j}$ is the area (ha) under ith crop at j^{th} departments; and n_j is the total number of crop in the j^{th} department.

3.4 Data collection and sources

Data for the computation of the different of residues potentials were gathered from different of sources and were supplemented where possible by assessment from experts in Brittany. Regionally specific data were used as much as possible to compute the residues generation potential. The data for field crops at provincial, national level were derived from DRAAF (Agreste, 2019), whose database provides yields and production statistics in France NUTS systems. Concretely economic production and harvested areas of wheat, maize, and rapeseed at national NUTS0 and subnational NUTS2 level for the period 2010-2017 were extracted from the statistics the French Ministry of Agriculture (Agreste, 2019). Economic and harvested areas for these three crops were also collected by contacting the different national statistic services in Brittany. Both datasets were integrated to generate a unique statistical dataset at regional level NUTS3. Yields and the production statistics were transformed to dry matter based on the moisture content reported by the DRAAF (Agreste, 2019).

3.5 Mapping theoretical and available agricultural residues in Brittany

Estimation of theoretical and available agricultural residues for bioenergy in Brittany was carried-out in several steps. First, we selected the agricultural residue types in Brittany, and then computed the extractable amount of residues and the corresponding spatial distribution. Besides the theoretical potentials, available residues for bioenergy was calculated by applying a number of reduction factors to account for ecological constrains and competing use. The results were imported to ArcGIS where spatial maps of 1km x 1km grid cells were generated.

3.6 Identification and mapping marginal lands in Brittany

As part WP2 activities in MAGIC, an EU wide map of marginal lands is created. The approach used for the creation of this map builds on the joint research center work to identify areas of natural constraints (Van Oorschoven et al. 2014, Terres et al., 2014) and other land evaluation systems for agronomic suitability. Biophysical factors were identified and used for the classification of severe limitations. 18 single factors were clustered into 6 factors: *(i)* adverse climate (low temperature and/or dryness) *(ii)* excessive wetness (Limited soil drainage or excess soil moisture), *(iii)* low soil fertility (acidity, alkalinity or low soil organic matter), *(iv)* adverse chemical conditions (Salinity or contaminations), *(v)* poor rooting conditions (low rootable soil volume or unfavorable soil texture), *(vi)* adverse terrain conditions (steep slopes, inundation risks). The poor rooting conditions class is the most extensive class in most regions as it covers six single factors, which all lead to limitations for plant rooting ability and workability of the soil. These single factors are unfavorable soil texture, presence of coarse fragments organic soils, abrupt textural differences, surface stones and rocks and shallow soils. The land units were identified with biophysical factors within the 20% margin of the threshold value of severity. This also allows mapping pair-wise limitations. When two factors are within this 20% margin, the land units were classified from sub-severe to severe. All severe classes are included in the marginal land class. A correction was made by excluding areas where natural constraints were neutralized via agronomic improvement measures such as fertilization, irrigation, drainage and creation of terraces to overcome the specific natural constraints. Different spatial data sources were used to identify the marginal lands where land improvements were made and intensive agricultural production now occurs. The latter was verified with detailed spatial data to verify that natural constraints were indeed neutralized.

3.7 Miscanthus as a candidate energy crop for marginal lands in Brittany

Miscanthus is a C_4 perennial herbaceous plant native of East Asia. It has a capacity to maintain high photosynthetic rates and high biomass production (Dohleman and Long, 2009; Naidu et al., 2003).

Introduced in Europe in 1935, miscanthus has been the subject of studies as an energy crops since the 1980's. Among the different species of miscanthus trialed in Europe, *Miscanthus x Giganteus* is the most productive of all the genotypes tested. As a perennial plant miscanthus is suitable to various European climates and because of its efficient recycling system, it needs fewer inputs than other perennial energy crops for a high production of biomass. Miscanthus has few known pests or diseases, leading to highly resilient crop in the field, with little pesticide or fungicide treatments. Its ability to grow on marginal lands without the needs of irrigation or heavy fertilization coupled to its high cellulosic fraction (43%) makes it a leading energy crop suitable for bioenergy such as biopower and second generation biofuels (Lewandowsky et al. 2003, Lewandowski & Schmidt 2006, Gabrielle et al. 2008, Xue et al., 2016). Due to its high water use efficiency and deep root system, miscanthus once established has a strong potential to prevent water depletion and soil erosion (Smeets et al. 2009, Xue et al. 2016), which addresses one of the serious concerns of growing energy crops in Brittany. If miscanthus substitutes corn, it may save half of the land and one third of water. Indeed, only 9 Mha of land and 45 km^3 of water can meet the biofuel targets of the USA using miscanthus, instead of corn, where 27 Mha of land and over 90 km^3 of water would be required (Zhuang et al. 2013). Moreover, miscanthus has a high carbon sequestration rate, an important parameter to consider when deploying energy crops. With these properties, miscanthus is seen as ideal energy crop to complement agricultural residues in Brittany where soil quality may be low and is prone to poor water availability and soil erosion risks.

3.8 Modelling the productivity of miscanthus on marginal lands in Brittany

Model description: The simulation of productivity of miscanthus on marginal lands in Brittany is carried out using the crop-environment resource synthesis (CERES-EGC) model (Otter-Nacke et al. 1991, Godwin et al. 1989). CERES-EGC is a module within the DSSAT Decision Support System for Agrotechnology Transfer (Hoogenboom et al. 1994). This process-based computer tool utilizes carbon, nitrogen, and water balance principles to simulate the growth and development of miscanthus within an agricultural system on a daily step (Gabrielle et al. 2006). Crop development proceeds through nine growth stages based on heat unit accumulation from planting to harvest, and leaf numbers are calculated during vegetative growth stages. Carbon assimilation is computed as a function of incoming solar radiation, leaf area index, plant population, the canopy extinction coefficient, and radiation use efficiency. Assimilated carbon is then partitioned to various plant parts, including leaves, and roots. Simulated plant growth responds to variation in management practices, crop cultivars, soil properties, and meteorological conditions. Management inputs required for model execution include plant population, row spacing, planting depth, planting and harvest dates, fertilizer/irrigation application rates and dates. Cultivar parameters are used to define vernalization requirements, day length sensitivity, radiation use efficiency, heat units needed to progress through growth stages, and growth potentials for specific plant parts. Soils are defined by their water retention and conductivity characteristics, bulk density, pH, and initial conditions for water, inorganic nitrogen, and organic carbon. Daily minimum and maximum temperature, solar radiation, wind speed, and precipitation are also required to run the model. The model simulates plant stress effects from deficit and excess water conditions and from deficit nitrogen conditions, which feedbacks on the daily plant growth simulation. The N_2O emissions module included in CERES-EGC enables to simulates the production of nitrous oxides and nitrogen oxides through nitrification and denitrification in soils (Hénault et al. 2005), while a microbiological module calculates the turnover of organic matter in the plough layer, involving decomposition, mineralization and immobilization within three pools of organic matter (microbial biomass, labile organic matter, and humads). Field emissions of CO_2, N_2O, NO_x, and NH_3 are calculated as a result of these transformations. More details about the CERES-EGC tool can be found in (Gabrielle et al. 2006), and model's web site[2]. The code is open-source and can be accessed from the SourceSup[3] development platform, which also serves as a repository of codes.

Model calibration: Model parameterisation or calibration is the adjustment of the parameters so that simulated values compare well with observed values. For calibrating and testing purposes, the CERES-EGC model was compared to field observations obtained in long-term trials in Estrées-Mons (northern France) and Rothamsted (south-eastern UK) involving different treatments for miscanthus in terms of fertilizer input rates and harvesting dates in both regions. Data from a larger network of 5 trials across France were also used in an independent testing phase (El Akkari et al. 2020). In Estrées-Mons the mean deviations between simulated and observed crop biomass yields for miscanthus varied between 1.21 t DM ha^{-1} (for the early harvest without fertilization) to 4.51 t DM ha^{-1} (early harvest with fertilization).

Model validation: Before any model can be used with confidence, adequate validation or assessment of the magnitude of the errors that may result from their use should be performed. Model validation, in its simplest form, is a comparison between simulated and observed values. Beyond comparisons, there are several statistical measures available to evaluate the association between predicted and observed values, among them are the correlation coefficient r and its square, the coefficient of determination (r^2). Wilmot (1982) has pointed out that the main problem with this analysis is that the magnitudes of r and r^2 are not consistently related to the accuracy of prediction. The mean deviation and root mean squared error (RMSE) are also commonly used statistics to evaluate the goodness of fit. Here, the observed miscanthus yields were higher than simulated yields in most sites and for all treatments, with one exception in Central France. The model managed to capture this difference over all experimental sites with a mean deviation -0.09 t DM ha^{-1} and an overall RMSE around 3 tDM ha^{-1} for the final yields of miscanthus.

2: https://ecosys.versailles-grignon.inra.fr/ceres_mais/ceres.html
3: https://sourcesup.renater.fr

Model Application to the Brittany region: After the calibration and validation stages of the CERES-EGC model, we applied the model at regional scale to a hypothetical case in Brittany (France) to determine the productivity and yields of miscanthus production on marginal lands in Brittany (France). The simulation set-up was as follows: we used the spatially explicit simulation system detailed by Dufossé et al. (2016), using the ARPEGE 2010-2035 series of short-term future weather data generated by the Dryas project (Dufossé et al. 2016). In a first run, miscanthus crops were supposed to be grown on current croplands, on the 1067 simulation units (polygons) resulting from the overlay of the EU soil map (1:1 000 000 scale ; same as used in WP2 to map marginal land).

To integrate the marginal land area determined in MAGIC WP2 (D2.6; Elbersen et al., 2018), this simulation map was overlaid with a map of lands considered as marginal or sub-marginal. The soil map used by CERES-EGC was intersected with the map produced in WP2 to point at the CERES polygons in which marginal factors occurred. There was a high degree of consistency between both maps (relying on the same soil map) since the 'rooting' constraint was often associated with a sandy soil in the CERES-EGC map. Each simulation polygon was given a marginality code. In terms of management practices, we assume a baseline fertilizer N input of 30 kg N ha^{-1} (midway in the 0 – 50 kg N ha^{-1} range of the Magic database for miscanthus), and no limitations from P/K availability in soils. The CERES-EGC model was modified to account for the two main marginality factors (rooting and chemical limitations) as follows:

- the **'rooting constraint'** was interpreted as implying a high stone content of soils, which in practice reduce the soil water holding capacity and its ability to store water for crop use. In this case the corresponding simulation polygons were ascribed an 'archetype' soil for this characteristic with a high sand content. Note that the MAGIC Crops database (D1.4) says that miscanthus is somewhat sensitive to shallow rooting depth (with a score of 2, i.e. a 25 to 50 % loss in DM yield compared to optimal controls). Coarse material and sandy texture have a sensitivity of 3 (50 to 75 % loss). So we should expect a 50 % loss compared to good soils, as a rule of thumb. This was somewhat the case in the end since the median yield of soils with rooting marginality factors is about 6 tons DM/ha whereas it amounts to 7.7 t DM overall (note that these statistics are not weighed according to cropland area, which would probably shift the overall median upwards).

- regarding the **chemical constraint:** MAGIC D2.6 states that: *«Adverse chemical conditions include: Salinity (Ec); Sodicity (Na/ESP); Natural toxicity (e.g. Al, S);* and *Toxicity by pollutants.* None of these are explicitly simulated by CERES-EGC, in terms of effects on soil-plant processes. Salinity was implemented in the original CERES models for maize (Castrignano et al., 1998), based on the concept of pre-dawn leaf water potential and increased osmotic pressure caused by saline soil water. Its parameterization is likely to be crop-specific, and none of the currently used miscanthus models account for salinity – so extrapolating from maize to miscanthus (short of proper testing against field data) may be doubtful. On the experimental side, a recent paper reported yield variations of miscanthus due to salinity, which were rather large (a 3-fold decrease in biomass yields when the NaCl concentration in irrigation water increased soil conductivity from 0 to 22.4 dS m^{-1} (Stavridou et al. 2017)). According to D6.2, the marginality threshold for saline soils is an Ec value of 15 dS m^{-1}, which corresponds to a 70 % reduction in biomass yields. Sub-marginal conditions (20 % above the threshold) would entail a ~ 60 % loss. This is somewhat in line but more stringent than the sensitivity score of 2 for salinity effects in the Magic list (implying yield losses ranging from 25 to 50%). In the Stavridou et al. (2017), an EU-wide extrapolation using modelled estimates for miscanthus potential (with MISCANFOR) and the Harmonized World Soil Data (HSWD) soil map for salinity showed no effect in Brittany (and an overall yield for the 1990-2008 time period of 15-18 t DM yr^{-1}). In this context, it would make sense to apply a moderate yield reduction factors (mid-way between 25 and 50%) to the yields simulated by CERES. We used a 30 % factor here.

3.9 Mapping miscanthus production on marginal lands in Brittany

The simulated yields of miscanthus at 1km x 1km grid cells using the CERES-EGC model were exported as a shapefile and imported into the ArcGIS software where polygon maps of miscanthus were made. The shapefile contains the cell ID, average yields, and share of the area under different land use for a given cell. The average yield of miscanthus and cell area accounts for the production on grid cells. The production on grid cells is aggregated to polygons, resulting in regional miscanthus production level. The modelling results, i.e. the spatial distribution of miscanthus production in Brittany are exported as digital ArcGIS-maps.

3.10 Results and Discussion of the Brittany case

3.10.1 Results

3.10.1.1 Agricultural residues

The assessment of residues production potential in Brittany is based on the approaches described in section 4.3 of this report. Table 2 shows that the total residue in Brittany in 2017 was 9293 kton dry matter. Corn stover showed the highest potential, with approximately 4726 kton yr^{-1} dry matter or 51% of the total residue potential in Brittany. Apart from corn stover, significant quantities of straw (4325 kton yr^{-1}) can be extracted from wheat production. Despite its high residue-to-crop ratio relative to both corn and wheat, rapeseed stalk (242 kton yr^{-1}) was the agricultural residues with the lowest potential in the region. This can be explained by the small agricultural areas devoted to rapeseed relative to that cultivated for wheat and corn in the region (Table 2). Note that the above estimates did not consider the environmental constraints or the competing use of these agricultural residues. When these constraints were considered the theoretical residue potential of each type of residue dropped to 4084 kton yr^{-1} for corn stover, 1492 kton yr^{-1} for wheat straw and 51 kton yr^{-1} for rapeseed stalk. While the factor for environmental constraints was similar among residues type, the competing use factor in contrast was higher for wheat straw than for corn stover and rapeseed stalk, suggesting high alternative uses for wheat straw than both corn stover and rapeseed stalk (Table 2).

Table 2: Potential residue generation and available residues for bioenergy in each of the department of Brittany (kton yr^{-1})

NUTS3 region	**Theoretical residues potential**			**Available residues for bioenergy**		
(departments)	Wheat straw	Corn stover	Rapeseed stalk	Wheat straw	Corn stover	Rapeseed stalk
Côte d' Armor	1314	1214	81	453.33	1048.90	17.11
Finistère	852	1093	40	293.94	944.35	8.45
Ille-et-Villaine	1221	1380	64	421.25	1192.32	13.52
Morbihan	938	1040	57	323.61	898.56	12.03
Total	**4325**	**4726**	**242**	**1492.1**	**4084.1**	**51.1**

The distribution of these agricultural residues in the region is shown in Figure 3a-c. Corn stover appeared to be fairly distributed in Brittany, with comparable volume in each department. This was however, not the case for wheat straw which was mostly concentrated in the Côte d'Armor (1314 kton yr^{-1}) and the Ille-et-Villaine (1221 kton yr^{-1}) departments. Similar conclusion can be drawn regarding the distribution of rapeseed stalk in Brittany (Figure 2, Table 2). The cumulated theoretical potential of agricultural residue amounts to 9293 kton yr^{-1} of which only 5627 kton yr^{-1} is available for bioenergy (Table 2). The potential bioenergy production from agricultural residues amounted to 96 PJ yr^{-1} (27 TWh yr^{-1}) of primary energy resources assuming an energy density of 17 GJ ton^{-1} for these residues. To utilise this potential, the agricultural sector must be developed as a supplier of biomass for the biobased economy. Indeed, farmers may perceived the development of a bioeconomy as an opportunity to generate profit from residues that they regards as low-value input materials.

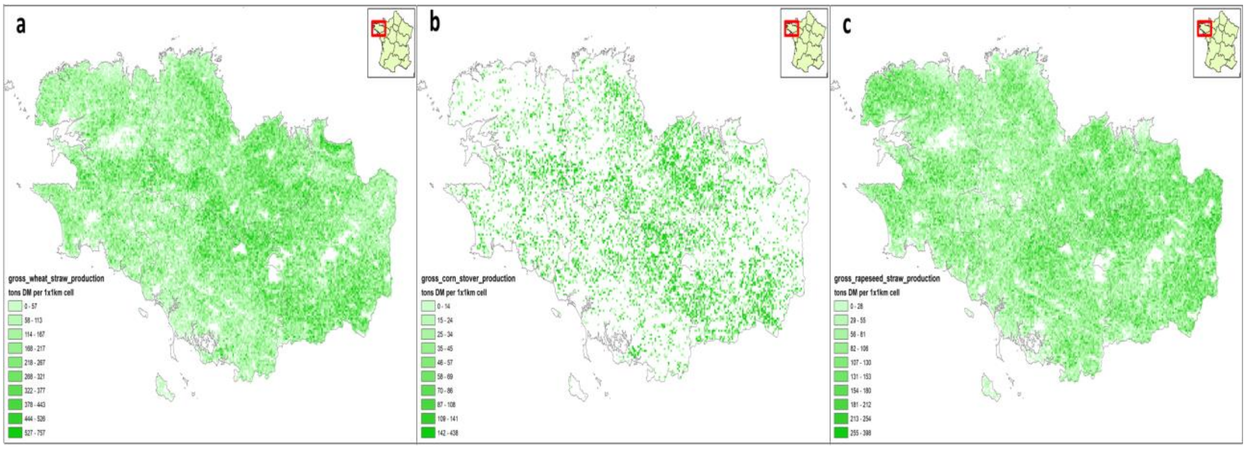

Figure 3: Distribution of residues generation potential in Brittany, (a) wheat straw potential, (b) corn stover potential, (c) rapeseed stalk potential

3.10.1.2 Marginal lands in Brittany

Figure 4 shows the distribution of the marginal lands that are potentially suitable for miscanthus cultivation in each department in Brittany (France). The total marginal lands available for growing miscanthus in Brittany was estimated at about 57544 ha lands, which represented about 3% of the total agricultural lands of the region. The largest areas of marginal lands were found in the Ille-et-Vilaine department (32695 ha) accounting for 2.1% of the regions' total agricultural lands (2.6 Mha lands), followed by the Morbihan department (13231 ha), the Finistère (7770 ha) and the Cote d'Armor department (3448 ha) which together represent the remaining fraction (1% of total agricultural lands). Rooting which leads to low rootable soil volume or unfavourable soil texture was found to be the most limiting factor and made-up more than half (55%) of the total marginal lands.

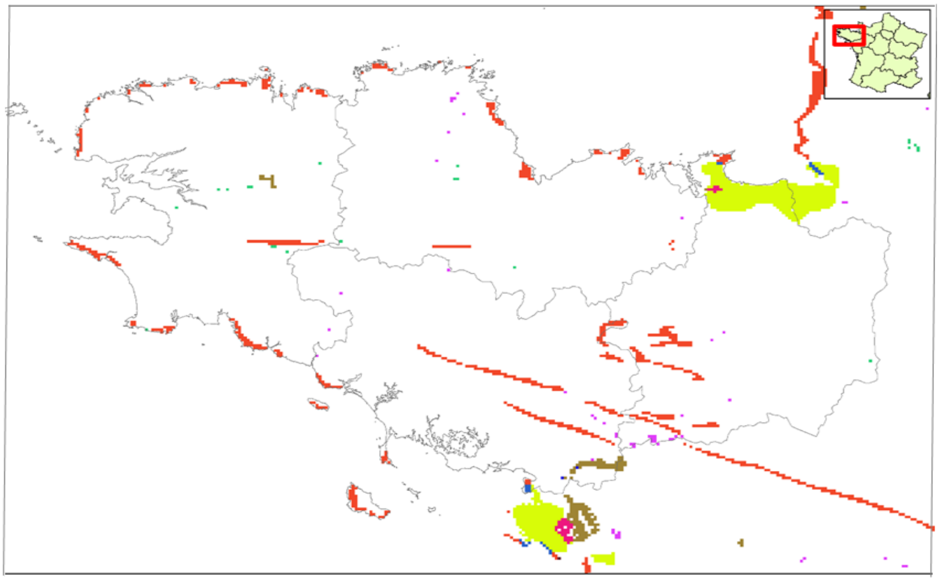

Figure 4: Distribution of marginal lands suitable for the development of energy crops in Brittany

Chemical limitations mainly due to high salinity were the second most important limiting factors and represented 34% of the total marginal lands (Table 3). As expected, areas with high salt content were located near the coastlines (Figure 4). The land cover type of the identified marginal lands consisted of pasture and meadow vegetation. Note that some of the identified marginal lands were not considered in the estimate of potentially suitable lands for miscanthus.

Table 3: Potential marginal lands in each province of Brittany

NUTS 3 regions (departments)	Potential marginal lands (ha)
Côte d' Armor	3847.50
Finistère	7770.44
Ille-et-Villaine	32694.67
Morbihan	13231.32
Total	**57543.93**

3.10.1.3 Yields and distribution of miscanthus on marginal lands in Brittany

With regard to biomass production on these marginal lands, the CERES-EGC simulation showed that the dry matter yields of miscanthus varied between 2 and 10 ton/ha/yr in Brittany. Miscanthus yields varied significantly across the different department of Brittany due to difference in marginality constraints, climate, soil quality, and landscape. The lowest yield of miscanthus was recorded for the Morbihan department while the highest biomass yield per hectare was in the Côte d'Armor department. The marginality factors that affected most the miscanthus yields were rooting and salinity. Indeed where this was encountered, the average yields of miscanthus in that department dropped by 60%. Despites this yield decrease, results of our investigation show that miscanthus may be a good crop in either rooting or soils affected high salinity in Brittany, depending on the environmental conditions. The distribution of miscanthus production in Brittany is shown in Figure 5.

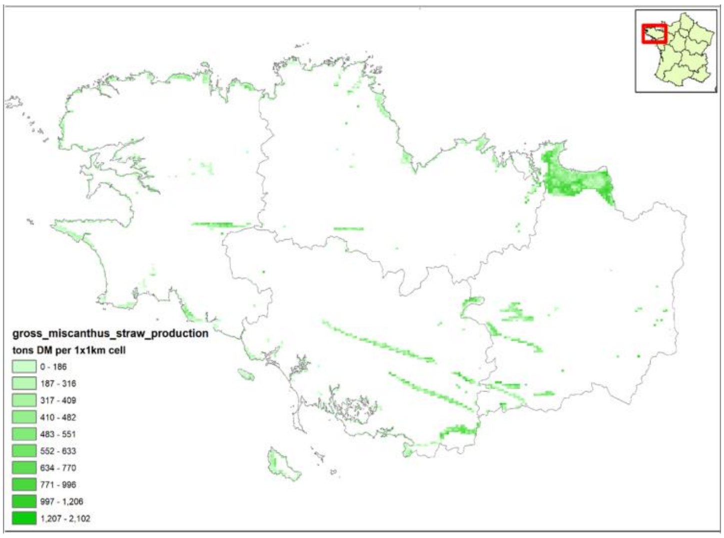

Figure 5: Distribution of miscanthus on marginal lands in Brittany.

These values should be seen as upper bound for the reason that not all available marginal lands in Brittany would be practically converted to miscanthus fields. Considering that there are approximately 57544 ha marginal lands available in Brittany, and assuming an average yield of 6.2 ton $ha^{-1}yr^{-1}$ for miscanthus on marginal lands, about 352 kton yr^{-1} biomass could be produced in a regular growing season if all available marginal lands were converted to miscanthus. This amount of biomass can potentially yield up to 6 PJ yr^{-1} (2 TWh yr^{-1}) of primary energy on average assuming a lower heating value of 17 GJ ton^{-1} for miscanthus. This would represent ~ 44% of the region's objective of bioenergy in 2030.

Table 4: Biomass resources for energy production in each department of Brittany (kton yr^{-1})

NUTS3 region	Agricultural residues	miscanthus	Total
Côte d' Armor	1519.34	90.48	1609.82
Finistère	1246.74	77.99	1324.73

Ille-et-Villaine	1627.09	98.97	1726.06
Morbihan	1234.20	84.11	1318.31
Total	**5627.34**	**351.55**	**5978.92**

3.10.2 Discussion

3.10.2.1 Agricultural residues

This chapter analyses the availability of agricultural residues for bioenergy purposes without impairing sustainability targets, it also assesses marginal lands that could supply additional biomass, and evaluate potential yields of miscanthus on these marginal lands in Brittany. With regard to agricultural residues, our analysis showed that all four departments of Brittany have sufficient agricultural residues to supply at least 100 pyrolysis plants such as the Empyro pyrolysis plant (30 kton biomass/yr). Much bigger plants could be considered in each of these departments, and this would decrease the production costs through the economy of scale. Thus, farmers in Brittany have the ability to contribute significantly to the achievement of bioenergy objectives of the region. Very few studies assessing and mapping the availability of residues at NUT3 level exist in the literature. However, our estimate of theoretical residue production compare well with the estimate of the ONBF (2018). We showed notable spatial variation in the distribution of agricultural residues in the different departments of Brittany. Depending on the respective department of Brittany, the total sustainable wheat straw is approximately 33% to 35% of the theoretical potential when competing use and environmental constraints are taken into account. These figures are in agreement with Gauder et al. (2015) who find that about 30% of the theoretical potential can be used for energy purposes or other industrial uses. Our estimates are also in line with those of Weiser et al. (2017) who concluded that the share of available cereal straw for bioenergy in different municipality of Germany was between 0 to 87% of the theoretical residues straw potential.

Our analysis of available residues potential for bioenergy did not consider the ‘4 per 1000’ initiatives launched by the French Government at the Paris climate summit in 2015 and which aims to boost carbon sequestration in agricultural soils by 0.4% each year to help mitigate climate change and increase food security. Consideration of this initiative could substantially reduce the amount of available agricultural residues for bioenergy since residue return to soils is a prime avenue to increase soil organic C content. It is possible to increase the current volume of agricultural residues in Brittany by using improved seeds or through the development of improved plant protection, mechanisation and use of fertiliser. Indeed, improved seeds or improved in agricultural mechanisation could substantially increase agricultural residue potentials due to changes in residues to grain ratios (Muth et al. 2013, Daioglou et al. 2016).

Available agricultural residues for bioenergy are sensitive to parameters such as the residue-to-crop ratio, the sustainable removal rates. However, a constant coefficient of residue-to-crop ratio, as well as constant values for the sustainability was assumed in our modelling of available residues. This means that differences in soil types as well as other regional factors that influence soil organic carbon storage were neglected in our study. The amount of residues collected is also be influenced by the profitability of biomass for farmer. However, socio-economic constraints were not considered in our analysis as we assumed that residues are by-products left in the fields after harvesting operations. There is currently no market for corn stover in Brittany (no competing uses). Thus, the development of a bioenergy plant such as Empyro in Brittany should have a positive impact for farmers, as it will bring additional income. Consistent biomass supply and feedstock price are important factors for the development and expansion of bioenergy in Brittany.

3.10.2.2 Marginal lands

We showed that Brittany has limited but non-negligible marginal land potentials for miscanthus production. Indeed only about 57544 ha of marginal lands are available in the region for growing energy crops for bioenergy. However, we did not estimate how much, if any, of the marginal land potentials may have already been utilized. This means we assumed that limited or no development at all had occurred on these lands. Thus, the amount of marginal lands in this study may have been overestimated. It is important to note that our analysis also excluded urban marginal lands, thus marginal land potentials of Brittany could increase significantly increase if we extended the analysis to include urban degraded/marginal lands.

3.10.2.3 Miscanthus on marginal lands

Cellulosic crops, such as Miscanthus, normally have higher nutrient-use efficiency (Lewandowski et al. 2003, Fargione et al. 2010) and possibly higher water use efficiency than food crops (Stewart et al. 2009, Zhuang et al. 2013). They could therefore grow on marginal lands instead of competing with food crops for fertile croplands. Our results indicated that about 352 kton yr^{-1} miscanthus biomass could be produced on marginal lands (57544 ha) in Britany based on an average yield of 6.2 ton $ha^{-1}yr^{-1}$. Field measurements of miscanthus on marginal lands show biomass yield ranges of 3 to 15 ton $ha^{-1}yr^{-1}$ (Searle & Malins, 2014). Our estimated mean yields of miscanthus on marginal lands in Brittany are similar to the yield ranges for miscanthus reported by Searle & Marlins (2014). These yields are somewhat lower than simulated or observed yields of miscanthus on fertile lands (Gelfand et al. 2013). This may be partly because that besides nutrient other factors could also affect biomass production on marginal lands, for example, water availability, climate conditions, and soil fertility (Cai et al. 2011). Several experimental sites around the world are testing the production of miscanthus and other energy crops on marginal lands. However, it is not sure that all the energy crops could exhaustedly be tested on the wide range of marginal lands being use today. Modelling experiments as the one carried-out in this case study can help in assessing the wide potential of energy crops on these lands.

We found that Brittany has a substantial amount of marginal lands available and that about 1660 GWh of bioenergy could be generated from these lands in the 4 contiguous departments of Brittany. To put things in perspective, Brittany consumed roughly 2300 GWh bioenergy in 2014. According to the results of our study, marginal lands of the 4 departments of Brittany could supply 72% of this amount of bioenergy. It is however, unrealistic to assume that all of the bioenergy potential on marginal lands could be realized, but even if half of that potential is developed, it can still contribute substantially to the renewable energy portfolio of the region. Marginal lands are particularly promising for the development of bioenergy technologies but also hold a great potential for other renewable energy technologies expansion (e.g. photovoltaic and wind). These renewable energy technologies (i.e. bioenergy, wind and photovoltaic) may have to compete for development on these marginal lands, although some could coexist (e.g. energy crops and wind power). Moreover, distribution of wind and solar in the region reduces to a large extend the competition among these renewable energy technologies.

As discussed above, the quantified amount of available agricultural residues for bioenergy may be overestimated because it ignores the '4 per 1000'intiatives of the French government. Factoring in the '4 per 1000' objectives would certainly reduce the residue removal rates and thus the volume of agricultural residues for bioenergy. However, because miscanthus has high potential to store carbon in the marginal soils, it will not only contribute to the '4 per 1000' initiatives of the French government but also allow keep the current residue removal rates - and thus available residues for bioenergy- unchanged. In fact, miscanthus can store about 0.66 tC ha^{-1} yr^{-1}, mainly due to leaf litter and development of belowground roots and rhizome systems (Don et al., 2011). This capability to store organic matter helps maintain soil structure, reduce soil erosion risks, and ultimately upgrades the soil quality of marginal lands. A careful assessment of the competing uses, including, carbon storage and habitat conservation is required when considering marginal lands to produce miscanthus to complement existing biomass resources.

While networks and logistics chains already exist for agricultural residues, there are challenges to implement logistic chains for biomass resources from marginal lands. Indeed marginal lands areas are often not accessible or poorly accessible due to the lack of roads for transporting the produced biomass. Although they are outside the scope of this report, the logistics of growing, harvesting, densifying, transporting and storing biomass collected from several sparsely located plots/parcels will be complex.

3.11 Conclusion of the Brittany case

Brittany has a non-negligible potential for biomass supply from agricultural residues, which poses less risks in terms of food security. Corn stover was the residues with the highest potential followed by wheat straw and rapeseed stalk whereas the department of Ille-et-Vilaine was the department with high concentration of agricultural residues. These raw materials (corn stover, wheat straw, rapeseed stalk) can contribute to the transition towards bioeconomy and supports the diversification of the current energy systems. The spatial differentiation of residue potentials in Brittany obtained here provides detailed information on the location and availability of these resources in the region. Lands classified as marginal vary extremely within the four department of Brittany with regard to their soil properties. Miscanthus has a high potential for cultivation on marginal lands in Brittany. Its yields on marginal lands are lower relative to miscanthus yields on productive lands, but superior to agricultural residue yields in Brittany. However, site-specific experimental data on cultivation and harvesting of miscanthus on the identified sites is necessary to validate its growth suitability on these marginal lands. The practical implementation of a sustainable bioenergy production from marginal lands is highly dependent on economic trade-offs as well as on supportive policy mechanisms and regulations. Moreover, additional financial supports and incentives for farmers are still needed to overcome the relatively low yields of energy crops on marginal lands compared to highly productive soils

4 Residues and energy crops generation potential in Soria (Spain)

4.1 Background

Castilla-Léon (NUTS2[4]) is an autonomous community in north western Spain encompassing the provinces of Avila, Burgos, Léon, Palencia, Salamanca, Segovia, Soria, Valladolid and Zamora. It is the largest Spanish autonomous community in terms of area (94222 km^2) and the 1st autonomous community in Spain in renewable energy production with 22% of the national total. This leadership of the community in renewable energy production has been possible owing to the development of clean energy that have been coordinated through the 2010-2020 bioenergy plan, which has established the basis for the promotion of the different uses of bioenergy (electricity, heat, fuel) in the last 10 years. Bioenergy is currently the largest source of renewable energy in Castilla-Léon and the region aims to increase its bioenergy production to meet the ambitious energy security and climate targets of the Spanish government. Soria is one of the nine provinces of the autonomous community of Castilla-Léon. This NUTS3 region is located in northern central of Spain at an altitude of 1063 m above sea level and it has a total land area of 10286 km^2. The province of Soria is composed of 10 NUTS3 *comarcas* (Almazán, Burgo de Osma, Campo de Gómara, El Valle, Pinares, Soria, Tierras Altas, Moncayo, and Medinaceli) as shown in Figure 6. Its geography features a very heterogeneous environment ranging from high mountains to deep valleys as well as the characteristics of summer grasslands. The average annual temperature is 10.5 ^{o}C and the average annual precipitation is about 500 mm. The climate conditions are continental-Mediterranean. Like other provinces of Castilla-Léon, Soria has established measures to foster bioenergy production from agricultural and forest residues as well as from energy crops.

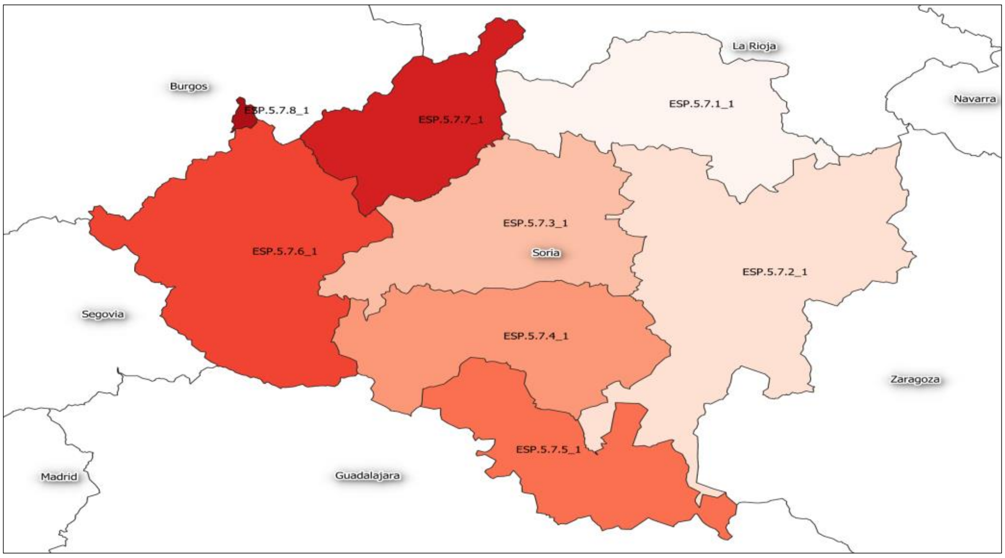

Figure 6: The province of Soria and its 10 NUTS3 Comarcas

[4]According to the NUTS classification, Spain (NUTS-0) is devided into clusters of autonomous communities (NUTS-1), autonomous community (NUTS-2), provinces (NUTS-3), and municipalities (NUTS-4)

Agriculture and forestry are the corner stone of industries that produce food, feed and biomaterial in the Soria. Both sectors represent together the largest sources of residues biomass in Soria. Agricultural biomass residues in Soria are predominantly stalk and straw from wheat, barley, and rye which are the main crops grown in the province for food and feed for livestock. Forest residues in the region consist of the foliage of trees, tree tops unmarketable parts, and undergrowth trees such as shrubs. The total volume of both agricultural and forest residues is large, but these residues will not suffice to meet the increasing bioenergy demand of the province given their current demand in other sectors of the economy as well as other environmental issues that satisfied. Use of energy crops such as tall wheat grass and Siberian elm can alleviate pressures on forest and agricultural residues in Soria, but unless grown on marginal lands, producing energy crops on fertile lands competes directly with food, feed and fibre production. The need for the cultivation of cellulosic energy crops on marginal lands is supported by the facts that *i)* there is an increasing need for fiber crops for biobased products; *ii)* there is need for second generation biofuel to meet the growing biofuel demands in Soria by 2030; and *iii)* climate change will force Spain and other southern European countries to shift to less intensive cultivation. However, a detailed assessment of the distribution of agricultural and forest residues for the province is missing. Moreover, high-resolution inventory assessments of marginal lands as well as estimates of productivity of energy crops that can growth on these lands have never been carried-out.

Several studies have assessed the global, regional, and national potential of agricultural and forest residues for bioenergy production (Berndes et al. 2003, Hoogwijk et al., 2005; Hamelinck & Hoogwijk 2007, Scarla et al. 2010, Dornburg et al. 2010, Chum et al. 2011). Although these studies agree that agriculture and forest residues are important feedstock for bioenergy, they achieve varying results due to inconsistent methodology and a poor understanding of the drivers for the availability of these biomass resources. Also missing in previous studies is the assessment and distribution of both agricultural and forest residues at provincial scale (NUTS3), rendering decision making about these biomass resources at local level tedious. Similarly, investigations on marginal lands have been limited to national, regional or global scales with little or no investigations at provincial (NUTS3) levels. It is evident from previous researches that several challenges must be addressed to ensure that residues and marginal lands can be used as valuable bioenergy feedstock. In particular, the uncertainty of biomass availability can increase the risk of wrong decision making in the biomass supply chain. The objectives of this case study are: *a)* to quantify and map agricultural and forest residues in Soria; *b)* to identify and estimate marginal lands suitable for energy crops that could supplement agricultural and forest residues in Soria; *c)* to simulate the yields and distribution of these energy crops on marginal lands in Soria

4.2 Land use and land cover in Soria

Figure 7 shows the land use and land cover of the province of Soria. Similar to the Castilla-y-Léon province, Soria has heterogeneous lands, with areas of forest in the north and agriculture in the south.

Arable lands prevail in Soria with 34% of the total land area, mainly in the southern, eastern and western parts of the province, followed by shrubs (24%) and forests (23%). These three land uses represent more than 80% the total land use in Soria. Forest dominates in the north while the southern, eastern and western parts of Soria are largely a mix of arable, shrub, and pasturelands with localised concentration of forests. The remaining land use is composed of pasture (13%), road (3%) water (1%) unproductive lands (0.7%) and 0.3% of total land destined to fruits production. Buildings and roads together represent a very small fraction <1%.

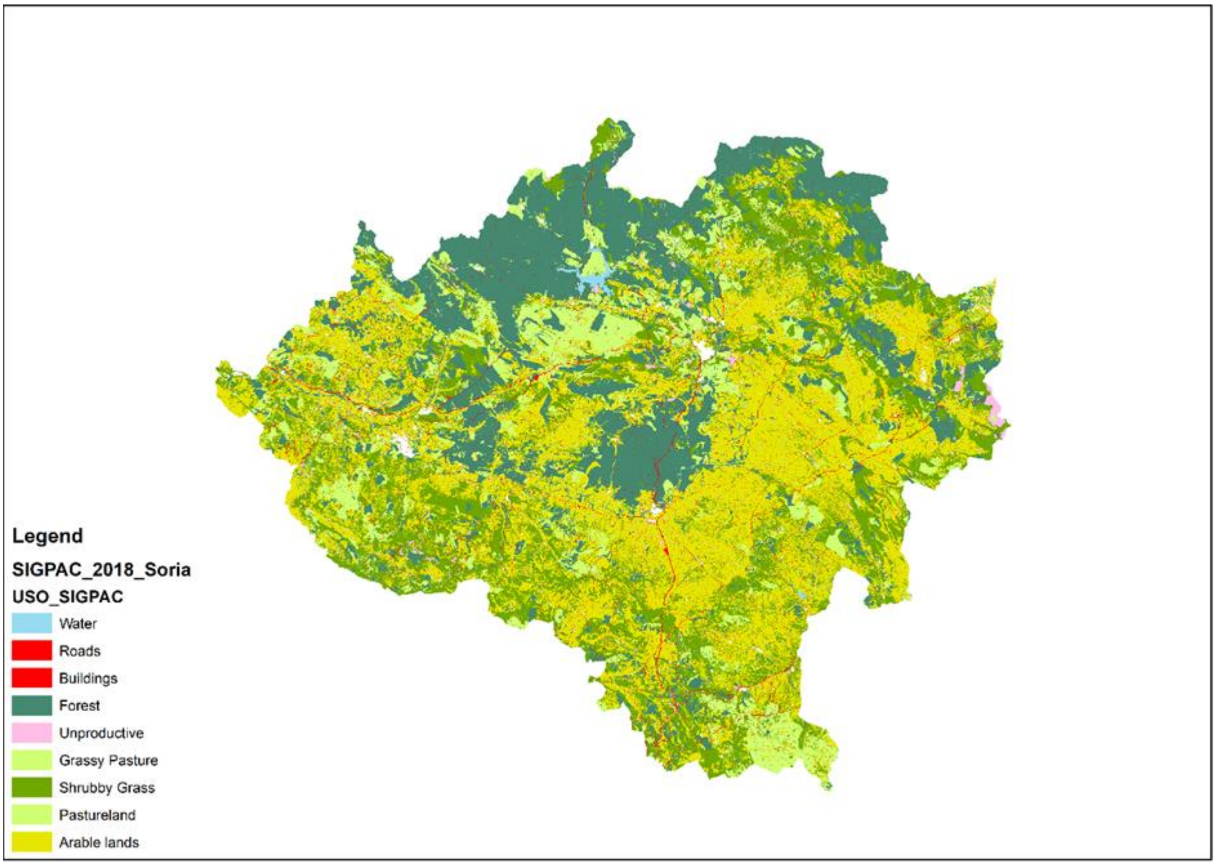

Figure 7: Land use/cover of the province of Soria (Spain) derived from SIGPAC 2018[5]

4.3 Residues considered in the Soria case study

Unlike in the Brittany case, two types of residues were assessed in the Soria, these are agricultural and forestry residues. Agricultural and forestry sector in Soria are important provider of cellulosic biomass. Agricultural residues constitute large biomass resources in Soria and the agricultural residues of interest in this case study include herbaceous crops by-products cereal straw, corn stover, and permanent crops residues like orchard pruning. Similar to the Brittany case, secondary agricultural residues (dung, manure, and slurry), agro-industrial by-products such as olive cake as well as residential and post-

[5] Land cover categories were simplified to depict the major categories analysed here

consumer wastes were excluded from this analysis because of their non-cellulosic nature and their low generation volume.

Forest residues represent a highly heterogeneous mix of biomass including small trees, branches, tops, and un-marketable wood left in forest after the cleaning, thinning or final felling of forest stands. They can be grouped into forest production and forest growth residues. Forest residues are forest biomass generated during the forest management and production processes. They are mainly generated during forest cultivation, tree production stages, soil fertility maintenance, forest pruning, stem fixing and cutting of pseudo-stem, young forest tending, thinning and harvesting. Forest growth residues are residual biomass resources that are not included in the industrial timber-harvesting plan such as shrub stumping. As for agricultural residues, by-products and coproducts of industrial wood processing (bark, sawmill, slabs, sawdust, woodchips) as well as other secondary forest residues were excluded from the assessment.

4.4 Estimations of forest and agricultural residues in Soria

Agricultural residues: To ensure consistency, we applied the same method for computation of agricultural residues in Britany to the case study in Soria. So except the residue-to-grain ratio which was unchanged because it is crop specific and not related geographical location, other parameters which are location specific (e.g., residue recovery rate) and affected by the management practices, harvesting equipment, and climate conditions (Monforti et al. 2015, Scarlat et al. 2010) were changed accordingly to reflect the local conditions prevailing in Soria. We also considered different competing use and soil sustainability factors for Soria relative to the Brittany case. Parameters used to estimate agricultural residues in Soria were collected from the literature and used in the equation 3-5 below to derive the available agricultural residues for bioenergy in Soria.

Forest residues: Forest residues sources are diverse and include amount other *i)* stem wood (branches, harvest losses), *ii)* young biomass from early thinning/pruning in young forest, *iii)* stumps/roots, and *iv)* shrubs. The theoretical forest residue potential was estimated for the 2018 period for the residue sources listed above. We estimated the theoretical forest residues in Soria based on the detailed forest inventory data in Spain. This theoretical potential relates to the maximum productivity under fundamental biophysical limits, taking into account increment, the age structure, and stocking density of the forests (Vis et al., 2011). To quantify the forest residues in Soria, we used the SIGPAC parcel information for spatial distribution of forest residues over Soria. A 1 km x 1 km grid was made covering Soria, and for each 1 km x1 km raster cell the areas of forest parcels were added to a sum of forest area within that cell. The total forest area for Soria was calculated by summing all areas of forest parcels in Soria.

4.5 Data collection and sources

The marketable volumes of logs and timbers needed for the calculation of the final felling and bucking residues were taken from the Spanish National Forest Inventory. The basic data for the estimation of tending and thinning residues is gathered the National Forestry resources statistics; when data was missing, literature estimates were used. The residue to production ratios of the different round production were collected from the literature.

4.6 Mapping potential and available agricultural and forest residues in Soria

Agricultural residues: Estimation of theoretical and available as well as the mapping of agricultural residues in Soria was carried-out in similar manner than in Brittany. After quantification of therotical residues, we applied some ecological and competing use constraints to derive the available residues in Soria. Finally a residues density map of a spatial resolution of 1 km x 1 km grid cells was generated using ArcGIS software.

Forest residues: To avoid overlap we applied a spatially explicit approach to quantify these environmental and technical constraints. We used datasets on: site productivity, soil surface texture, soil depth, and soil bearing capacity natural soil susceptibility. A spatial datasets was combined with the relevant constraints values for the different mobilization scenarios. A raster layer was created for each constraint with a resolution of 1 km x 1 km grid cells. Finally, all relevant layers were combined and the lowest, permitted extraction rate was defined for each pixel. The resulting raster layers were combined with the Spanish forest map to calculate the weighted average restrictions per region. This was done separately for the constraints related to logging residues and stumps from thinnings and final felling.

4.7 Identifying and mapping marginal land resources in Soria (Spain)

We used the same approach as described in section 4.6 of this report to identify and map marginal lands in Soria. First, a number of biophysical factors were used to identify, screen, and to characterise marginal lands in Soria. A correction was the made by excluding areas where natural constraints were neutralized as result of improvement in agronomic practices such as fertilization, irrigation, drainage and creation of terraces, to overcome the specific natural constraints. Different sources of spatial data were used to identify the marginal lands where land improvements were made and where intensive agricultural production occurs now. A detailed spatial analysis was performed to verify that natural constraints were indeed neutralized.

4.8 Tall wheatgrass and Siberian elm cultivation on marginal lands in Soria

Perennial C_3 crops may be well suited in regions where winter rainfall is available, such as in the continental-Mediterranean climate of Soria. Perennial C_3 crops, like tall wheatgrass (*Thinopyrum* *ponticum*) and Siberian elm (*Ulumus pumila*) may require less irrigation in mediterranean climates because of their ability to grow during the wet cooler months. Tall wheatgrass is a perennial grass native to Turkey, Asia and Russia (USDA, 2008). It can tolerate up to 1% soluble soil salts. In its native habitat it is often associated with saline or alkaline soils (Suyama et al. 2007). It grows particularly well in moderately to severe saline areas and persists in winter waterlogged soil that dry out in summer, it grows equally well in acid and alkaline soil (Robinson et al. 2004). Tall wheatgrass is a promising bioenergy crop, being used as a perennial alternative for pastures sown in non-saline and low-rainfall environments. The crop has also demonstrated a high potential for use in soil conservation roles in many places. Dry matter production of tall wheatgrass depends on soil types, water supply and fertilization. It ranged from 13 to 25 ton ha^{-1} yr^{-1} while the carbon sequestration rate of this crop can be similar to that of switchgrass which ranges from 0.4-0.68 tC ha^{-1} yr^{-1} (Anderson-Texeira et al.2009). The life-span of tall wheatgrass cultivation for energy purposes can be 10-15 years long.

Siberian elm is (*Ulumus pumila*) is a fast growing deciduous tree native to northern China, eastern Siberia, and Korea (Fu et al. 2002). It prefers well-drained, fertile soil and full sun. However; it is highly adaptable and easily it tolerates a variety of condition such as poor, dry soils, and cold winters and long periods of summer drought (Wu et al. 2003). It has shown considerable biomass productivity under rain-fed conditions in Europe, and owing to this capacity, it is being considered as feedstock in large-scale bioenergy projects in areas above 300 mm annual rainfall (Perez et al. 2014). The biomass yields of Siberian elm on poor soils with limited water availability have been reported to vary between 12-14 ton $ha^{-1}yr^{-1}$ in the mediterranean areas of Spain (Geyer et al. 1987, Perez et al. 2014). Like many perennial woody crops, Siberian elm store carbon in soil during plant growth and the reported carbon sequestration rates of Siberian elm in the literature could be similar to that of poplar, which varies from 0.3 to 1.16 t C ha^{-1} yr^{-1} (Sierra et al. 2013). The lifespan of Siberian elm can extend beyond 50 years. There are numerous environmental and economic benefits of perennial grasses and perennial trees for producing bioenergy compared with food crops, such as corn. These benefits together with increase biodiversity and increased net economic returns are among other the main incentives to grow Siberian elm on marginal lands (Pacala et al. 2004, Lemus et al. 2005, Follett et al. 2001, Bekessey et al. 2008). Although both tall wheatgrass and Siberian elm have been little studied compared to other lignocellulosics (Laurent et al., 2015), sufficient data are available to simulate their yields on marginal lands and to estimate the contribution they might make to bioenergy supply in Soria if used as feedstock for bioenergy production.

4.9 Productivity of tall wheatgrass and Siberian elm on marginal lands in Soria

Simulation of biomass yields of tall wheatgrass and Siberian elm in Soria was carried-out using a similar procedure similar to that described in the Brittany case (section 4.9). However, given the lack of process-based crop models for both crops, switchgrass was first simulated as a proxy from which information on the spatial variability of tall wheatgrass and Siberian elm could be derived using yield ratios following the meta-analysis of Laurent et al. (2015). Both crops were also tested in local trials run by the CEDER research centre of CIEMAT in Soria (Val et al. 2015, Garcia, 2016), along with some of the crops reviewed by Laurent et al. (2015). Unfortunately, neither tall wheatgrass nor Siberian elm was present in this meta-analysis on the productivity ranking of lignocellulosic crops, but canary grass featured in both this global database and the Soria trials (Val et al., 2015). So it could be used as an intermediate proxi crop to work out a ratio of switchgrass to tall wheatgrass and Siberian elm. Canary grass yields twice less than switchgrass overall, according to Laurent et al. (2015), tall wheatgrass yields about 40% more than canary grass in Soria – as a consequence, the yield ratio of tall wheatgrass to switchgrass would be around 70% in the Soria area.

The respective yields of tall wheatgrass and Siberian elm still warrant a thorough comparison based on the Soria trials, but overall they seem to perform in a similar range: tall wheatgrass yields varied between 1 and 2 ton ha^{-1} yr^{-1}, whereas the range for Siberian elm was 1.2 - 2.5 ton ha^{-1} yr^{-1} in rain fed conditions (Perez Garcia, 2016). A yield ratio of 1 to 1.1 may be used pending further analysis of the annual (or tri-annual for Siberian elm) data. To map out switchgrass yields in this region, the CERES-EGC model was used with a similar setup as for the Brittany case, albeit for this particular crop (see section 4.9 for a detailed description of the model and its testing). The gridded weather were derived from another source as part of the FP7 project Animal Change (Marco Carozzi, pers. communication, May 2019) - for the data point corresponding to the Villasayas municipality in the centre of the simulation domain (41.375° N ; -2.625° E). The series pertain to past and future climate data over the 2010-2030 time, out of consistency with the Brittany simulations.

Soils data extracted from Soils Grids repository from ISRIC (www.soilsgrids.org), clipped to the Soria province with pixels ~ 1 km² in area, and total of 38 700 pixels in the simulation domain (3.87 Mha in size). The following properties could be extracted (down to 2 m depth) : soil water content at wilting point, sand and silt content, organic C stock (tonnes C ha^{-1}), gravel content, pH (in water). Bulk density and soil depth (depth to bedrock) were not available, unfortunately. By default they were set to the values estimated by M. Carozzi (pers. comm.) for the Villasayas grid point: a depth of 1.35 m to bedrock for soils (corresponding to a rooting depth), and a bulk density around 1.39 g/cm^3 soil. In a first run, no marginality factors were applied except the effect of low pH, based on the tolerance scores reported in the Magic Crops database. In terms of management, switchgrass was fertilized with annual inputs of 60 kg N ha^{-1}, as per the recommendations of the MAGIC Crops database (WP1), which mentions a 50 – 100 kg N $ha^{-1}yr^{-1}$ range. No limitations from P/K availability were taken into account (since CERES does not simulate them). Yields, N_2O emissions and soil C changes over 28 years were averaged over the crop growing cycle (28 years) and exported to a csv format file used for mapping purposes.

4.10 Mapping the yields of tall wheatgrass and Siberian elm on marginal lands

Mapping of tall wheatgrass and Siberian elm is Soria was carried out in similar way as the mapping of miscanthus in Brittany. Model estimates were used to generate the spatial distribution of biomass production of tall wheatgrass and Siberian elm on marginal lands in Soria.

4.11 Results and Discussion of the Soria case

4.11.1 Results

4.11.1.1 Agricultural and forest residues

The theoretical and available agricultural residue potentials for each of the 10 *comarcas* (groups of municipalities) of the province of Soria are presented in Table 5. The total theoretical residue potential from cereals, corn and oil crops is estimated at 1574 kton yr^{-1}, but only 521 kton yr^{-1} is available due to sustainability and competing uses issues. The total unavailable amounts of cereal straw required to meet the sustainability and competing uses amounted 876 kton yr^{-1}, resulting in a net cereal residues availability of 472 kton yr^{-1}. The theoretical residue potentials from corn and oil crops were 3 ktons and 222 ktons, respectively. However, 14% of the theoretical potential for corn and 79% of the theoretical potential for oil crops are required for maintaining soil carbon and for proving livestock bedding. This leads to net available potentials of 2 kton yr^{-1} for corn stover and 47 kton yr^{-1} for oil crops stalk (Table 5). Assuming energy density of 17 GJ ton^{-1}, the total bioenergy from these agricultural residues was 9 PJ yr^{-1} (3 TWh yr^{-1}).

Table 5: Potential residue generation and available residues for bioenergy in Soria (kton yr^{-1})

NUTS3 region (province)	**Theoretical residues potential**			**Available residues for bioenergy**		
	Wheat straw	Corn stover	Oil crop stalk	Wheat straw	Corn stover	Rapeseed stalk
Total	1348.4	2.6	222.8	471.9	2.2	46.7

Apart from agricultural residues, another source of lignocellulosic biomass in Soria include is forest residues. The total theoretical forest residues for all comarcas of the province of Soria were estimated at 39 kton yr^{-1} (Table 6). The total theoretical forest residues in Soria depended on the biomass potential type that is considered. The majority of this potential is composed of coniferous forest residues (79%) and broadleaved forest residues (21%), respectively (Table 6).

Table 6: Theoretical forest and available residues production for bioenergy in Soria (kton yr^{-1})

NUTS3 region (province)	**Theoretical forest residues potential**		**Available forest residues for bioenergy**	
	Broadleaved forest	Coniferous forest	Broadleaved forest	Coniferous forest
Total	8.2	30.9	5.9	22.2

A large fraction of these residues is located in the comarca of Pinares, the comarca Tierra Altas, and the comarca of Soria, while the comarca with low forest residues are located in the southern parts of the province of Soria (Almazan, Gomara) (Figure 7). The northern regions of the Soria province possess high amount of agricultural residues and can be seen as a hotspot region in terms of biomass potential for biorefinery. The total forest residues of Soria accounted for 2 % of the total forest residues of Spain. As in the case of agricultural residues, about 0.48 PJ yr^{-1} bioenergy (0.13 TWh yr^{-1}) can be produced from these forest residues, if energy density of 17 GJ ton^{-1} is assumed. The computation of available forest residues for bioenergy does not capture the effect of protected areas. It is recommended that at least 10% of the total forest area should be protected and not used for wood production. Doing this will reduce the total available forest residues for bioenergy. But it will also increase the overall biodiversity of these forests given that these areas will not see any management.

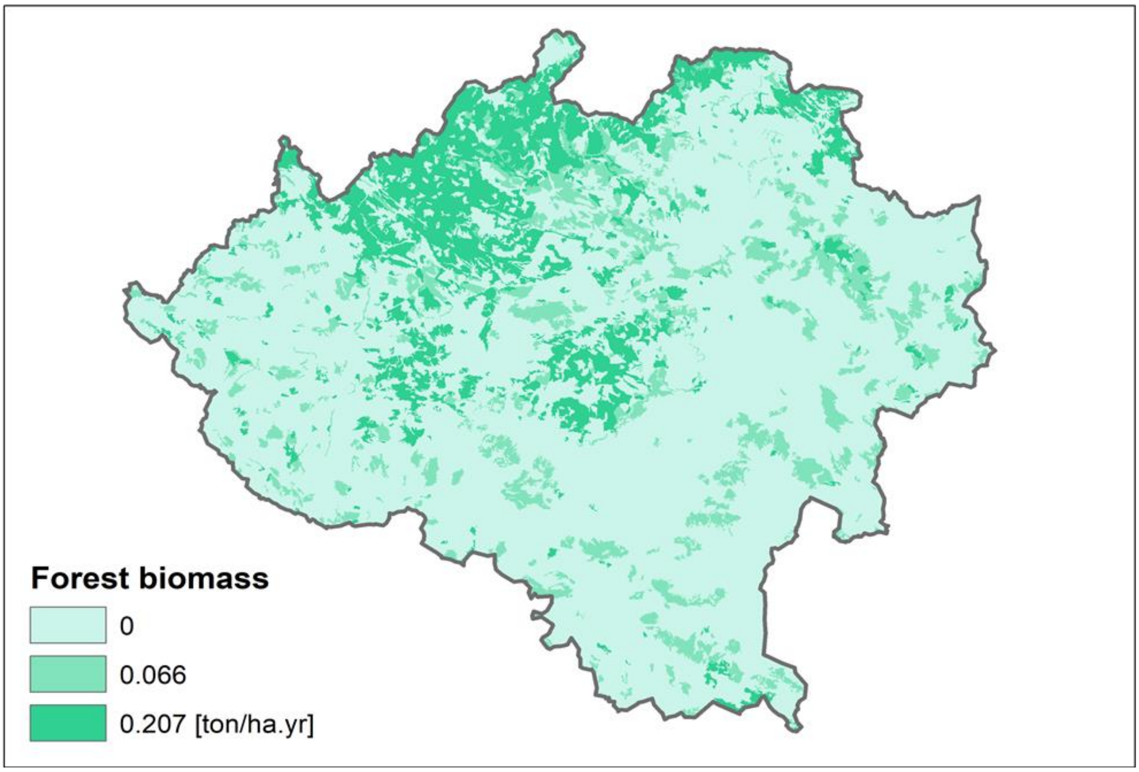

Figure 7: Productivity and distribution of forest residues in Soria

4.11.1.2 Marginal lands in Soria

There are about 376500 ha (3765 km^2) of marginal lands in the province Soria that are potentially suitable for energy crops cultivation, which represented about ~37% of the total cropland area in the province of Soria (Table 7).

Table 7: Contribution of marginality factor to the total marginal lands in Soria

Marginality factors	Surface (ha)	Share of the total (%)
Climate	6300	0.61
Climate-rooting	12600	1.22
Climate-fertility	300	0.03
Climate fertility-rooting	5600	0.54
Terrain	1100	0.11

Rooting	323100	31.39
Rooting-terrain	200	0.02
Fertility	13900	1.35
Fertility-rooting	13400	1.30
Total marginal lands in Soria	**376500**	**36.58**
Non marginal lands in Soria	**652600**	**63.42**
Total arable land in Soria	**1029100**	**100.00**

The prominent marginality constraint in the province of Soria was low rooting potential arising low rootable soil volume or unfavorable soil texture. Fertility and climate limitations related to low precipitation and short growing season were also a cause of marginality in Soria. These factors mostly occur in combination with rooting limitations (Table 7).

4.11.1.3 Productivity of tall wheatgrass and Siberian elm on marginal lands in Soria

Tall wheatgrass and Siberian elm were selected among the energy crops that could grow on these marginal lands due to their suitability and adaptability to those areas. According to the CERES-EGC simulations, potential yields of tall wheatgrass on marginal lands in Soria varied between 3.1 and 4.3 ton $ha^{-1}yr^{-1}$ with a mean yield of 3.8 ton $ha^{-1}yr^{-1}$ over the whole identified marginal areas in this region. Siberian elm slightly produced more biomass on these lands than tall wheatgrass, its yields ranged from 2.8 to 6.7 ton $ha^{-1}yr^{-1}$, with an average yield of 4.2 ton $ha^{-1}yr^{-1}$ over the identified marginal lands in Soria. The total biomass production from marginal lands in Soria varied between 1431 and 1582, kton yr^{-1}, depending on the energy crop cultivated on these lands.

4.11.2 Discussion

4.11.2.1 Agricultural and forest residues

The results show that about 521 kton yr^{-1} biomass residues are available for bioenergy production in Soria. This estimation is comparable to value obtained in previous study (S2Biom, 2017). It is clear that Soria has limited residue potentials, but their recovery for energy purposes not only solve the problems related to their disposal, but also reduces the fuel load present in forest ecosystem, thus reducing the risks for wildfire, increasing biodiversity and offering better conditions for native species. By providing data on the available biomass types, the status of biomass potential in Soria is clear and straightforward. This can assist the policy makers to develop relevant legislation that can assist the development of regional solutions that will be optimized for the locally available biomass. This can reduce the costs and carbon footprint from the transportation of biomass.

4.11.2.2 Marginal lands in Soria

Potential marginal land areas for energy crops cultivation in Soria are ~376500 ha. Land marginality is a fundamental limiting factor for plant growth. Therefore, the selection of the most adapted species to these extreme conditions is of major importance to the sustainable biomass production. Both tall wheat grass and Siberian elm were found suitable for cultivation in most of these sites in Soria. The suitability of a marginal land for cultivation of bioenergy crops does not assure sustainable bioenergy production. Feedstock quantities, continuous supply, cultivation and harvesting techniques, as well as transportation and processing to final bioenergy products are other aspects of the value chain that should be considered. Moreover, the environmental, economic, and social impacts of bioenergy production should be studied.

4.11.2.3 Tall wheatgrass and Siberian elm on marginal lands in Soria

There is growing interest to establish energy crops on marginal lands to meet ever-increasing demand of bioenergy and to fulfil national and international obligations on reducing fossil fuel related greenhouse gas emissions while avoiding conflict with food crop production and carbon emissions from land use change (Schemer et al. 2005, Tilman et al. 2009, Dillen et al. 2013). Biomass yield is a key factor in the selection of candidate energy crops. Our analysis showed that Siberian elm had higher biomass yield than tall wheatgrass on marginal lands in Soria. No study exists that compare biomass yields of tall wheatgrass and Siberian elm on marginal lands or on fertile soils. Studies comparing the biomass yields of herbaceous and woody energy crops are inconclusive. For instance, Ashiq et al. (2017) show that biomass yields of poplar were significantly higher than that of switchgrass on three marginal lands in Canada. In contrast, Amaducci et al. (2017) compared the yields of six biomass crops including poplar and switchgrass and found that switchgrass yielded more biomass than poplar. Mann (2012) did not find any difference in biomass yields during the first growing season of poplar and switchgrass in Ontario (Canada). Similar results were reported for the 5th growing season of the same crops on the same site by Marsal et al. (2016). In general, tall wheatgrass, like other herbaceous energy crops is harvested once a year while Siberian elm is harvested over a short rotation of 2-5 years. Siberian elm is also considered better than tall wheatgrass due to higher energy density and lower ash content, which are essential elements to consider for industrial scale biomass production and easy processing (Mann, 2012). Siberian elm also has the advantage of shedding its leaves every year, which adds nutrients to soil (Hangs et al. 2014). On good soils with sufficient nutrients, biomass yields range from 4 -17 ton $ha^{-1}yr^{-1}$ for Siberian elm (Geyer et al. 1993, Perez et al. 2014), and from 5 -14 ton $ha^{-1}yr^{-1}$ for tall wheatgrass (Lauriault et al. 2002, Pedroso et al. 2014). Yields obtained in this report are much lower than those of both energy crops on good soils. Consequently, most of these marginal lands would be able of producing only low to medium yields. This is in line with studies that have concluded that yields are much lower on marginal lands than on croplands.

4.12 Conclusion of the Soria case

This analysis has established that available agricultural and forest residues for bioenergy in Soria is limited (~28.1 kton yr^{-1}), especially when compared to Brittany where large amount of agricultural residue is available. However, the potential of marginal lands in Soria is large (376500 ha) which could provide additional biomass for bioenergy supply in the region without conflicting with food production. Both tall wheatgrass and Siberian elm have shown great potential for biomass production on these lands. Together, both residue and energy crops from marginal lands could provide a more secure and sustainable source of biomass to support second generation biorefining operations, allowing technological advancement and the development of future added value products. This approach would contribute to Soria’s bioenergy requirement in the short term and support the economic growth and environmental sustainability over a long period. Bioenergy development is important, but full of challenges. Further research should focus on choosing the best suitable energy crop, improve marginal land resources using more accurate data.

5 Overall discussion

5.1 Agricultural and forest residues

We estimated the agricultural and/or forest residue potentials of two regions (Brittany and Soria) within two EU's member states (France and Spain). We found that the theoretical residue potential in Brittany was 5627 ktons yr^{-1} and mainly consisted of agricultural residues while in Soria the potential was 1613 kton yr^{-1} and made of agricultural residues (97.6%) and forest residues (2.4%) under current conditions. In the French case for example, we included only agricultural residues for the reason that Brittany has limited forests cover, while for the Spanish case both agricultural and forest residues were taken into account. Residue types studied in Brittany are cereal straw, corn stover, and rapeseed stalk, while in Soria sunflower stalk was also studied in addition to cereal straw and corn stover. With regards to forest residues in Soria, both residues from broadleaved and coniferous forests were investigated. It is crucial to mention that estimates of residues in this report may be affected by the availability and reliability of data on crop and tree species, crop yields, forest productivity, harvest index, location, soil properties, and seasonal variation. Moreover, the potential of agricultural residues as a bioenergy source is complicated by their numerous competing uses including feeding, fodder, fertilizer, and industrial fuels.

Several authors have assessed the availability of agricultural and forest residues biomass at global regional, EU and state levels (Verkerk et al.2011, Di Fulvio et 2016, S2Biom 2017, Jonsson et al. 2018). Our study extends the existing studies by providing information on potential biomass from agricultural and forest residues at NUTS3 levels and their distribution in these regions. However, it is difficult to compare our finding to those reported in the literature as very few studies provide estimates of agricultural and forest residues at NUTS3 level. Differences in estimates of this study with those in literature include differences in methodology and models used, data used and sources, difference crop/forest residues considered, assumptions used (e.g., harvested crops/forest areas, requirements for livestock feed etc.) as well as social constraints that limit the mobilization of agricultural and forest residues (Verkerk et al. 2011).

A few EU member states have introduced policies that stimulate the deployment of second generation bioenergy/biorefinery technologies with minimal climate impacts and low land requirements. Agricultural and forest residues have low or no additional land requirements (Creutzig et al. 2015), but to be sustainable residues extraction should not lead to erosion or losses in soil fertility, biodiversity, carbon stocks or ecosystem services (Lal 2005, Liska et al. 2014, Raffa et al. 2015, Repo et al. 2015). Quality and logistical constraints may reduce the quantity of agricultural and forest residues that can be used in reality or increase transport and processing costs. If transport distances to processing locations are for instance too large, high transport costs may render residues use infeasible, while GHG emissions from transport could make residue use undesirable (Pereira et al. 2015).

5.2 Marginal lands in the studied cases

As mentioned in the Methods section, the definitions of marginal lands vary widely in the literature. In this study, marginal lands was defined, selected and mapped according to biophysical factors. We found that about 57544 ha and 37650 ha marginal lands are available in Brittany (France) and in Soria (Spain), respectively, for the production of energy crops. Stoniness, salinity, fertility, climate and the organic matter content were the most marginality constraints in these two regions. Together, these three factors represented more than 95% of all the marginality constraints assessed in this report. Like other previous studies, our analysis did not include issues such as lack of vegetation, soil microbial diversity, micro- and macronutrients that affect the physicochemical characteristics of the soils, which in turn will affect growth and survival of energy crops. The analysis also ignores the social and environmental constraints and tradeoffs associated with marginal lands. The lack of agronomic practices for the cultivation of biomass and energy crops on marginal lands is another technological issues impeding energy crops production on these lands, although it has been addressed in a recent MAGIC deliverable (D4.1). Suitable packages of practices are very essential for maximising the energy efficiency as well as human labour for producing energy crops from marginal lands and directly condition the relevance of farming these lands. Consequently, our estimates should be seen as upper bounds. However, it is important to note that even a precise map of physical area of marginal lands would significantly overestimate its potential by neglecting its myriad social, environmental and political constraints (Lambin et al. 2013). It is also crucial to point that some types of potential marginal lands were not included in this study. These are urban marginal lands, abandoned or degraded croplands, flood prone lands, compacted or susceptible to compaction, contaminated soils and reclaimed mines site. For example, it was shown that urban degraded/marginal lands represent 2600 ha in Boston (Saha and Eckelman, 2015). If considered, these land types may add to the total marginal lands in the studied case studies, thus increasing the overall potential marginal lands in these Brittany and Soria. Several literature studies give estimate of marginal lands for different countries. However, these are mainly at much larger scale (NUTS0 and NUTS2). Given the limited studies assessing marginal lands at regional level (NUTS3), it is hard to compare estimate of this study to those find in the literature. However, one of the common agreements between our study and those in the literature is that the distribution of marginal lands varies substantially between departments of a given region.

5.3 Energy crops on marginal lands

Our simulation experiments showed that miscanthus yields ranged from 2 to 10 ton ha^{-1} yr^{-1} in Brittany, while in Soria the biomass yields varied from 3.1 to 4.3 ton ha^{-1} yr^{-1} for tall wheatgrass and between 2.8 and 6.7 ton ha^{-1} yr^{-1} for Siberian elm. Yields varied strongly across marginal land types, which are in line with previous research showing that the yields of energy crops on marginal lands depended also on management and climatic conditions. More data from field experiments on biomass yields of energy crops on different types of marginal lands are needed. These data are also useful for the calibration and validation of models used to accurately estimate the yields potential of energy crops on marginal lands at local, regional and global scales (Qin et al., 2015). Despite the insufficient experimental data, the following conclusions can be drawn: *(a)* yields of energy crops are lower on marginal lands than on fertile soils, *(b)* intensively managed marginal lands can produce more biomass than extensively manage marginal with no addition of chemicals. On average, about 6 tons DM ha^{-1} yr^{-1} biomass could be produced from miscanthus in Brittany. This average yield is slightly higher than the threshold yield of 5 ton ha^{-1} yr^{-1} set for cellulosic energy crops on marginal lands to be economically viable (Marra et al. 2013). In Spain, the average yields of tall wheatgrass and Siberian elm were much lower than the threshold yield stated above.

Note that the simulated yields in this report are potential yields on marginal lands for the reason that these yields are only limited by the biophysical constraints related to marginal lands. Factors such as pest, disease, insufficient fertilizer supply, or damage from extreme weather that depress energy crop yields (Miguez et al. 2009) were not considered in the CERES-EGC model. Previous studies indicate that planting miscanthus, tall wheatgrass or Siberian elm can lead to a carbon sink and can improve ecosystem functions. Thus, converting marginal lands to cultivated lands for miscanthus, Siberian elm or tall wheatgrass production in Brittany and in Soria can improve carbon sequestration in soils and help to retain future environmental sustainability in these regions. Cultivating miscanthus in Brittany and tall wheatgrass/Siberian elm in Soria can improve local soil nutrients retention through increased soil organic matter and reduce vulnerability to erosion (Lal et al. 2009, Fisher et al. 2010). The specific advantages of cultivating marginal lands in these regions include improved water quality due to lower fertilizer and pesticide usage for energy crops, reduced erosion risk as miscanthus and tall wheat grass or Siberian elm provide year round minimization of exposed bare ground. Theses crops also improve wildlife habitat as they have longer growing seasons and later harvesting time windows.

5.4 Problems encountered and possible solutions

We could not map the marginal lands potential in Romania, nor model the productivity of castor bean in Cluj, Romania as initially planned. However, works are underway to overcome the hurdle faced in this region. The reason for the delay here is due to absence of data on land cover and land use transition. This lack of detailed information is not surprising because fine scale multi temporal land use maps or agricultural census data are often unavailable or of unknown reliability (Filer & Hanouek, 2002). Mapping post-socialist land use change/land cover change based on satellite images is a solution in such case, and primitive map layers well suited for this purpose. Once maps of marginal land in Cluj will be generated, they will serve as support for modelling the productivity of castor beans on marginal lands based on biophysical constraints.

Modelling for castor bean will be carried out by adapting the CERES-Sunflower model (Villalobos et al. 1996) via calibration, which will force the model to mimic the growth dynamics of castor bean without the formalisation of algorithm to simulate the specific traits of castor bean. There are limited literature on castor bean cultivation in Europe, therefore to obtain reliable data that will be used to calibrate the CERES-Sunflower model (Villalobos et al. 1996), we purchased from Kaiima (Israel) and shipped to Ecoricinus (Romania) four varieties of castor seeds. Despite some delays due to administrative issues, the seeds were finally sent to Ecoricinus in Cluj, Romania. Once the Organisation received the castor seeds, they conducted a field trial to evaluate different cultivars of castor beans in various locations around Cluj featuring different rainfall, temperature, and soil conditions. Four-castor bean cultivars were planted to investigate their performance in 4 locations. The seeds were sown at the rate of 13 kg/ha, at 0.7 m rows and a plant spacing of 0.2 m within the row. Recommended dose of nitrogen and phosphorus were applied at rates of 30 kg N ha^{-1} and 60 kg P ha^{-1} to fulfil the nutrient requirement of the crop. The fields were visited regularly and necessary management practices were performed in order to provide optimum crop growth conditions. Seeds were harvested at the end of the growing season and the measure yields were around 4 tons grains $ha^{-1}yr^{-1}$. Two types of data are of particular importance in these field trials for our modelling experiment: agronomic parameters (e.g. yields, maturity day) and quality parameters such as oil concentration. Data collected in these fields experiment will be used to calibrate crop genetic parameters in the CERES-sunflower model and to simulate the growth and development of castor bean as function of climatic variables and soil properties.

6 Conclusion

The overall goal of this work was to estimate and map marginal land resources in three selected EU regions, assess the productivity of energy crops on these marginal lands, and to quantify the amount of forest and agricultural residues that could supplement energy crops from marginal lands in these regions. The assessment shows that considerable quantities of residues remain unused in Brittany and in Soria. Available agricultural residues that could be removed in 2018 amounted to 5,627 kton for Brittany and 1,574 kton in Soria. Most of these residues come from corn stover and wheat straw as both residues represented more than 90% of the total residue available in each of these regions. Our residues assessment also shows a wide geographic variation in the production agricultural and ecological constraints for recovering these residues in these two regions. A non-negligible forest residue volume is available in Soria and the theoretical forest residues in this region for the year 2019 was 39 ktons. Unlike agricultural residues, which were fairly distributed in the province/department, forest residues were concentrated in the northern part and central parts of Soria. Additional sources of biomass may come from marginal lands which amount 57,544 ha and 376,500 ha in Brittany and Soria, respectively. Three species of energy crops namely miscanthus, tall wheatgrass and Siberian elm were found suitable to be grown on these marginal lands and have potential for bioenergy development. Indeed, about 351 ktons additional biomass and between 1,431 and 1,582 ktons biomass could be sourced from marginal lands in Brittany and Soria, respectively. However, site-specific experimental crops production and harvesting on these lands is necessary to validate the suitability. The use of agricultural and forest residues for bioenergy as well as the use of marginal lands for the production of energy crops is without doubt one of the main strategy to increase bioenergy production and food security by reducing dependence on food crops along with several environmental and ecosystems benefits.

Despite a lot of efforts have been made in recent years in estimating the available amounts of agricultural and forest residues, the quantities of residues that can be sustainably removed is an ongoing topic of discussion and evaluation. We caution not to lose sight of the implications on social aspects (e.g. use of residues as domestic fuels, farmers who produce residues as by-products) when collecting data and making calculations. Limited information currently exist on how farmers themselves see their situation and trade-offs they make willingly or unwillingly concerning residues generation and use. Further analysis and field experience in the forest and farming communities is needed to solidify consensus views regarding the amount of residues that need to remain in the field, and the associated costs for harvesting and supplying these residues for use as energy feedstocks. Given these uncertainties, the current estimates represent our best understanding of the availability of biomass in each of these regions at this point in time. The quantification of agricultural and forest residues as well as biomass from marginal lands provides grounds for the development of industrial crops in Brittany and Soria without relying too much on first generation crops. Policy toward second generation crops and energy prices will have significant impacts on the amounts of agricultural/forest residues and biomass from marginal lands produced for second-generation bioenergy purpose. Since different biomass utilization concepts oppose each other, policy should promote the most efficient and advantageous biomass utilization concepts. Quantification and mapping of biomass availability in a given region may also provide information about sites with the lowest and the highest feedstock availability, thereby reducing the overall risks of investing in bioenergy/biorefinery facility. Moreover, our work also contributes to the design and optimization of bioenergy/biorefinery supply chains.

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