D5.6 – Demand-driven supply chains and logistics plans for industrial crops from marginal lands for existing biorefineries: case study in three European regions

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Publishable executive summary

The objective of this study was to assess the economic and environmental impacts of pyrolysis oil production from marginal lands-based energy crops. Four types of energy crops (miscanthus, tall wheatgrass, Siberian elm and sorghum) were studied in three regions of three European countries (France, Spain, Italy). These energy crops were selected as representative candidates crops for energy valorization in these regions. The biomass yields of these crops on marginal lands were simulated using the CERES-EGC model using high-resolution data layers on soil properties, land cover and biophysical marginality factors. Biomass logistics were subsequently modelled using LocaGIStics, a tool developed in WP5 of the MAGIC project to estimate supply chain costs, energy use, and GHG emissions. The model accounted for the following value-chain stages: biomass production and harvesting, pre-processing, transport, storage and conversion to bio-oil by mean of pyrolysis. Two harvesting scenarios (as chips, bales or bundles) and three biomass delivery scenarios (no intermediate storage vs. one or two intermediate storage points) were assessed assuming road transport.

In the Brittany region, a marginal area of 57,544 ha was identified with rooting obstacles (55%) and salinity (34%) as the dominant marginality factors. Miscanthus yields on these lands varied from 5 - 19 t DM ha^{-1} y^{-1} and were lower in saline than in stony soils. The delivery costs ranged from 81 to 108 € t^{-1} of dry biomass, depending on the yield, harvest forms, and storage scenario, whereas the energy use was 311 to 604 MJ t^{-1} and the GHG emissions varied from 6 to 19 kg CO2 t^{-1}. Bale was the cheapest and environmentally friendly biomass form as was the logistics configuration with no intermediate collection point. Bio-oil production costs varied between 19 and 20 € GJ^{-1} oil.

The occurrence of marginal land was 10 times larger in the Soria province (Spain) compared to Brittany, with rooting limitations predominating. On the other hand, crop yields were about 5 times lower, ranging from 1.2 to 3.2 t DM ha^{-1} y^{-1}, and with Siberian elm being slightly more productive than tall wheatgrass. As a result, feedstock delivery costs were 5-10% higher than in Brittany, despite lower transportation distances, and a similar pattern occurred for bio-oil production costs.

In Emilia Romagna, the focus was on degraded land and land with steep terrain in the hills south of the region. Crop yields were twice larger than in Brittany, averaging about 16 t DM ha^{-1} y^{-1}. As a result, the costs of biomass delivery and bio-oil production were 10% lower than in Brittany and this region presented the best configuration in terms of logistics and biomass production potential from marginal lands. However this came at the expense of GHG emissions which were 50% to 100% larger than in the other regions due to the larger fertilizer requirements of sorghum.

Overall, procuring biomass from marginal lands in the three cases investigated here involved costs in the higher end of costs estimated than non marginal land in Europe, making this option less attractive than sourcing from non marginal lands, or residues in general. However biomass from marginal lands was still efficient in terms of energy use and GHG emissions, which were comparable with other sources of biomass. Compared to other sources of biomass or types of lands, the absence of indirect land-use effects and the possibility to sequester carbon in soils were a major asset in mitigating the

GHG emissions of energy crops. Despite the logistics constraints it entrails, sourcing biomass from energy crops grown marginal lands can offer a potentially sustainable solution for bio-oil production in the three EU regions investigated here, and lead to a range of bio-based end-products, including 2G biofuels. However, economic incentives are needed to encourage production on marginal lands given the high delivery costs of biomass from these lands.

1 Introduction

Biofuels are considered as a promising environmentally friendly substitute resource for carbon-based fuels and chemicals. Although non-renewable fuels (oil, gas, coal) will still remain the dominant sources of energy over the coming decades, the depletion of non-renewable fuels reserves has been recognized as the main challenge to energy supply in the coming decades. Owing to the growing population of the world, unstable oil prices, and stricter remissions standards, the demand for alternative fuels is growing.

Biofuels have been proposed as a viable alternative fuel and part of the solution to decrease the heavy reliance on fossil fuels and to mitigate climate change, because the biomass feedstock can be produced renewably from a variety of domestic sources such as energy crops, agricultural and forestry residues, and the production and use of biofuel products have potentially lower environmental impacts than their fossil fuel counterparts (El Akari et al., 2018). Thus, many countries have set national biofuels targets and provide incentives and supports to accelerate the growth of biofuel industries (Fargione et al., 2008). In the EU for example, the Renewable Energy Directive Recast (RED II) sets a target of 32% renewable energy in energy mix by 2030 and included a 7% cap on food and feed crop-based biofuels (EC, 2018).

These conditions are set with sights on a two-fold objective : (i) to suppress first generation biofuels (most frequently derived from food crops), currently dominating the biofuels sector; (ii) to stimulate the development of second generation biofuels (Londo et al. 2018). These include agricultural and forest residues, as well as various lignocellulosic crops grown specifically for their energy value. Unlike food crops, lignocellulosic crops are able to adapt to a wide range of climate and soils conditions, meaning that they can successfully be grown on lands not ecologically suited for conventional farming practices, and food/feed crops in particular (Gabrielle et al., 2014a).

Establishment of lignocellulosic crops on marginal, degraded and/or contaminated lands for biomass production has been considered by the biorefinery/bioenergy industries as an alternative to croplands for feedstock supply that could help to address the food vs fuel debate challenging the industry's further development. Europe (i.e. the EU) has a sizable amount of marginal and degraded lands available, which hold potential for the production of energy crops. It is estimated that 30 Mha of marginal lands are available in the EU and suitable for energy crops (Von Cossel et al., 2019). Planting energy crops on marginal and degraded lands could bring these lands back to production (Goor et al. 2003, Van Slycken et al. 2013). However, the production of energy crops on marginal and degraded lands carries its own drawbacks, among which high production costs which are the main obstacle to the economic viability of sourcing biomass from these lands (Panoutsou and Chiaramonti, 2020). Although increasing biomass yields can reduce production costs, managing feedstock supply chain and its logistics activities are persistent issues.

Logistics is a major component of the supply chain of biomass from marginal/degraded lands. It includes the harvest, pre-processing, transport, and storage of biomass to the biorefinery plant. Because of its low bulk densities, biomass feedstock creates logistics challenges in terms of its volume that must be handled, pre-processed, transported to, and stored at the biorefinery plant (Gold and Seuring, 2011; Perrin et al., 2017). The number of vehicle movements and the costs of moving biomass feedstock from supply fields to biorefinery/bioenergy plants can be prohibitive, and in some cases the costs may exceed market values for the biomass itself (de Jong et al. 2017). This is especially true when sourcing biomass from marginal lands, which may be scattered across the biomass supply area and difficult to reach due to steep terrain or a lack of access roads. Logistics can also be a major contributor to the environmental impacts (i.e. energy consumption and greenhouse gas (GHG) emissions) of the supply chain of feedstocks from marginal lands.

1.1 Objectives and target groups

The objectives of this study are:

i. To design supply chains and test the supply chains of marginal/degraded lands based biomass and their subsequent conversion to bio-oil in three European regions
ii. To estimate the supply chain economic and environmental impacts of these energy crops and their subsequent conversion to bio-oil.

Three case studies were conducted in three European regions (Brittany (France), Soria (Spain), and Emilia Romagna (Italy)). These regions are part of agro-ecological zones 2 (central Europe) and 3 (Mediterranean), as defined in the MAGIC project. In these regions, the lignocellusoic crops are produced on marginal lands (Brittany and Soria cases) and degraded lands (Emilia Romagna), respectively. The target audience for this report includes internal and external stakeholders, as well as the general public. Internal stakeholders are project members that have to be informed about the progress of the work package activities and results (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 (a growers’ cooperative in Brittany).

1.2 Contribution of project partners and link to other activities in the MAGIC project

The report is written by INRAE/AgroParisTech and WUR. The contribution of INRAE is related to the simulation of yields of energy crops on marginal lands, the techno-economic assessments of energy crops and bio-oil supply chains, while the role WUR is related to the development of the LocaGIStics tools and to the identification, quantification and the mapping of marginal lands. CIEMAT contributed data and expertise on lignocellulosic crops in Spain, and NovaBiom expertise on miscanthus in Brittany, and BTG on the industrial conversion process common to the case-studies (pyrolysis). Arkema was also involved in the case-study design and a potential case involving the conversion of castor bean oil to biopolymers. Unfortunately this case-study could not be developed for lack of a suitable region in which to collect data on such a case. However, the case-study developed in Italy for lignocellulosic crops could serve as a basis for such a case-study using data collected in another task of WP5 in 2021 on castor bean harvesting, and agronomic data on this crop in Bologna. Thus, the Emilia-Romagna could be considered as a surrogate (or preliminary study) for an logistics and industrial case on castor oil.

This deliverable is connected to other work-packages and tasks of MAGIC (WP2 in particular). This deliverable draws on work detailed in the following MAGIC deliverables: D.2.1., D.5.2 and D.5.3.

2 Material and methods

2.1 Regions and biomass resources investigated

Three regions (Brittany, France ; Soria, Spain, and Emilia Romagna, Italy) in three different EU member states were selected to cover differences between countries and across regions. In each region, a number of lignocellulosic biomass resources were assessed, includes energy crops grown on marginal lands, which could be possibly complemented with agricultural and forest residues (although this is beyond the scope of this report).

2.1.1 Brittany (France)

Brittany (48° 00'N, 3° 00'W) is one of the 12 administrative regions of metropolitan of France. It is located in the Northwestern corner of France and covers 27200 km^2. The climate of Brittany is oceanic with annual rainfall varying from 700-800 mm and average annual temperature of about 12°C. Agriculture is one of the dominant economic activities in the region. It occupies 1.73 Mha lands in 2020 and accounts for 4.2% of the total employment in Brittany. The lignocellulosic biomass studied in this region was miscanthus, a perennial energy crop (PEC) which is already grown in this region.

2.1.2 Soria (Spain)

Soria (41° 45'N, 2.3° 13' W) is one of the nine provinces of the autonomous community of Castilla-Léon. This region is located in the northern central of Spain at an altitute of 1063 m above sea level. It has a total land area of 10286 km^2. The annual temperature is 10.5 °C and the annual precipitation is about 500 mm. The climate conditions are continental-mediterranean, and the region features a very heterogenous environment ranging from high mountains to deep valleys as well as the characteristics of summer grasslands.

2.1.3 Emilia Romagna (Italy)

Emilia Romagna (43° 44' N ; 9° 11' E) is a region in central Italy lying between the ranges of the Appennine mountains and the Po plain, bordered by the Adriatic Sea on the East. It has a total land area of 4930 km^2 and the elevations range from 0 m above sea level (Po River) to approximately 2165 m above sea level at southern boundary. The average annual precipitation ranges from 515 to 2444 mm and the mean annual temperature varies from 7.4 to 13.8 °C.

2.2 Identification and mapping of marginal land

The identification of marginal lands in Europe was done as part of another activity in the MAGIC project (Elbersen et al., 2018), and detailed for two of the case-studies in a previous deliverable (MAGIC D5.3). Briefly, the approach builds on the identification of natural constraints and other land evaluation systems for agronomic suitability. The results describe the location and amount of marginal land area across Europe and what the main characteristics are in terms of biophysical limitations.

Eighteen biophysical marginality factors were identified, clustered into six factors and used to for the classification of severe limitation. These six factors are : (i) adverse climate (low temperature and/or dryness), (ii) excessive wetness (limited soil drainage, inundation or excess soil moisture) (iii) low soil fertility (acidity, alkalinity or low soil organic matter), (iv) adverse chemical conditions (salinity or contamination), (v) poor rooting conditions (low rootable soil volume or unfavorable soil texture), (vi) adverse terrain conditions (steep slopes, flooding risks). The land units were identified with biophysical factors within the 20% margin of the threshold value of severity. This also allowed to map pair-wise limitations. When two factors fell within this 20% margin, the land units were classified from sub-severe to severe. All severe classes were classified as marginal lands. At the end a correction was made by excluding areas where natural constraints were overcome via agronomic improvement measures such as fertilizer inputs, irrigation, drainage and the creation of terraces to overcome specific natural constraints. The data used for identification of marginal lands originated from different sources (see Elbersen et al. 2018 for more details).

Maps of marginal lands for the Brittany and Soria regions were presented in MAGIC D5.3. In the case of the Emilia Romagna region, simulations were run across all types of lands (marginal and non marginal).

2.3 Crop growth simulation and mapping

2.3.1 Simulation and mapping of miscanthus yields in Brittany

The growth of the selected energy crops on marginal as well as on degraded lands in these three European regions was simulated using the CERES-EGC model (El Akkari et al. 2020). Prior to its use for simulation of miscanthus growth in Brittany, the CERES-EGC was calibrated and tested by comparing its outputs to field observations obtained in long-term trials in Estrées-Mons (northern France). The trials involved various treatments for miscanthus in terms of fertiliser inputs and harvesting dates (El Akkari et al. 2020). After calibration, the model was ran over the Brittany region. In a first run, miscanthus was assumed to be cultivated on current croplands on the 1,067 simulations units (i.e. polygons), resulting from the overlay of the EU soil map, the latest Corine Land Cover maps and administrative limits (countries). To integrate the identified marginal lands in the crop modelling, we overlaid the marginal land map (Elbersen et al., 2018) with the soil map used by CERES-EGC to point at the polygons in which marginal factors occurred. Regarding management practices, we assumed a baseline fertilizer input of 30 kgN/ha and no limitation for P/K availability in soils. To account for the main marginality factors (rooting, chemical limitations), CERES-EGC was modified as followed: for rooting constraints were assumed to correspond to a high stone content of soils, which in practice reduces the soil water holding capacity. In this case, the corresponding simulations were assigned an archetype soil for this characteristic with a high sand content (and low plant available water). With regard to chemical constraints (e.g., salinity etc.), none of the chemical constraints is explicitly simulated by the CERES-EGC in terms of effects on soil-plant process. However, a 30% reduction in yields of miscanthus was assumed in this study to account for the moderate effects of salinity on miscanthus yields, in line with Stavridou et al. (2017). Simulated yields of miscanthus and associated GHG emissions at 1km x 1km grid cells were exported as shape file and imported into the LocaGIStics model where polygon maps were made.

2.3.2 Simulation and mapping of tallwheat grass and Siberian elm 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. 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 center of CIEMAT in Soria (Del Val et al. 2015, Perez-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 (Del Val et al., 2015). So it could be used as an intermediate proximal 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 yielded 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 one and 2 ton ha^{-1} yr^{-1}, whereas the range for siberian elm was 1.2 - 2.5 ton ha^{-1} yr^{-1} in rainfed 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, including for switchgrass). The gridded weather were derived from another source as part of the FP7 project Animal Change (Carozzi et al., 2015) - for the data point corresponding to the Villasayas municipality in the center of the simulation domain (41.375° N ; -2.625° E). The series pertains to past and future climate data over the 2010-2030 time slice, out of consistency with the Brittany simulations.

Soils data extracted from Soils Grids repository from ISRIC (*soilsgrids.org*), clipped to the Soria province with pixels ~ 1 km^2 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), 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 Carozzi et al. (2015) 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 Data Base. 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 are averaged over the crop growing cycle (28 years) and exported to a csv format file used for mapping purposes

2.3.3 Simulation and mapping of shorghum in Emilia Romagna

The simulation of sorghum growth and yield in Emilia Romagna followed a procedure similar to that detailed in the above section for Soria: weather data, average soil properties and crop management data were derived from the data base of the Animal Change project (Carozzi et al., 2015). A winter wheat – maize – wheat – sorghum rotation was implemented based on recommended practices in the region, with typical N input rates (Acciai, 2021). Gridded soil data were derived from the same database as Soria, with the addition of a “slope” factor accounting for the orientation and slope of steep fields in the mountainous part of Emilia Romagna. Solar radiation data were adjusted to factor in this effect of slope on crop yields, to match the effect of slopes on crop yields relative to flat terrain (Acciai, 2021). The model simulations were verified by comparing the average regional yield obtained with CERES-EGC for sorghum with a “benchmark” value of 18 t DM ha^{-1} yr^{-1} cited by Acciai (2021) for good soils. Sorghum yields, N_2O emissions and soil C changes over 28 years of crop rotation were averaged and exported to a csv format file used for mapping purposes

2.4 Feedstock supply chains

We considered a biorefinery plant that uses a single biomass sources to meet feedstock demand and specifications for conversion of this biomass into bio-oil via pyrolysis processes. A fixed annual feedstock demand of 40 kt dry biomass is assumed for this biorefinery plant, following recommendations from BTG based on the Empyro unit in the Netherlands (D. Van den Berg, BTG, pers. comm., Sept. 2018). It is assumed that such a biorefinery would be located in the above-mentioned regions, selected in the MAGIC project for the simulations of lignocellulosic biomass supply from marginal lands.

We developed three biomass delivery scenarios which represent a feedstock supply scenarios consisting of the following activities: biomass production, harvesting into different forms (bundles, chips, bales), transport, and storage either at the field or at the intermediate collection points. Scenario 1 assumes that the three biomass forms are collected from the fields and transported directly to the biorefinery plant located near the biomass fields. The average supply distance set by the LocaGIStics model for this scenario is 42 km for Brittany (France), 28 km for Soria (Italy), 35 km for Emilia Romagna (Italy). These distances are set using the measurement tools in Google map, ie as the crow flies. Scenario 2 considers that after harvest and field collection, the feedstock is transported to the intermediat collection point (ICP) where it is stored for a while and delivered later on demand to the biorefinery (i.e. pyrolysis) plant. The average distance to the biorefinery gate is set to 125 km, 44 km, and 64 km, for Brittany, Soria and Emilia Romagna, respectively. In scenario 3, the feedstock is transported from the fields to two distinct ICPs depending on their proximity to the fields, and later transported as required to the biorefinery plant. Here, LocaGIStics set a supply distance of 187 km for Brittany, 110 km for Soria, and 173 km for Emilia Romagna. Even though transportation distances increase with the use of ICPs, those can still be relevant since they reduce storage costs at the biorefiniry site. This, increasing the number of ICPs (and the transportation distance) trade-offs with on-site storage costs, providing another relevant optimization factor.

In all scenarios, the LocaGIStics model prescribes the optimum number of fields required to meet the total biomass demand of the biorefinery plant, and the assignment of farms to storage locations. The cheapest biomass is collected first in each scenario, and this continues until the biorefinery demand is met. This means the collection at the ICPs starts only when there is no cheaper biomass near the biorefinery. It is further assumed that each ICP has enough capacity to store biomass for three months until requested by the biorefinery plant.

The logistics model used to simulate the supply chains (LocaGIStics) is presented in details in a previous deliverable (D5.3). Briefly, it is a regional biomass supply chain assessment tool that simulates the supply of biomass from production fields to a given conversion plant. It consists of different modules that can be connected to form a complete supply chain. Each module represents an unit operation or process (e.g. transport, drying, and harvesting) and is independently constructed with a set of inputs and outputs. Data on costs, energy use, and GHG emissions common to all operations and processes are gathered into individual modules as well. These modules (that determine supply chain cost, energy use, GHG emission modules) were first constructed in an Excel spreadsheet and imported to the model (which is coded in python and associated with the GIS software package QGis). The same is true for the biomass production module which relies on the CERES-EGC agro-ecosystem model (see section 2.4), and then imported into LocaGIStics for spatial mapping. In the LocaGIStics model, biomass moves from one module to the next one through connectors. The modelling of costs, energy use and GHG emissions are done externally in an excel based calculation model, then included into LocaGIStics for spatial assessments integrating multiple information layers.

2.5 Feedstock economics and environmental impacts

2.5.1. Feedstock costs

The supply chain costs of the delivered biomass were estimated using an activity based costing approach. This method uses activities to trace the direct and indirect costs associated to biomass supply chains. Seven major cost factors were distinguished in the biomass production costs: land costs, capital costs, labour costs, fertilizer costs, rhizome costs, pesticide/herbicide costs, harvesting costs. Cost items such as land costs, labour costs, and capital costs are independent of management intensity levels, while fertilizer, pesticide and seed costs are the cost factors directly linked to production figures, hence independent on the land area involved. The biomass production cost was annualised and normalised to 1 t dry matter (DM). Handling costs included loading and unloading costs. Both loading and unloading costs comprised fixed costs and variable costs of the loader (i.e., front-end loader or forklift). Handling costs per t DM was obtained by dividing the loader cost (€ h^{-1}) by the loader efficiency (t DM h^{-1}). The transportation costs also included both fixed and variable costs and computed as the sum of fixed costs and product of variable costs and transport distance. We further assumed a single-trip transport distance. One percent biomass loss was further assumed for transport to the biorefinery plant. Storage costs included the storage facility construction, costs, land costs, machine costs, insurance costs, and dry matter losses. Finally the total supply chain delivery costs was calculated by summing the costs of the supply chain components namely biomass production (including harvesting), handling, transport and storage. These components of the supply chain were built outside the LocaGIStics tool and then incorporated into it.

2.5.2. Feedstock energy use

We accounted the direct and indirect energy inputs for miscanthus production, harvest, handling, transport and storage. The additional energy required to reduce the marginality constraints (e.g., removal and disposal of stones prior to tillage of stony fields, irrigation needed to reduce salinity/sodicity of the field before growing miscanthus thereon) were included in the analysis. Energy inputs for miscanthus production on all marginal lands in Brittany were estimated by combining energy values for manufacturing, packaging, and transportation of agricultural inputs with literature data or farmer-reported data on input levels such as the tillage method, fertilizer (N/P /K) rates, rhizome planting density, pesticide/herbicide rate, and harvesting. Energy use for stones removal was based on the number of field operations and the associated fuel requirement. Irrigation energy was based on electricity consumed to pump water and the volume of water pumped. Diesel consumption during biomass transport was based on vehicle fuel economy of a given truck, the transport volume, and the transport distance, as well as the embodied energy to manufacture the truck. Energy consumption during biomass storage accounted for the energy spend to construct the storage area.

2.5.3. GHG emissions

The GHG emissions due to fossil fuel consumption during the production and delivery of biomass to the biorefinery were estimated in the same manner as the energy use. So, for the direct CO_2 emissions, we multiplied the amount of fuel consumed by a given activity by its carbon intensity. To calculate the indirect CO_2 emissions, we multiplied the CO_2 intensity of a given material by the amount of that material used in a given activity. Soil-borne emissions of N_2O as well as soil carbon stock (SOC) variations under energy crops were obtained from the CERES-EGC simulations. Emissions of CH_4 and N_2O were converted to CO_2 equivalents using GWP_{100} values of 25 and 298 for CH_4 and N_2O, respectively. The annual carbon stock change is converted to CO_2 equivalents by multiplying the value by 3.6 (the ratio of molar mass of CO_2 and carbon). Finally, for each field we summed up the SOC stock change, field emissions, and CO_2 emissions from fossil-fuel burning during miscanthus production, harvesting miscanthus. These data were supplemented with data on CO_2 emissions from handling, transport and storage and the result was imported into the LocaGIStics model for spatial distribution and mapping. Since marginal lands contain negligible amount of biomass, and because crops are harvested annually or every 3 years, the changes in aboveground biomass were assumed zero (i.e. no indirect LUC effect). As for the costs and energy use, the GHG emissions of the components of the supply chain were built outside and incorporated into the LocaGIStics model.

2.6 Bio-oil economics and environmental impacts

2.6.1 Bio-oil costs

The analysis considers a pyrolysis plant (based on the Empyro plant) with a bio-oil plant with a production capacity of 5400 t oil/yr over the next 20 years, taking 2021 as the base year for analysis. Estimates of costs correspond to annual operations (i.e. in €/year) and were accordingly converted to unitary costs in conformity with the functional unit (€/t oil). A mass and energy balance was established based on BTG pyrolysis processes. Purchased equipment costs were gathered from the literature and from the manufacturer's website. These costs were adjusted to the the plant capacity, operating pressure and materials construction with scaling and installation factors. Direct and indirect costs were added to the adjusted equipment costs to determine the fixed capital investment. Fixed capital investment (FIC) was estimated as the ISBL and OSBL plant costs (PCISBL and PCOSBL), engineering cost (Ceng) and contingency cost (Ccont) FCI = PCISBL + PCOSBL+ Ceng+ Ccont. ISBL is the costs of the plant itself, and included equipment costs, pipping costs, instrumentation costs etc. In this case, it is the sum of reactor, cooler costs. OSBL is the offsite costs that include the costs of the infrastructure to accommodate the new plant; and was assumed to be 40% of the ISBL costs. Engineering costs and conetingency costs were assumed to be 10% and 15% of the sum of ISBL and OSBL costs, respectively. The total capital cost investment was finally calculated as the sum of the fixed capital investment, land cost and working capital. The total operating costs is the sum of fixed and variable costs. Employee salaries were estimated based on a pyrolysis biorefinery described in the literature, and adjusted using a labor cost index.

2.6.2 Bio-oil energy use and GHG emissions

The production of bio-oil via pyrolysis can be divided into two main processes : pyrolysis oil production and stabilization of pyrolysis oil and upgrading. The system boundary includes the production of biomass, harvesting, transport, storage and conversion to bio-oil, The stabilization of pyrolysis as well as the upgrading and transport of bio-oil to distribution center was excluded. The functional unit was defined as 1 ton of bio-oil. A complete inventory for bio-oil production was developed based on the detailed mass and energy balances established for the BTG processes. Energy consumption and GHG emissions from biomass production, harvest, transport and pyrolysis operations were included in the analysis. We considered the direct energy use and GHG emissions (i.e., energy use and GHG emissions at biofinery) and indirect energy use and GHG emissions (i.e, energy use and GHG emissions associated with the production of materials used at biorefinery). Since pyrolysis processs also produces heat and electricity, the energy allocation method was used to allocate environmental impacts (i.e., energy use, GHG emissions) between bio-oil and its co-products (heat and electricity). Data for bio-oil life cycle were gathered from literature and estimation of energy use and GHG emissions followed the same methodology as for feedstock production. Energy consumption by a given process within the biorefinery was estimated by multiplying the indirect energy use (i.e., embodied energy) of a given material by the amount of material consumed by the process. Similarly, we multiplied the quantity of material consumed by its specific GHG emission factor to calculate the GHG emissions of all biorefinery processes. We then summed up the energy use and GHG emissions of all processes within the biorefinery to estimate its total energy use and GHG emissions. Finally we use the energy allocation method to apportion the total energy use and GHG emissions at biorefinery to bio-oil, heat and electricity on the basis of their energy contents.

3 Results and discussion

3.1 Brittany case

3.1.1 Marginal land area, yields and carbon sequestration of miscanthus on these lands

Figure 1 shows the location, distribution, amount and characteristics of available marginal lands for growing miscanthus in Brittany. About 57,544 ha lands were identified as biophysically marginal lands. This represents about 3% of the region's total utilisable agricultural area. Rooting constraints resulting from low rootable soils volume or unfavourable soil texture were the dominant marginality factors and occurred on more than half (55%) of the region's total marginal lands, followed by chemical limitations (34%) due to high salinity. As expected, salt affected lands were mostly located near the coastlines (Figure 1), and the land cover of these marginal lands were mostly temporary grasslands (65%) and permanent grasslands (35%). Ile-et-Vilaine was the department with the largest area of arginal lands (32,695 ha), followed by the Morbihan (13,231 ha), the Finistère (7,770 ha), and the Cote d'Armor (3,848 ha). Ile-et-Vilaine and the Morbihan departments are thus the marginal land hotspots for the Brittany region.

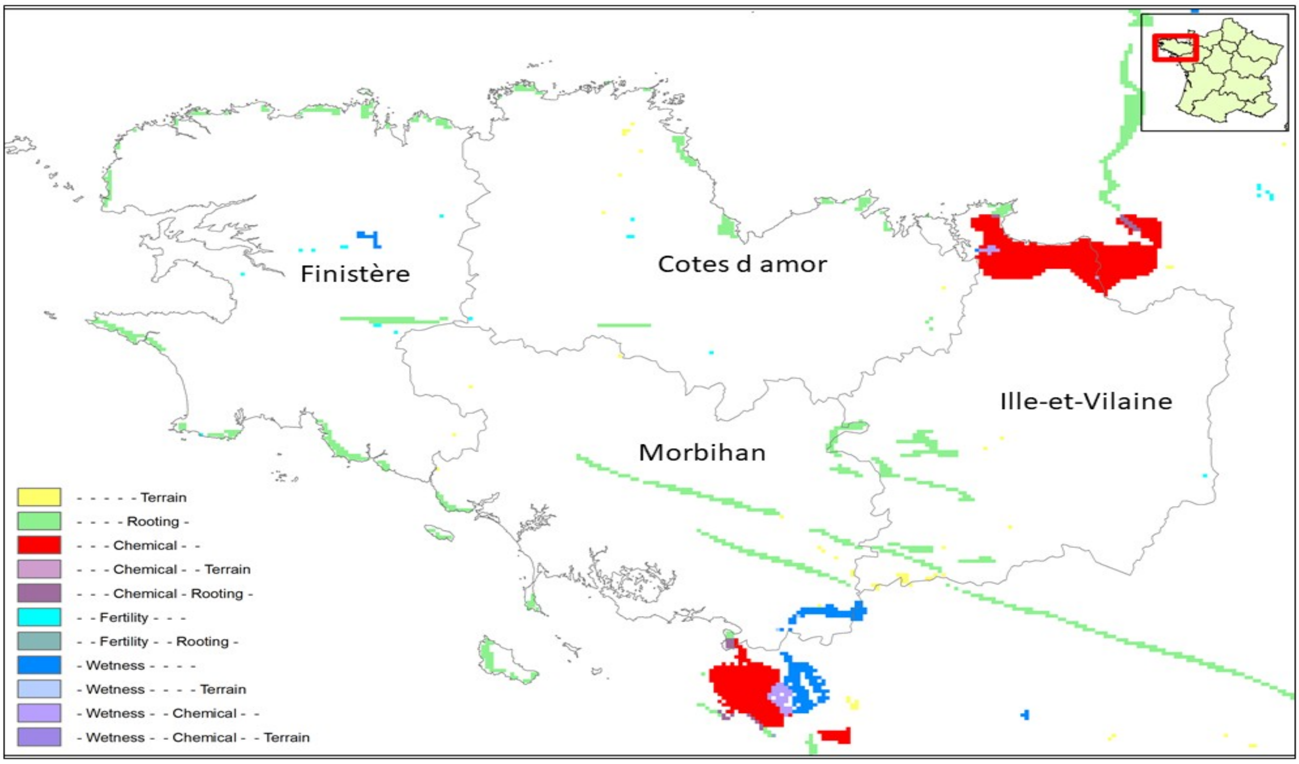


Figure 1: Map of marginal land in Brittany, and their marginality constraints. The names correspond to the French departments (administrative units).

Miscanthus was selected as a potential energy crop for marginal lands in Brittany. The simulations with the CERES-EGC model, factoring in marginality constraints shows that miscanthus can grow on these marginal lands and produce moderate yields over its 20-year growing cycle. Miscanthus yields on these marginal lands varied from 5 to 19 t DM $ha^{-1}y^{-1}$ (with a regional average of 9 t $ha^{-1}y^{-1}$), depending on marginality constraints, climate, and soil quality (Figure 1). This yield level highlighted the low agronomic potential of marginal lands. We noted 30% reduction in yields under salinity constraints relative to rooting limitations, which suggested that salinity adversely affects the growth of miscanthus on marginal lands than rooting limitations. The limitation to the growth of miscanthus on saline soils is due to a number of environmental and ecological factors that affect the metabolism of miscanthus and the development of its root system. Yields were lower in the Morbihan department than in other departments of Brittany due to the high share of salt affected soils in the former (Figure 1). The total collectable biomass from these marginal lands were 518 kt y^{-1} (8.9 PJ y^{-1} of energy). Ile-et-Vilaine had the highest biomass potential because of both the high share of marginal lands and higher yields of miscanthus in this region. Concerning carbon sequestration, some sites were a small sink while other were a small source of carbon. Overall, growing miscanthus on marginal lands in Brittany resulted to modest soil carbon sequestration in most sites (with an average gain of 0.54 t C $ha^{-1}y^{-1}$), but with a substantial intra-regional variability (range: - 1.45–1.29 t C $ha^{-1}y^{-1,}$; a negative number implies a carbon loss). The differences in soil moisture, marginality constraints, available nutrients, and the associated biomass yields explained the differences between the soil organic sequestration rates on these sites. Overall, these data suggest that miscanthus retains its potential to sequester carbon even poor soils such as marginal lands thanks to its high nutrient and water use efficiencies as well as its stress resistant character.

3.1.2 Supply chain design and average supply distances

Supplying a 40 kt y^{-1} biorefinery plant in Brittany would require transportation distances of 42, 125 and 187 km for scenarios 1, 2 and 3, respectively (Figure 2). All scenarios assume a 100% biomass availability in the land units identified as marginal. Obviously, the average supply distances for the scenarios with storage points were 3 to 4 times greater than in the scenarios with no storage points. The amount of biomass delivered to biorefinery ranged from 40,006 to 40,013 t y^{-1}, depending on the scenario. In each scenario, the quantity of biomass delivered to biorefinery was slightly higher than the demand due to small losses in the logistics chain. These losses were more important in scenario 1 and scenario 3 than with the scenario 2.

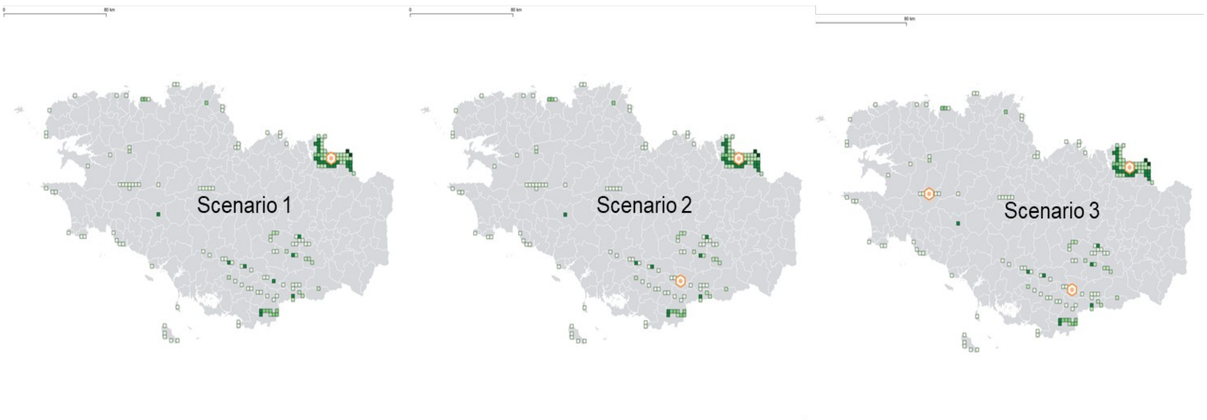


Figure 2: Location of marginal land units producing miscanthus biomass (green cells), and intermediate collection points (red circles) for the 3 supply-chain scenarios. The biorefinery is located in the northeastern tip of the region (red circle of scenario 1), where the marginal lands are denser.

Feedstock	Chips				Bundles				Bales		
Costs	Sc1	Sc2	Sc3		Sc1	Sc2	Sc3		Sc1	Sc2	Sc3
(€/tDM)	84.8	85.5	85.4		91.9	93.0	93.1		85	85.5	85.8
Products	Bio-Oil				Bio-Oil				Bio-Oil		
Costs	Sc 1	Sc2	Sc3		Sc1	Sc2	Sc3		Sc1	Sc2	Sc3
(€/ton PO)	302.9	304.0	304.4		314.1	315.8	315.9		303.5	305	305.1
(€/GJ PO)	18.9	19.0	19.2		19.5	19.7	19.9		19.0	19.1	19.1

Table 1. Value-chain costs in terms of feedstock supply costs and overall bio-oil costs, for the 3 harvesting scenarios.

The total annual costs for delivering biomass to biorefinery plant of capacity of 40 kt/y ranged from from from 3.8 to 4.6 M€/y depending on the biomass harvest form and scenarios. The unit delivery costs ranged from 85 to 93 €/t, depending on the harvest form. Although bales were the most expensive biomass form at the farm gate, it delivery costs at the biorefinery plant gate were comparable to those of chips and bundles because the densification (i.e. baling) reduced the number of truck loads relative to both chips and bundles. Since the cheapest biomass form is transported to the biorefinery plant, these unit costs thus represents the minimum supply costs of miscanthus to the conversion plant.

Our farm-gate biomass supply costs (53 to 80 € t^{-1}), which agree well with ranges of 56 to 120 € t^{-1} reported for miscanthus production on marginal lands in the literature (Wagner et al., 2019), higher than the farmgate costs (63 - 102 € t^{-1}) reported for cellulosic feedstocks grown on croplands in Europe (Lewandowski et al., 2000). The delivery costs of miscanthus biomass to the biorefinery in this study ranged from 85 to 93 € t^{-1}, depending on the biomass form. Factoring in farmers' profits, Simon et al. (2010) reported delivery costs ranging from 100 to 120 € t^{-1} for miscanthus and from 95 to 115 € t^{-1} for cereal straw in France. Our delivery costs, which excluded farmers' profits surpassed the delivery costs of cropland-based woody energy crops (58 to 103 € t^{-1}; Mishra et al., 2013) in Europe. Consequently, PECs from marginal lands may not be attractive without subsidies. Subsidies can make the supply chain costs of miscanthus from marginal lands more attractive, particularly if farmers are rewarded for carbon stored in marginal lands during plant growth. Given that miscanthus is efficient in increasing the soil carbon content, the economic efficiency of this crop would certainly improve if carbon credits were paid for it.

The annual production costs of bio-oil ranged from 7.7 to 8.1 M€/yr. The unitary costs of this bio-oil ranged from 303 – 316 €/ton PO, depending on the biomass form and the supply scenario. For a given biomass harvest form, the supply chain scenarios with no storage requirements resulted to lowest costs compared to scenarios with one or two storage requirements (Table 1). However, differences between these scenarios were very little and could be neglected. These findings suggest decentralized biorefining schemes with few storage requirements maybe be cost-competitive compared to centralized ones having no intermediate storage/collection points.

The share of each process or stage to the total supply costs of bio-oil is shown in Figure 3. Feeedstock dominated the bio-oil production costs with a share ranging from 44% to 50% of total costs, followed by financing (35 -39%), personnel costs (5-7%), and other fixed and variable costs. The shard of feedstock costs (which include logistics costs) varied according to the harvesting scenarios, being lowest with bales which are denser and more efficient for the range of transportation distances involved in this case-study (42 kms for scenario 1). This type of economies of scale is also found in Perrin et al. (2017) for a similar logistics chains in Burgundy (France).

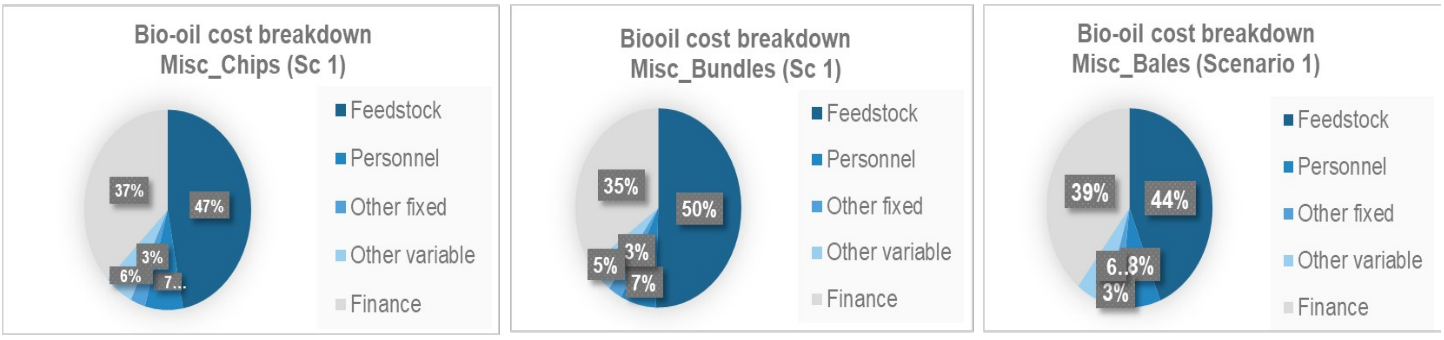


Figure 3. Breakdown of bio-oil costs for the 3 miscanthus harvesting scenarios in Brittany.

3.1.3 Energy use and GHG emissions

Scenarios	Feedstock Input	Bio-Oil Ouput	CED GJ/ton Oil	ER	GHG emissions ($kgCO_2$/ton Oil)	GHG emissions ($kgCO_2$/GJ Oil)
Scenario 1	Chips	PO_chips	0,42	38	11,64	0,73
	Bundles	PO_bundle	0,57	28	15,68	0.98
	Bales	PO_bale	0,45	35	14,93	0.93
Scenario 2	Chips	PO_chips	0,51	31	17,97	1.12
	Bundles	PO_bundle	0,65	25	24,35	1.52
	Bales	PO_bale	0,47	34	16,66	1.05
Scenario 3	Chips	PO_chips	0,51	31	18,10	1.13
	Bundles	PO_bundle	0,65	25	24,74	1.55
	Bales	PO_bale	0,47	34	16,79	1.10

Table 2: Energy use and GHG emissions of bio-oil production in Brittany, for the 3 miscanthus harvesting scenarios. ER: energy efficiency ratio (ratio of output to input energy).

The life-cycle energy use of bio-oil ranged from 0.42 to 0.65 GJ t^{-1} depending on the harvest form and scenarios (Table 2). This translates to an energy efficiency (i.e. ratio of energy output to energy input) ranging from 25 to 38 assuming an energy density of 17 GJ/t DM for miscanthus biomass. Consequently, bioenergy from marginal lands provide net gains, despite the low yields and logistical constraints. The GHG emissions varied from 11 to 25 kg CO_2 t^{-1} depending on biomass harvest forms and supply-chain scenarios (Table 2). As for the costs, these estimates represented conservative estimates in terms of energy use and GHG emissions to deliver miscanthus biomass to biorefinery. Bales had lower delivery costs and environmental impacts than both chips and bundles because of their higher bulk density, which reduced the number of truckloads and storage needs. Storage is indeed a key factor in terms of supply chain costs for biorefineries (Gabrielle et al., 2015). For biomass form with a low bulk density such as bundle and chips, the volume limit was reached before the payload limit of trucks, and more trips and storage volume were necessary to deliver the required quantity of biomass to the biorefinery.

The delivery costs, energy use, and GHG emissions increased from scenario 1 to scenario 3 for all biomass forms due to the additional storage and transport needed to supply biomass to biorefinery. However, differences in the delivery costs among the three scenarios were much smaller than the differences in energy use and GHG emissions between them. Transporting marginal land based-biomass over long distance (eg, exceeding 200 km) is likely to increase the supply energy use and GHG emissions than the supply chain. The observed variations in delivery costs, energy use, and GHG emissions in the different scenarios suggested that supply chain of biomass from marginal lands is site-dependent and influenced by biomass forms and logistics configurations.

The conversion of miscanthus to pyrolysis oil resulted to energy consumptions ranging from 0.42 to 0.65 GJ t^{-1} PO. Thus, the energy ratio ranged from 25 to 38 for bio-oil production. Thus, converting biomass sourced from marginal lands to bio-oil has a posititive energy balance and can play a key role in reducing our reliance on fossil fuels. The related GHG emissions ranged from 12 to 25 kgCO_2 t^{-1} PO (Table 2). The breakdown of costs showed that biomass production (contributing 61% to 71% of the costs) dominated, followed by conversion conversion (with a 29–39% share). A similar pattern was observed for GHG emissions. Note that the contribution of biomass production also includes that its transport. Overall, these data showed that miscanthus from marginal lands offer attractive long-term solution to meeting Brittany’s energy need in an environmentally sustainable way because of the high net energy gains and low GHG emissions. Compared to fossil fuels which emit between 70 and 80 kg CO_2 t^{-1} (EC, 2018), the bio-oil produced has a 98% abatement potential.

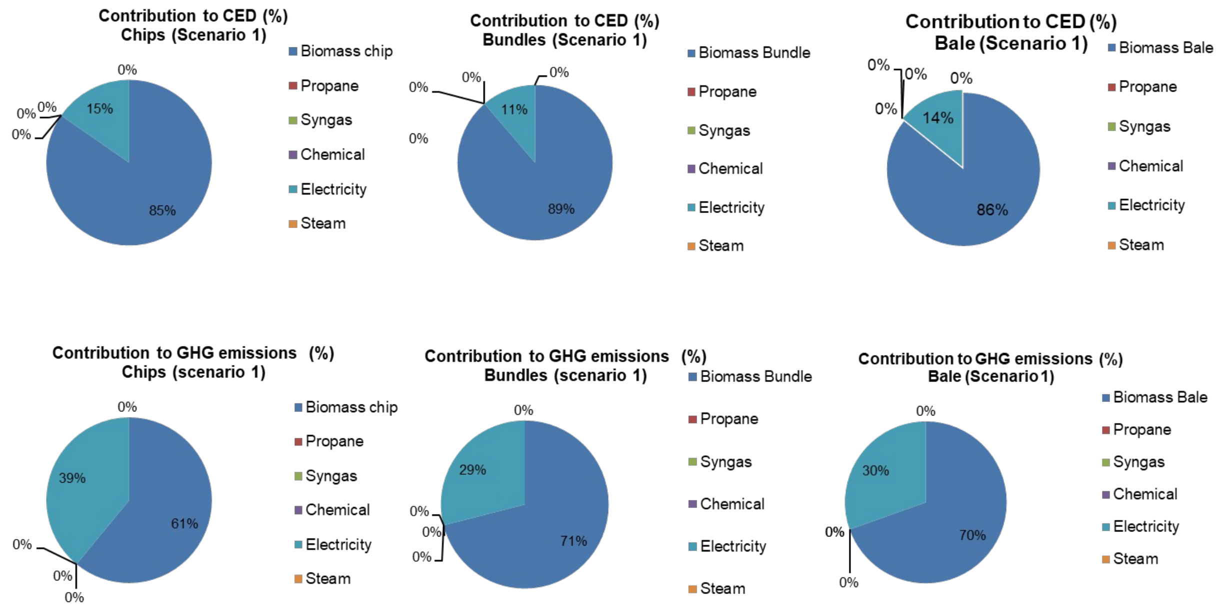


Figure 4: Breakdown of energy use (Cumulative Energy Demand, CED) and GHG emissions for the 3 miscanthus harvesting and logistics scenarios.

3.2 Soria case

3.2.1 Marginal lands, yields and carbon sequestration of energy crops on these lands

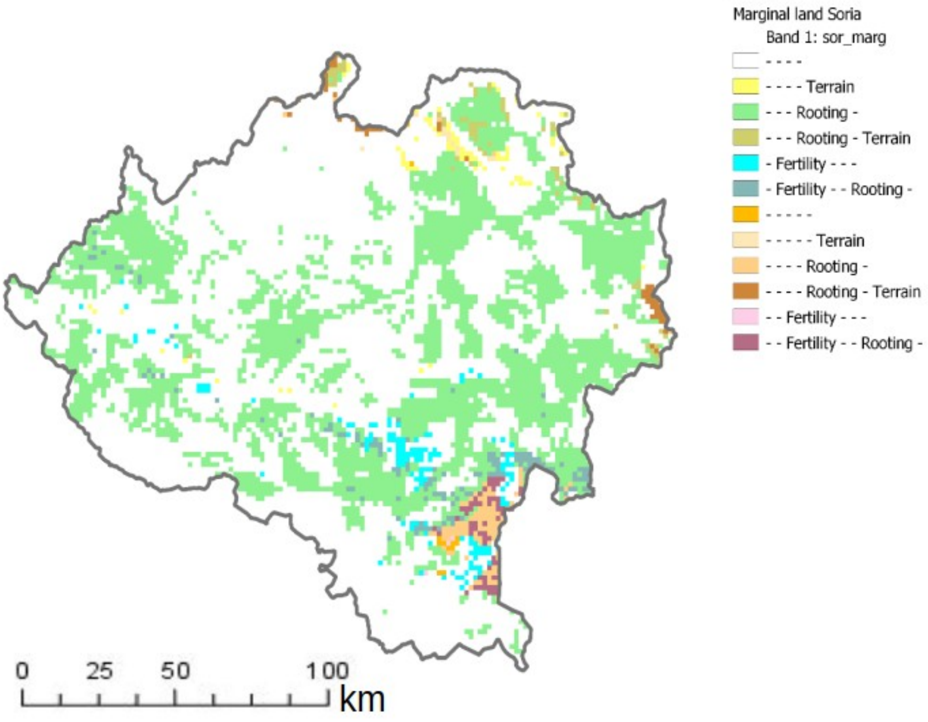


Figure 5: Map of marginal lands in the Soria province, depicting marginality constraints and their combinations.

Our simulation shows that there are about 376500 ha (3765 km^2) of marginal lands in the province Soria that are potentially suitable for energy crops cultivation (Figure 5). This represented ~ 37% of the total cropland area in the province of Soria, a 10-times larger fraction than in Brittany (France). The prominent marginality constraint was rooting limitations (with a 86% share), arising from low rootable soil volume or unfavorable soil texture, with a relatively even distribution over the province. Fertility (4%) and climate limitations (4%) related to low precipitation and short growing season (because of Soria being located in a high-altitude plateau at about 1100 m a.s.l.) were other, more minor causes of marginality in Soria. These factors mostly occur in combination with rooting limitations (Figure 6).

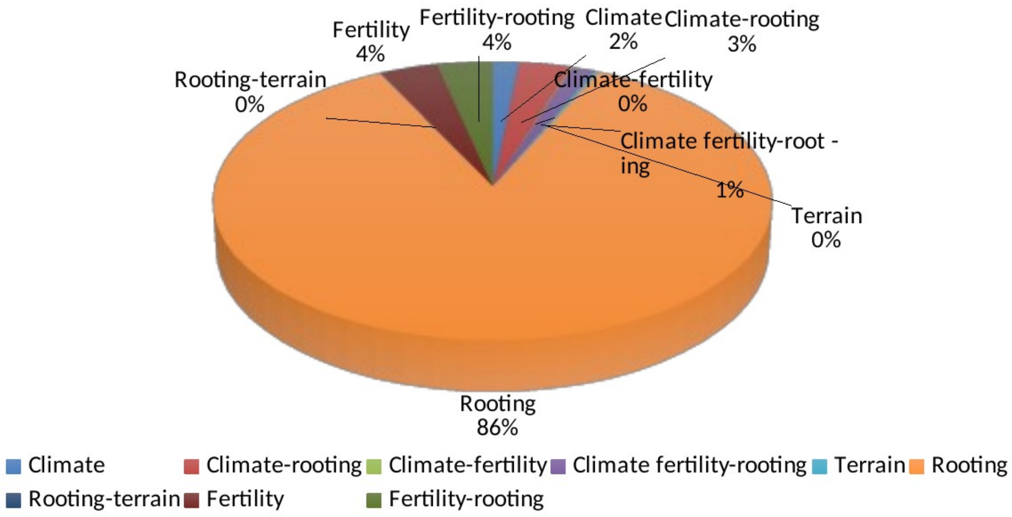
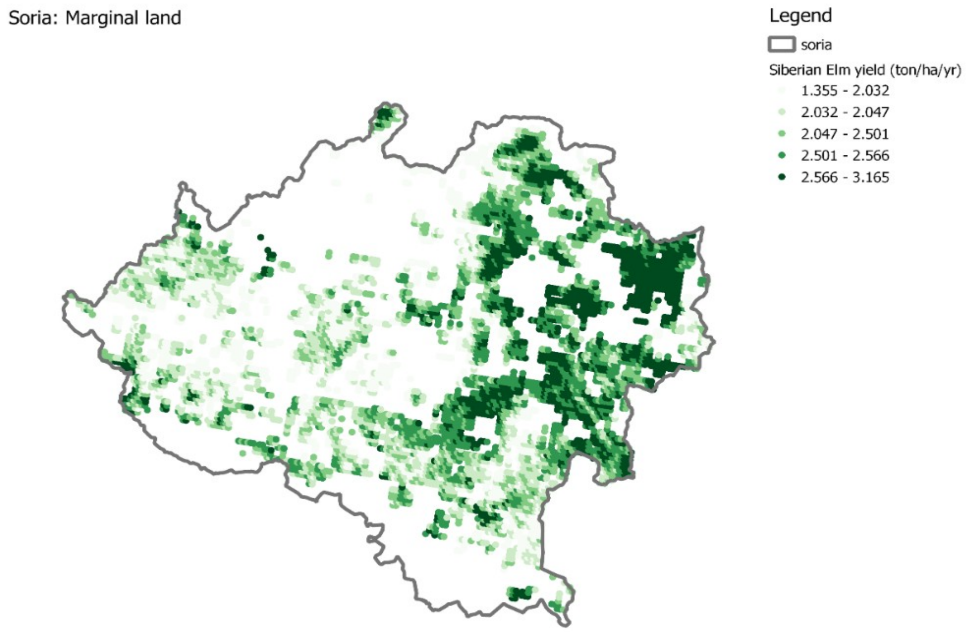


Figure 6: Frequency of occurrence of marginality constraints in Soria, and their combinations.

The productivity of tall wheat grass and Siberian elm on marginal lands in Soria is shown in Figure 7. The yields of tall wheat grass on marginal lands in Soria varied between 1.2 to 2.7 t DM ha^{-1} y^{-1}, with a mean value of 2.2 t DM ha^{-1} y^{-1}. Siberian elm produced slightly more biomass on these lands than tall wheatgrass, its yields ranged from 1.4 to 3.2 t DM $ha^{-1}y^{-1}$, with an average yield of 2.6 t $ha^{-1}y^{-1}$ over the identified marginal lands in Soria. These ranges are in line with the values given by Perez-Garcia (2016) for unirrigated trials conducted in the same province.

The total biomass production from marginal lands in Soria varied between 828 and 979 kt DM y^{-1} (or 14.2 to 16.8 PJ y^{-1} in terms of energy content), depending on the energy crop cultivated on these lands.



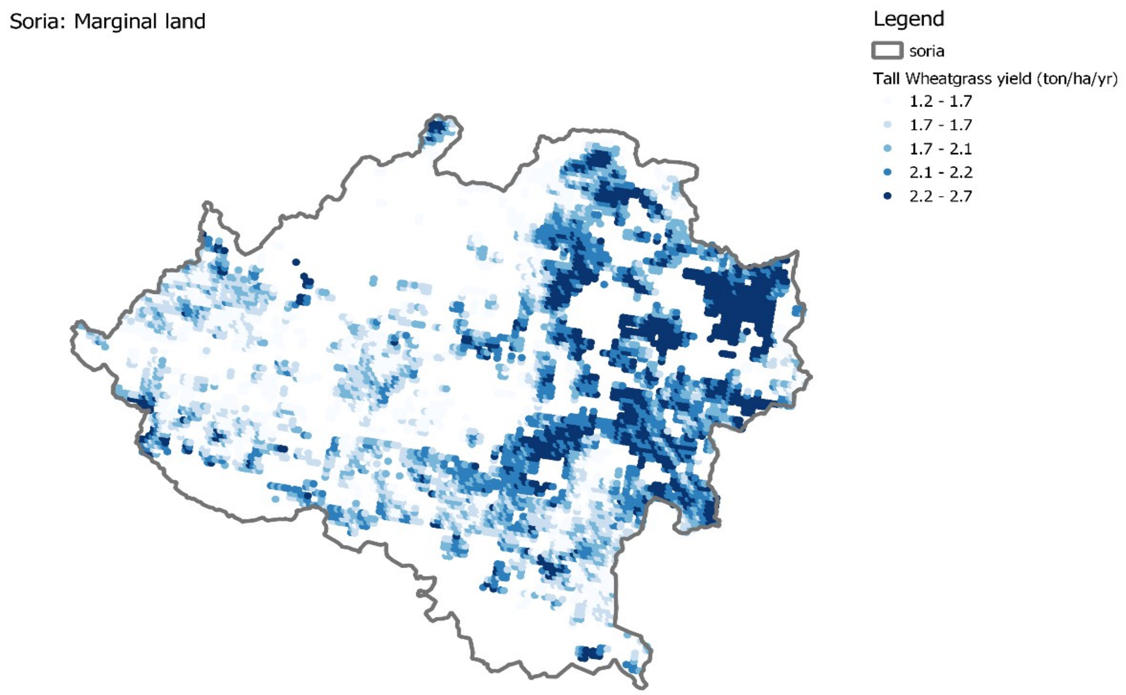


Figure 7: YIeld map for Siberian elm (top) and tall wheatgrass (bottom) as simulated by CERES-EGC in Soria.

3.2.2 Supply chain design and average supply distances

Assuming a 100% biomass availability in the province, supplying a 40 kt y^{-1} biorefinery plant in Soria would require a distance of 28 km for scenario 1, 44 km for scenario 2, and 110 km for scenario 3 (Figure 8). Here also, we noted an increase in average distance from scenario 1 to scenario 3. Small losses in biomass occurred in the logistics chain and so the amount of biomass was slightly higher than the demands. Depending on the scenario, the amount of biomass delivered to biorefinery plant in Soria varied from 40,002 to 40,008 t y^{-1}.

3.2.3 Feedstock supply costs

Considering that both tall wheatgrass and Siberian elm will be cultivated on same marginal land plots and given there was little differences in the biomass yields of these feedstocks, we selected the feedstock with the higher yields (i.e; Siberian elm) for the supply chain costs assessment. Note that both feedstocks are compatible with the Empyro process (as determined in D5.4 of MAGIC and the Bio2Match Tool data base and model).
The total annual costs for delivering biomass to biorefinery plant of capacity of 40 kt y^{-1} ranged from from from 3.9 to 4.9 M€ y^{-1} depending on the biomass harvest form and scenarios. The unit delivery costs ranged from 96 to 101 € t^{-1}, depending on the harvest form and scenarios considered. As in the Brittany case, bales were least competitive relative to both chips and bundles, although this gap decreased as transportation distances increased (from scenario 1 to scenario 3). Since the cheapest biomass form is transported to the biorefinery plant, these unit costs thus represents the minimum (or optimal) supply costs of biomass from marginal lands to the conversion plant.
Feedstock supply costs were about 15% higher than in Brittany with miscanthus. The 10-times larger density of marginal lands in Soria, which reduced transportation distances and logistics costs, could not compensate for the 3 to 4-fold lower biomass yields compared to Brittany, even when selecting the highest-yielding crop in Soria. As discussed for miscanthus in Brittany, the 96 to 101 € t^{-1} range of biomass delivery costs estimated here are in the higher end of those reported for other feedstocks in Europe, and make a sourcing from marginal lands less attractive than other options. This is also reflected in the bio-oil production costs, which are about 7% larger than in Brittany. From an economic perspective, the Soria case appears less favorable than Brittany, despite is larger availability of marginal lands.

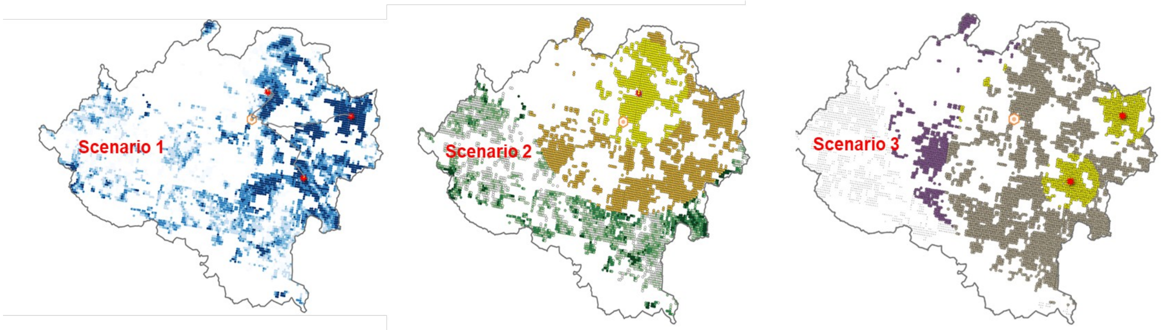


Figure 8: Map of land units (pixels) collected to supply a 40 kt/year biorefinery in the Soria province. The location of the biorefinery is indicated by a red circle, and the intermediate collection points by red dots.

Table 3. Feedstock supply costs and bio-oil production costs for the Soria case, for 2 supply chain scenarios: no intermediate collection points (Sc. 1) or 1 or 2 such collection points (Sc. 2 & 3), and for three harvesting scenarios.

	Chips			Bundles			Bales		
Feedstock Costs	Sc 1	Sc 2	Sc 3	Sc 1	Sc 2	Sc 3	Sc 1	Sc 2	Sc 3
(€/ton DM)	96.2	99.2	97.5	97.4	100.4	98.7	99.3	102.3	100.6
	PO_Chips			PO_Bundles			PO_Bale		
(€/ton PO)	321	326	325	323	327	325	326	330	328
(€/GJ PO)	20.1	20.3	20.2	20.2	20.5	20.3	20.4	20.6	20.5

3.2.4 Bio-oil production costs, energy use and GHG emissions

The conversion of Siberian elm to pyrolysis oil resulted to energy consumption ranged from 0.52 to 0.67 GJ/ton PO (Table 4), corresponding to energy efficiencies ranging from 24 to 31. This is similar to the range achieved in the Brittany case (with an ER varying between 25 to 38), albeit slightly lower again due to the lower biomass yields. Conversely, the production of Siberian elm or tall wheat grass in Soria resulting in negative GHG emissions due to the strong soil C sink associated with these two perennial energy crops relative to the current land-use. This is a striking difference with the Brittany case, and shows an interesting trade-off between energy and agronomic efficiency versus soil C sequestration. Overall, the life-cycle GHG emissions of bio-oil ranged from -126 to -136 kg CO_2/ton PO (Table 4). Soil C into marginal lands more than offset GHG emissions from logistics as well as conversion of feedstock into bio-oil. Such negative emission patterns have seldom been reported for bioenergy chains (see eg the meta-analysis by El Akkari et al., 2018, with no such instances), but may occur because of the marginal land context (Gabrielle et al., 2014b; Panoutsou and Chiaramonti, 2020).

Table 4. Energy consumption, energy efficiency (ER), and GHG emissions of bio-oil under different logistics scenarios in Soria. PO: pure bio-oil.

Scenario	Harvest forms	CED (GJ/ton PO)	Energy ratio	GHG emissions ($kgCO_2$/ton PO)	GHG emissions ($kgCO_2$/GJ PO)
Scenario 1	PO_chips	0.52	31	-134.4	-8.40
	PO_bundles	0.53	30	-133.7	-8.35
	PO_bales	0.61	26	-127.4	-7.96
Scenario 2	PO_chips	0.59	27	-131.8	-8.2
	PO_bundles	0.59	27	-131.7	-8.2
	PO_bales	0.67	24	-125.5	-7.8
Scenario 3	PO_chips	0.55	29	-133.6	-8.35
	PO_bundles	0.56	29	-132.8	-8.30
	PO_bales	0.64	25	-136.5	-8.53

The breakdown of energy use and GHG emissions (Figure 9) shows that both feedstock production and conversion were the key processes. With regard to energy use, feedstock production contributed 88 to 90% total energy use, depending on the biomass harvest form, followed by conversion (10 -12%). Concerning the GHG emissions, here the contribution of feedstock production to total GHG emissions of bio-oil was negative overall, depending on the biomass harvest form, while that of biomass conversion was positive and mainly due to electricity consumption at the biorefinery plant. Overall, these data showed that Siberian elm from marginal lands offer attractive long-term solution to meeting Soria's energy need in an environmentally sustainable way because of the high net energy gains and negative GHG emissions.

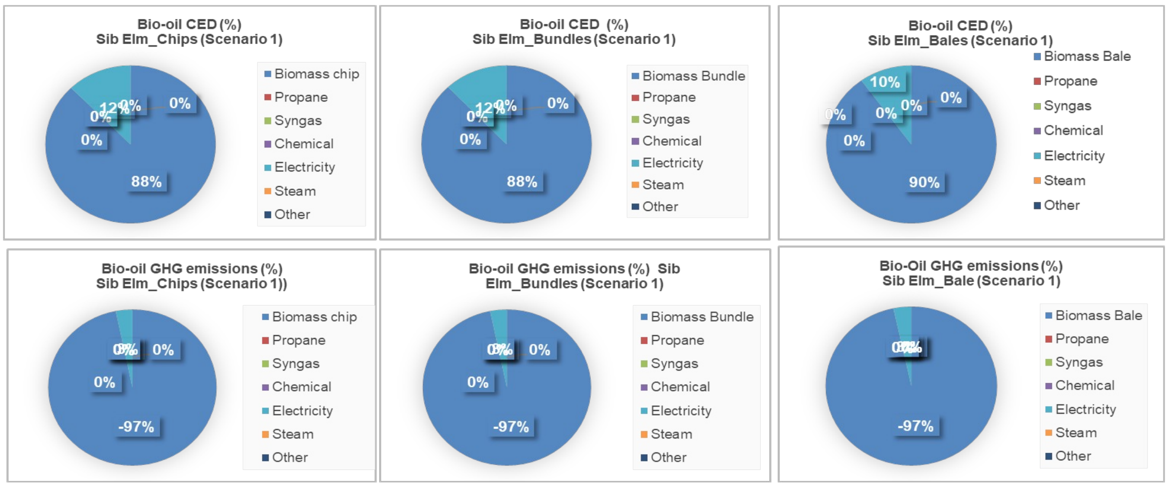


Figure 9: Breakdown of energy consumption (CED) and GHG emissions for bio-oil production in Soria, under scenario 1 (no intermediate biomass collection point).

3.3 Emilia Romagna case

3.3.1 Mapping of biomass resources and feedstock supply costs

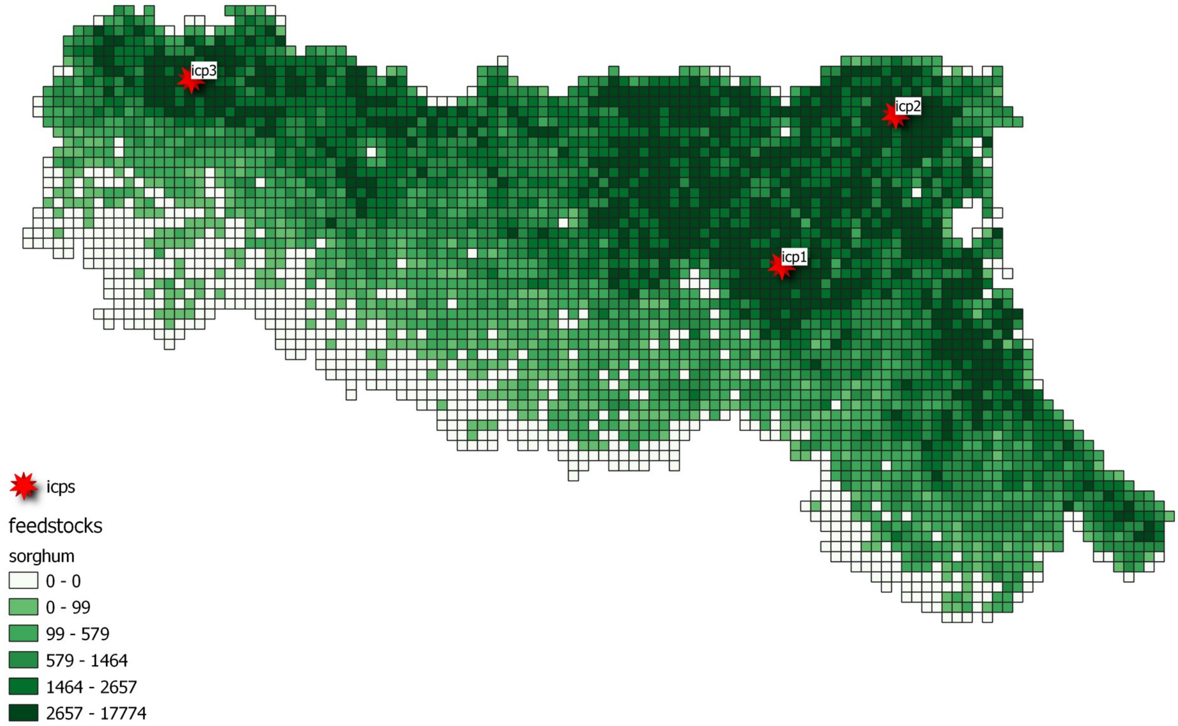


Figure 10: Map of biomass output (in t DM/yr) from sorghum in Emilia Romagna (Italy), and intermediate collections points for the 3 logistics scenarios (ICP1 corresponds to the location of the pyrolysis biorefinery). Each pixel is 2.5 km x 2.5 km in size.

Figure 10 depicts the spatial distribution of biomass availability throughout the Emilia Romagna region, simulated with the CERES-EGC model and taking into account marginality factors both in terms of marginal land area and impact on sorghum yields. Overall, sorghum achieved 2-fold larger yields than miscanthus in Brittany, albeit with about double the amount of fertilizer N inputs (50 vs. 30 kg N ha^{-1} y^{-1} in Brittany). This input rate was selected to match the yield level observed for sorghum in non-marginal conditions (around 20 t DM ha^{-1} y^{-1}), which was obtained in a control run of CERES-EGC in the absence of stress factors related to marginality traits (Acciai, 2021).
In terms of spatial structure, biomass supply was denser to the North of the region, with less stringent marginality factors and more agricultural land available in general, compared to the Southern half with a higher relief overall and steeper terrain conditions (and slopes often higher than 10%). The location of the biorefinery was set in the vicinity of Bologna, the regional capital with a high energy demand – also because it was situated in a dense patch of sorghum production.

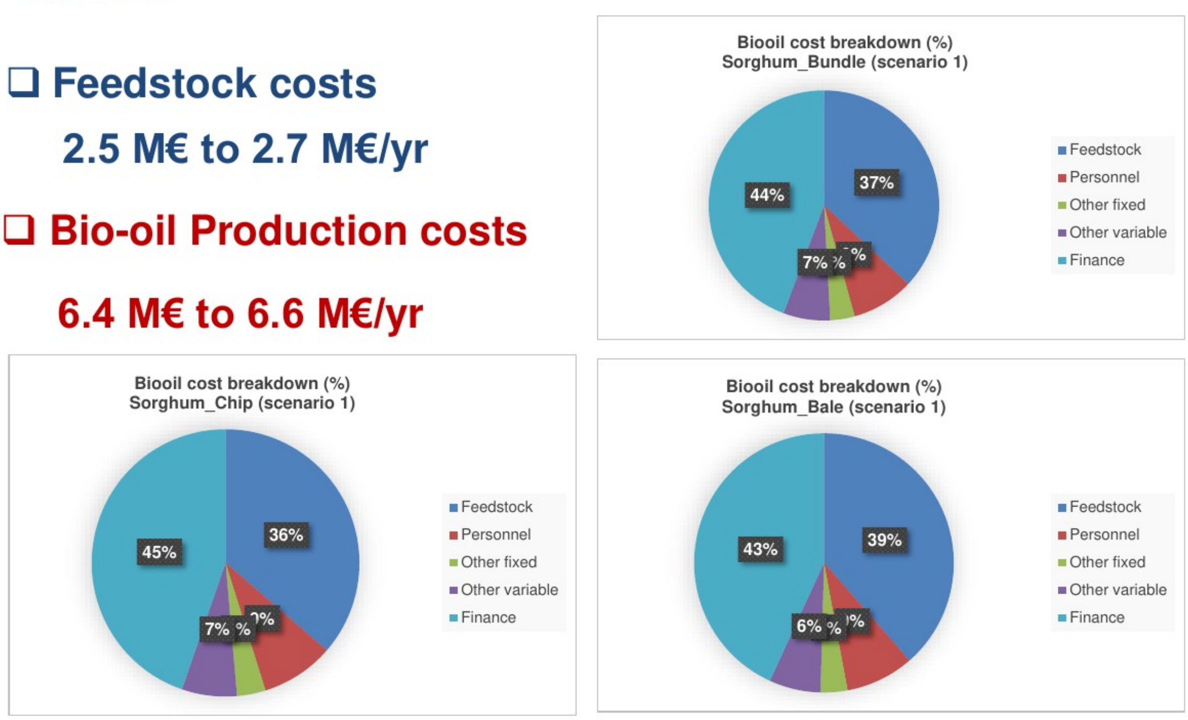


Figure 11: Feedstock and bio-oil production costs, and breakdown for logistics scenario 1 (no ICP) in Emilia Romagna.

Feedstock	Chips				Bundles				Bales		
Costs	*Sc1*	*Sc2*	*Sc3*		*Sc1*	*Sc2*	*Sc3*		*Sc1*	*Sc2*	*Sc3*
(€/tDM)	61,9				63.6				68.1		
Products	**Bio-Oil**				**Bio-Oil**				**Bio-Oil**		
Costs	*Sc 1*	*Sc2*	*Sc3*		*Sc1*	*Sc2*	*Sc3*		*Sc1*	*Sc2*	*Sc3*
(€/ton PO)	**267.2**				**269.8**				**276.8**		
(€/GJ PO)	**16.7**				**16.9**				**17.3**		

Table 5: Feedstock supply and bio-oil production costs for the 3 sorghum harvesting scenarios in Emilia Romagna.

3.3.2 Bio-oil production costs, energy use and GHG emissions

Feedstock supply costs contributed the largest share of bio-oil production costs, in line with the other 2 cases (Figure 11). However, because of the much higher biomass yields per hectare, feedstock supply costs were lowest in this case, ranging from 62 to 68 € t^{-1} DM – about 35% less than the costs estimated in Soria, which came out as the worst configuration of the 3 cases investigated here. These costs fall in the mid-range of those cited in the Brittany case for non-marginal lands, and could be considered as a best-case scenario. Despite an average transportation distance larger than in Brittany (64 km vs. 44 kms, respectively), due to a lower density of crops around the biorefinery site, the 2-times higher yields resulted in 20% cheaper biomass procurement costs in Emilia Romagna.

Bio-oil production costs were also cheapest in this region, begin 10-15% lower than in Soria, and 10% lower than in Brittany. Although it is difficult to benchmark the production costs of bio-oil since there is no market yet for this product, the review by Chum et al. (2011) mentions a 19-42 US$(2005)/GJ range for production costs, which could be directly translated into euros of today by compounding inflation and the € to $ exchange rate. So overall the ranges found here for bio-oil based on marginal land fall within the lower end of this literature range which does not rule out this option.

Scenarios	Feedstock Input	Bio-Oil Ouput	CED GJ/ton Oil	ER	GHG emissions ($kgCO_2$/ton Oil)	GHG emissions ($kgCO_2$/GJ Oil)
Scenario 1	Chips	PO_chips	0,49	32.6	39.5	2.4
	Bundles	PO_bundle	0.50	32.0	40.4	2.5
	Bales	PO_bale	0.57	28.1	45.7	2.9

Table 6: Energy consumption (CED), efficiency (ER) and GHG emissions of boi-oil production from sorghum in Emilia Romagna.

The relatively high productivity of sorghum traded-off with somewhat larger GHG emissions and energy consumption compared to the other cases, because inorganic fertilizer N inputs are energy and CO2 intensive (Table 6). The CERES-EGC simulated a small soil C sink (of 150 kg C ha^{-1} y^{-1}) under the sorghum crop (or the crop rotation it took part in, actually), on average, which was not enough to compensate for the other, positive, life-cycle emissions due to agricultural inputs and machinery use, logistics, and conversion to bio-oil. However, even though these emission levels were double those of the Brittany case (the only other case with positive life-cycle emissions), they remain far lower than most biofuels or bioenergy chains, on a GJ basis (Chum et al., 2011). For instance, Njkou Djomo et al. (2011) mention a 0.6 to 10.6 kg CO2 GJ of biomass energy content for short rotation coppice, even before conversion to an end-product, and energy ratios varying between 22 and 38. Thanks to pyrolysis being a self-sufficient process in terms of energy use, the environmental performance of bio-oil was close to that of its feedstock, which in turn benefited from the particular status of marginal lands. Indeed, these lands, although challenging from the perspective of production potential and supply chain logistics, were still favorable thanks to their C sequestration capacity and the absence of indirect effects, although this is still debatable since marginal lands is usually qualified as a “low iLUC” option (see eg Traverso et al., 2020) implying indirect effects cannot be completely ruled out altogether.

4 Conclusion

Sourcing biomass from marginal lands is urgently needed to support the broader effort to increase the development of biorefinery industries. However this poses agronomic and logistical challenges as crop yields are expected to be substantially lower on marginal lands, and due to the difficulty of collecting biomass from unevenly distributed plots with access problems due to steep terrain or remoteness.

We combined a GIS, a process-based crop model (CERES-EGC), and the LocaGIStics model to assess the potential of such a configuration to supply a pyrolysis unit with an annual demand of 40 kt of lignocellulosic biomass in three regions of the EU with contrasted production potential or marginal land availability. These cases involved various crops (annual and perennial grasses, and a short rotation woody species) and 9 logistics scenarios (3 harvest types and from none to 2 intermediate collection points - ICP).

Overall, the number of ICPs had a strong influence on the average transportation distance to deliver biomass to the plant gate, but a trade-off with storage costs on the biorefinery site mitigated this effect on delivery costs. Those were generally lower in the absence of ICPs, but only to a slight extent. Similarly, harvesting as bales (versus bundles or chips) was slightly more costly, but relative cost differences between harvesting methods did not exceed a few percentage points. Differences were larger for energy use and GHG emissions, with bundles being more energy intensive, and bales more energy efficient than than the other 2 harvests. Regarding GHG emissions, the ranking between bales and chips depended on the number of ICPs and the average transportation distance, with bales being less CO2 intensive for distances over 100 kms.

There were strong inter-regional effects on crop yields and the availability of marginal lands, with yields in Soria (Spain) averaging 4 to 5 times less than those of miscanthus in Brittany (France), and sorghum in Emilia Romagna (Italy) achieving double the yield of miscanthus in the latter region. This was directly reflected in the feedstock delivery costs, which were 15% higher in Soria and x% lower in Emilia Romagna compared to Brittany. Bio-oil production was therefore more expensive (by 7%) in Soria and cheaper in Italy, given that processing costs were similar across all cases.

Since the logistics of biomass from marginal lands is still an immature operation, there is scope to significantly reduce the delivery costs, energy use, and GHG emissions by improving or modifying the way the supply chain is operated. Still, procuring biomass from PECs grown on marginal lands is substantially more expensive than souring it from regular cropland, especially when scaling up the production. Keeping the transportation distance under 100 kms is highly desirable to keep the procurement costs affordable, which means marginal lands – at least in the regions studied here – will not suffice to answer the demand a large-scale biorefinery such as a full-blown 2G biofuel plant.

Our study can support decision making related to supply chain assessments of biomass from marginal lands. Further efforts have to be made to integrate the different tools into an integrated model for both identification and supply chain assessments of biomass from marginal lands also taking a wider spectrum of sustainability impacts and opportunities into account.

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