Marginal lands for Growing Industrial Crops

D.5.3 – A NEW LOGISTICS MODEL AND ITS APPLICATION TO CASE-STUDY VALUE-CHAINS

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Table of contents

1 Introduction 5
1.1 Background and rationale 5
1.2 Objectives and target groups 6
1.3 Contribution of project partners and link to other activities in Magic project 6
1.4 Structure of this report 7
2 Materials and Methods 8
2.1 Study area 8
2.2 Description of the LocaGIStics model 8
2.3 Identification and Mapping of Marginal Lands in Brittany 9
2.4 Miscanthus growth simulation and mapping 9
2.5 Miscanthus supply chain and scenario description 10
2.6 Supply Chain Costs, Energy use and GHG emissions 11
2.6.1 Cost Calculations 11
2.6.2 Energy Use 11
2.6.3 GHG emissions 12
3 Results 13
3.1 Marginal lands in Brittany 13
3.2 Miscanthus Yields on Marginal lands in Brittany 13
3.3 Feedstock production costs, energy use and GHG emissions 14
3.3.1 Feedstock production costs (farm gate) 14
3.3.2 Feedstock energy use (farm gate) 16
3.3.3 Feedstock GHG emissions (farm gate) 16
3.4 Feedstock delivery costs, energy use, GHG emissions 17
3.4.1 Feedstock delivery costs (biorefinery gate) 17
3.4.2 Feedstock delivery energy use and GHG emissions (biorefinery gate) 18
3.4.3 Contribution Analysis 18
4 Discussion 20
4.1.1 Availability of marginal lands to grow an industrial crop 20
4.1.2 Miscanthus yields on marginal lands 21
4.1.3 Miscanthus production Costs, Energy, GHG emissions (farm gate) 21
4.1.4 Miscanthus Supply Chain Costs, Energy, GHG emissions (Biorefinery gate) 22
5 Conclusion 24

Publishable executive summary

Little is currently known about the amount and spatial distribution of marginal lands, as well as the economic and environmental impacts of regional supply chains of biomass sourced from marginal lands. Here we combine three tools: GIS data layers, CERES-EGC and LocaGIStics to (i) quantify and map marginal lands in Brittany (France), (ii) simulate yields of miscanthus on these lands, (iii) assess the economics and environmental impacts of a biomass supply chain from these crops. Three miscanthus harvest forms (chips, bundles, and bales) and three supply scenarios (no intermediate storage, one storage point, and two storage points) were studied.

We found a total of 57,544 ha of marginal land in Brittany, which are suitable for miscanthus production. The prominent marginality constraints were rooting (55%) and salinity (34%). The simulated yields of miscanthus yields on these lands varied from 2 to 19 tons dry matter (DM) $ha^{-1}y^{-1}$ and were much lower in saline than in stony soils. The farm-gate production costs of miscanthus on these lands ranged from 53 to 104 € DM ton^{-1} whereas energy use varied from 199 to 431 MJ ton^{-1}, depending on crop yields, management and harvesting methods. The farm-gate GHG emissions of miscanthus (-71 to 116 kg CO_2 ton^{-1}) showed that the crop was a net GHG sink in some fields, while in others it represented a small source of GHGs compared to other similar biomass feedstock. The logistics models showed it costs 91 to 121 € DM ton^{-1} to supply a biorefinery plant with a 40 kton yr^{-1} biomass processing capacity. The associated environmental impacts were an energy demand of 492 to 1,290 MJ DM ton^{-1}, and GHG emissions ranging from 11 to 66 kg CO_2 DM ton^{-1}, depending on the harvest form and the storage scenario. Miscanthus was economically and environmentally more viable when delivered as chips than as bundles or bales in all scenarios. Chips should thus be favoured over bundles and bales for short transport distances. A deeper analysis of the supply chain showed that biomass production, transport and storage dominated the total delivery costs, energy use, and GHG emissions. Compared to another feedstock type such as agricultural residues, miscanthus from marginal lands presented a competitive advantage, with a lower risk in terms of biomass sourcing. This study improves our understanding on the distribution of marginal lands and on the supply chain of miscanthus in Brittany. It also provides a proof-of-concept regarding the logistics of supplying biomass from marginal lands, which are highly challenging due to their lower production potential and the uneven spatial distribution.

1 Introduction

1.1 Background and rationale

Climate change and energy security are challenges faced by many countries around the world. The latest IPCC assessment report concludes that sustained GHG emission reductions are needed to maintain global temperature below 2 ^oC above the pre-industrial level by the end of this century [1]. The goal of keeping the global temperature within 1.5 ^oC above the pre-industrial level requires drastic actions: a lower carbon budget of about 400 to 600 Gt of CO_2, leading to a 45% emission reduction by 2030, and net zero CO_2 emissions by 2050 [2]. Responding to these challenges, the European Union (EU) has set targets to increase the share of renewable energy in the supply mix by 32% by 2030 and to reduce GHG emissions by 40% relative to the 1990 levels by 2030 (RED II, 2018). Beside these targets, the EU also has ambitions to build a carbon neutral future mostly relying on concept of circular economy. Biomass is becoming an increasingly important resource in the context of circular economy, economic development, energy security and climate change. It is an abundant, versatile, environmentally friendly, and carbon neutral renewable energy source and can play a prominent role in circular economy in terms of material products, provision of energy, and reduction of GHG emissions [3].

Among the various biomass feedstock currently considered for the development of circular economy, perennial energy crops (PECs) have been identified as the most relevant one for bioenergy production. PECs are seen as an option for producing additional biomass efficiency and sustainably while avoiding competing with agricultural and forest biomass resources. Miscanthus (*Miscanthus giganteus*), among others, is seen as the PEC with high potential for cultivation on marginal lands. Miscanthus is characterised by their fast growth, high and sustained yields, good energy density, high cellulose and hemicellulose contents, high carbon storage potential, low maintenance costs and low environmental impacts[4-6]. Miscanthus is seen as carbon neutral crop because it absorbs atmospheric CO_2 through photosynthesis and the net CO_2 emissions from its conversion can be much less than those from burning fossil fuels [7-9]. Miscanthus based bioenergy system could even become a negative emissions technology if the carbon emitted during the conversion of miscanthus is captured and stored to the soil [10]. Despite its high yield and high carbon storage potential, miscanthus represents only a very small fraction of the current energy portfolio. This is in part due to its production costs relative to fossil fuels and to agricultural and forest residues.

However, because miscanthus is well adaptable to a wide range of soils and climate conditions, it could be cost-competitive if grown on marginal lands[11]. Although the concept of marginal land can vary depending on the context [12, 13], the term is used to refer lands having biophysical constraints, which in aggregate hamper the production of food or feed crops [14]. These lands may be the best choice among all the possible lands for growing miscanthus. Resorting to such lands is likely to give miscanthus a competitive advantage compared to alternative food or feed crops in the same location. Marginal circumstances will cause lower yield for all crops, but a perennial crop like miscanthus is likely to cope better with these limitations and still be economically viable[15, 16]. This option will also avoid the food vs fuel conflict [17], reduce the indirect land-use change effects associated with the expansion of land for bioenergy, and offer opportunities for strengthening the local economy [18, 19]. Moreover, producing miscanthus on marginal lands could provide ecosystem services such as of soil carbon storage and water quality improvements[7, 20-22].

Different working definition, methods, land cover inventories, datasets, and assumptions have been used in previous studies to assess the potential of marginal lands at global level[23, 24], at continental level [14, 18, 25], and at national/local scales [26-29]. Collectively, all these studies point to a substantial potential of marginal lands. However, little attention is paid to the effects of environmental and biophysical constraints on crop productivity and the suitability of marginal lands for PEC cultivation [30]. Some of these studies (e.g.[24, 31] could neither locate these marginal lands, nor provide the productivity of PECs on these lands. More recent studies have combined geographic information systems (GIS), crop models, and multi-factors analyses and have shown that biomass yields on marginal lands depends on location and the types of PECs grown thereon[17, 23, 27, 32, 33]. However, these more recent studies did not provide an estimate of the production costs or carry out an assessment (whether economic or environmental) of the biomass supply chain. Supply chain costs, energy use, and GHG emissions are key factors affecting the commercialisation of PECs from marginal land. However, little information currently exists on analyses of supply chain configurations of biomass from marginal lands in Europe [11]. Locating and quantifying potential marginal lands, along with the economics assessing the PECs grown thereon and assessing the supply chains of PECs from these lands are essential to determining the feasibility of a biorefinery plant depending on bio-resources.

1.2 Objectives and target groups

The objectives of the work reported in this deliverable are three-fold:

(i) To quantify and map marginal lands in Brittany (France)
(ii) To assess the productivity of miscanthus on these lands
(iii) To quantify the supply chain costs, energy use and GHG emissions of miscanthus biomass sourced from marginal lands.

The analysis was conducted for the Brittany case that represents one of the three agro-ecological zones (AEZ) selected in the MAGIC project. Two other case studies will be developed within WP5 of MAGIC in the other two AEZ. This deliverable focuses on the Brittany case to showcase model development and application to this value-chain. The extension to the two other case studies (in Spain and Greece) will be reported on in the final deliverable of MAGIC (D5.5).

The target audience for this report includes internal and external stakeholders as well as the general public. Internal stakeholders are project members who 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 (a cooperative developing miscanthus in Brittany).

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

The report was written by INRAE and WUR. The contribution of INRAE is related to the simulation of yields of energy crops on marginal lands, techno-economic assessment of miscanthus 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. This deliverable is connected to other work packages and tasks of the magic project (D.2.1., D.5.2)

1.4 Structure of this report

This report is divided into five sections: section 1 gives a short introduction on miscanthus on marginal lands and on the supply chain of energy crops. The second section deals with the methodology used in this report to assess the potential of marginal lands in Brittany: simulating the biomass yields of miscanthus on these lands, assessing the production and delivery costs, energy use and greenhouse gas emissions of miscanthus supply chains. Results are presented in the third section of this report, followed by a detailed discussion in section 4. Finally, section 5 presents the main conclusions of this analysis.

2 Materials and Methods

2.1 Study area

Brittany (48° N; 30° W) is the westernmost administrative region of France, covering about 27,200 km^2. This NUTS2 region is composed of four departments (NUTS3 units): Côtes d'Armor, Finistère, Ille-et-Vilaine and Morbihan (Fig. 1). Brittany has an oceanic climate, with annual rainfall varying from 700-800 mm and average annual temperature of about 12^{o}C. The majority of soils in Brittany are deep silty clay loams and the main vegetation cover types are cropland and pastures, making up 80% of the region's overall area. Agriculture is one of the dominant economic activities in the region. It occupied 1.73 Mha of land in 2013 and represents 4.2% of the total employment in Brittany. Livestock breeding is the primary agricultural activity and animal feeds include wheat, soybean, oilseed rape, fodder maize, luzerne and grass (from temporary and permanent grasslands). At the moment PECs production, represent a small but steadily growing part of the total biomass production in the region.

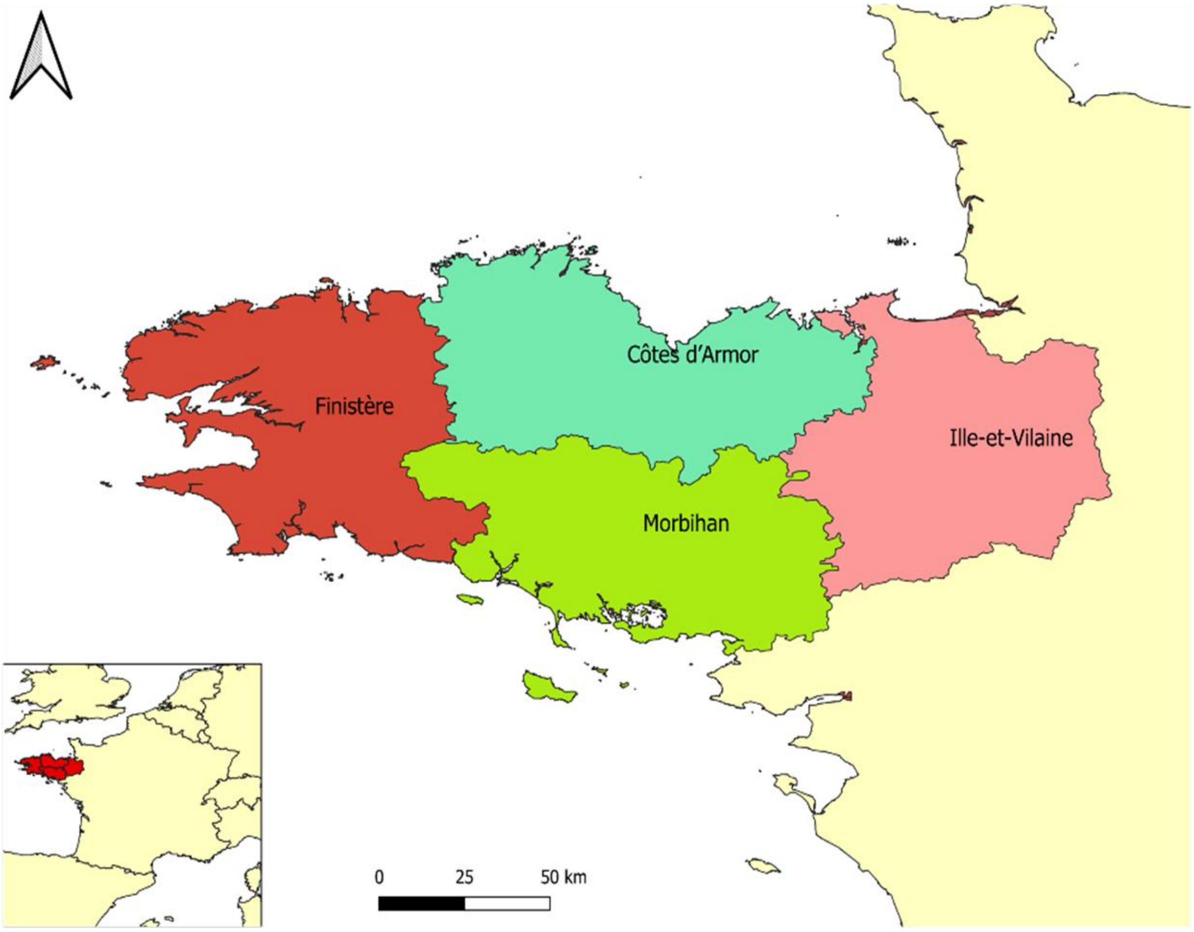

Fig. 1 Brittany (France) and its different department.

2.2 Description of the LocaGIStics model

Supply chain logistics were simulated with the LocaGIStics model. 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 a unit operation or process (e.g. transport, drying, and harvesting) and is independently constructed with a set of inputs and outputs. In the LocaGIStics model, biomass moves from one module to the next one through connectors. The strength of this model is its flexibility and ability to model multiple types of feedstock, logistical sourcing options (direct, or with intermediate collection points), and biomass conversion processes. It can accommodate other models such as CERES-EGC and supply chain modules built outside of LocaGIStics. Its geospatial features allow it to determine the biomass used and transport distance required, based on biomass availability maps. The tool handles both single and multi-modes of transport and can help the users to design and analyse multiple delivery chains to find the optimal solution. In the LocaGIStics model, the 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). Modelling of costs, energy use and GHG emissions are done externally in Excel based calculation model, and then included in the LocaGistic model to be included in the spatial assessment integrating multiple information layers. 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.

2.3 Identification and Mapping of Marginal Lands in Brittany

The identification of marginal lands available across Europe and their main characteristics was done as part of another activity in the MAGIC project [34]. The approach builds on the JRC work to identify Areas of Natural Constraints [35] and other land evaluation systems for agronomic suitability. 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 tempereature 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 unfavourable 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 neutralised via agronomic improvement measures such as fertilisation, 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).

2.4 Miscanthus growth simulation and mapping

Miscanthus was chosen as the suitable PEC for Brittany, in line with recent work, which combines biophysical and environmental information to determine the most suitable location for development of suitable biomass crops in Europe[21]. The suitability of Brittany for the growth of miscanthus is also further confirmed by the the fact that there are already 500 hectares of miscanthus established in the region. The growth of miscanthus on marginal lands in Brittany was simulated using the CERES-EGC model [36]. The model requires inputs such as soil properties, precipitation, maximum/minimum air temperatures, and management description (planting, harvest, fertilizer, tillage). The model was calibrated prior to its utilisation for the simulation of miscanthus growth on marginal lands. 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 (southeastern 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 [37]. After the calibration the model was ran. In the first model 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. To integrate the identified marginal lands in the CERES-EGC model, we overlaid the marginal land map [14] with the soil map used by CERES-EGC to point at the CERES-EGC polygons in which marginal factors occurred. Regarding management practices, we assumed a baseline fertilizer input of 30 kg N/ha and no limitation for P/K availability in soils. To account for the main marginality factors (rooting, chemical limitations), the CERES-EGC was modified as followed: for rooting constraints, 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 these characteristics with a high sand content. 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 [18]. Simulated yields of miscanthus and associated GHG emissions at 1km x 1km grid cells were imported as shape file into the LocaGIStic model, where polygone maps were made.

2.5 Miscanthus supply chain and scenario description

To better understand the supply chain performance of miscanthus from marginal lands, we developed and analyzed three delivery scenarios (Fig. 2a-c).

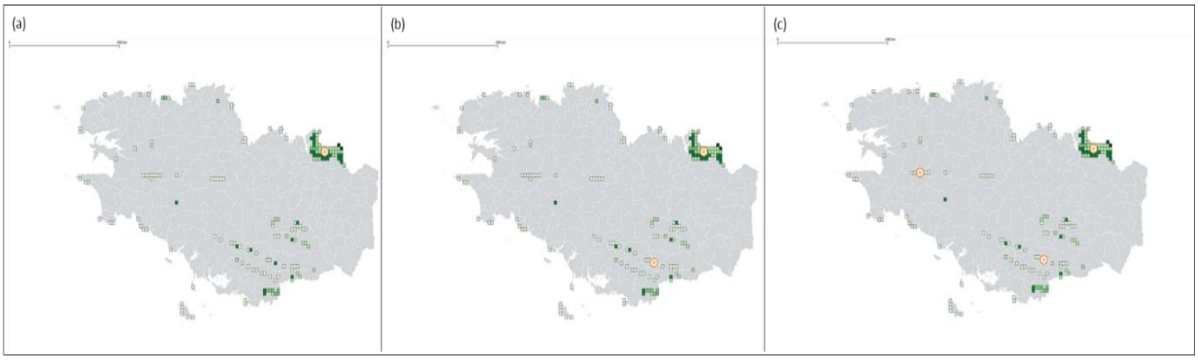

Fig 2. Location of the storage and intermediary collection point (ICP) sites in the different scenarios.

Each of these scenarios represents a biomass supply chain and consists of the following activities: biomass production, harvesting into different forms (bundles, chips, or bales), loading, transport, unloading, and storage at field/or at intermediate collection point, transport and delivery at the biorefinery plant. The first scenario (SC1) assumes that the three biomass forms are collected from fields and transported directly to the biorefinery plant located at less than 10 km from the fields (Fig 2a). The second scenario (SC2) considers that after field collection, the biomass is transported to the intermediate collection point (ICP) where it is stored for a while and delivered later to the biorefinery plant as required. The total average distance until the delivery at the biorefinery is 125 km (Fig 2b). In the third scenario (SC3), the biomass forms are 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, the LocaGIStics tool set a supply distance of 187 km for this scenario (Fig 2c). In all scenarios, this model prescribes the optimum number of fields required to meet the total biomass demand of the biorefinery plant (i.e., 40 ktDM y^{-1}), and the assignment of farms to storage locations. In each scenario, the cheapest biomass is collected first and this continues until the biorefinery plant demand is met. This means the collection at the ICPs starts only when there is no cheaper biomass in the vicinity of the biorefinery. It is further assumed that ICPs have enough capacity to store biomass for three months until processed by the biorefinery plant. Although each ICP could further process the biomass form into pellets or briquettes, this pre-processing is not envisaged in this study. A constant biomass supply of 40 kton y^{-1} is assumed in all scenarios. This supply level has been shown to be financially feasible in a small-medium scale bioenergy facility [38]. Since miscanthus is feedstock is sold by mass, a functional unit of 1 ton of dry-equivalent biomass delivered to the biorefinery plant was used [39]. The supply costs, energy use, and GHG emissions of each scenario were thus normalized to this functional unit. For each scenario, we also estimate the total biomass delivery costs, energy consumption and GHG emissions. A three rigid-axles truck was assumed in all scenarios and the effects of different truck configurations were assessed in a sensitivity analysis.

2.6 Supply Chain Costs, Energy use and GHG emissions

2.6.1 Cost Calculations

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 are 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 variable factors directly linked to production figures, hence independent of the land area. The biomass production cost was annualised and normalised to 1 ton of dry matter (tDM). 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 tDM was obtained by dividing the loader cost (€ h^{-1}) by the loader efficiency (tDM h^{-1}). As for the handling costs, transportation costs include both fixed and variable costs and are computed as: $Tc = Fc + Vc*Td$, where Fc is the fixed costs (€/tDM), Vc is the variable costs (€ $tDM^{-1}km^{-1}$) and Td is the transportation distance (km). No dry matter losses were assumed during the transport of biomass to the storage facilities or to the biorefinery plant. Storage costs included the storage facility establishment costs, handling costs, insurance costs, and dry matter losses. Finally, the total delivery cost was estimated by summing-up the costs of the supply chain components (i.e., biomass production, handling, transport and storage). All these components of the supply chain were built outside and brought into the LocaGIStics model.

2.6.2 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 computed 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 rate, pesticide/herbicide rates, 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.

2.6.3 GHG emissions

The GHG emissions due to fossil fuel consumption during the production and delivery of biomass to the biorefinery plant were estimated in the same manner as the energy use. For the direct CO_2 emissions, we multiplied the CO_2 intensity by the amount of fuel consumed for a given activity. 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 emissions of N_2O as well as soil carbon stock (SOC) variations under miscanthus were obtained from the CERES-EGC model. Emissions of N_2O were converted to CO_2 equivalents using GWP_{100} values of 298. 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 to C). 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 LocaGIStics for spatial distribution and mapping. Since marginal lands contain negligible amounts of biomass, and because miscanthus is harvested annually, the changes in aboveground biomass were set to zero. As for the costs and energy use, the GHG emissions of the components of the supply chain were built outside and incorporated into LocaGIStics.

3 Results

3.1 Marginal lands in Brittany

The amount and characteristics of available marginal lands for growing miscanthus in Brittany are shown in Fig 3. About 57,544 ha (i.e. 3.3% of the region's total agricultural lands), was identified as biophysically marginal lands. Rooting which leads to low rootable soils volume or unfavorable soil texture was the dominant marginality constraint and made-up more than half (55%) of the region's total marginal lands, followed by chemical limitations (34%) due to high salinity. These salt affected lands were mostly located near the coastlines (Fig 3). We found that dominant current land uses in these marginal lands were temporary grasslands (65%), while permanent grasslands represented only minor fractions (35%). Ile-et-Vilaine was the department with the largest area of marginal lands (32,695 ha), followed by the Morbihan (13,231 ha), the Finistère (7,770 ha), and the Cote d'Armor (3,848 ha).

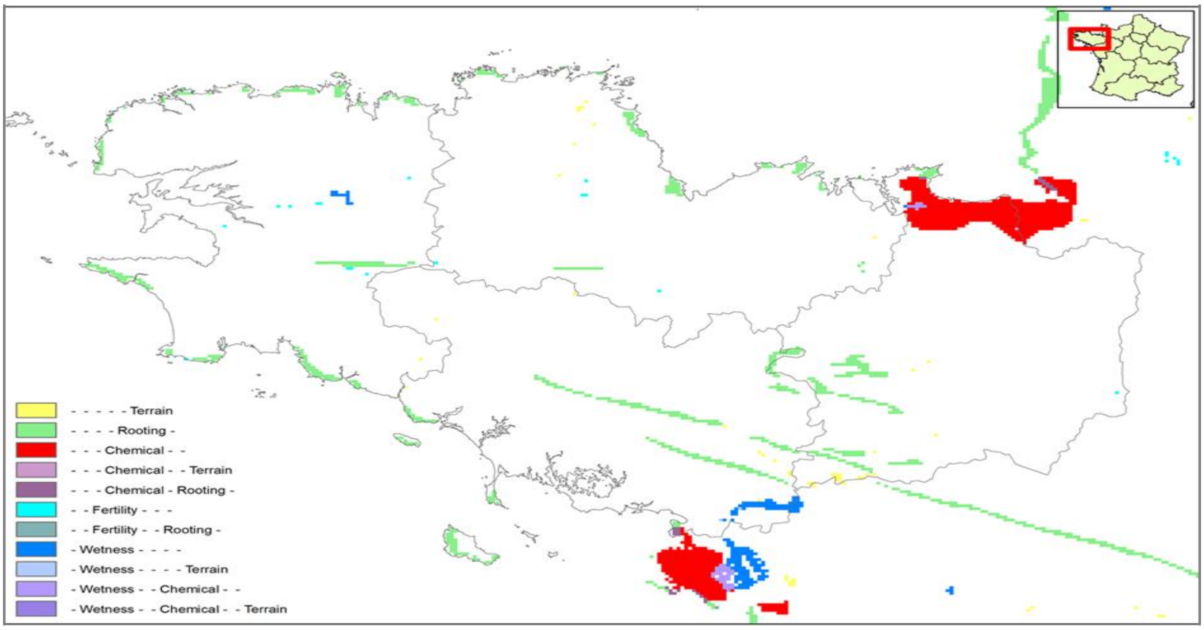

Fig.3 Map of marginal lands and their marginality constraints.

3.2 Miscanthus Yields on Marginal lands in Brittany

Fig 4 shows the dry matter yields and distribution of miscanthus on marginal lands in Brittany. Average dry matter yield of miscanthus on marginal lands was 9 tDM $ha^{-1}y^{-1}$ (range from 2 to 19 tDM $ha^{-1}y^{-1}$). Yields varied significantly across the different departments due to differences in marginality constraints, climate, and soil quality. The lowest yield of miscanthus occurred on salt-affected soils, which were mostly located in the Morbihan department, while the highest yields were obtained for rooting constraints, which were more prominent in the Côtes d'Armor department (Fig. 4). This suggests that some biophysical factors might severely affect yields of miscanthus than others. In fact, we noted ~ 30% reduction in miscanthus yields under rooting limitations relative to salinity constraints. Considering the average biomass yields (9 tDM $ha^{-1}y^{-1}$), the total biomass from marginal lands in Brittany amounted to 518 ktDM y^{-1} (or 8.9 PJ y^{-1} of primary energy). Ile-et-Vilaine had the biggest potential for siting a biorefinery because of the high share of marginal lands and high yields of miscanthus in this department (Fig. 4). Overall, these findings suggest that Brittany may be able to produce large quantities of miscanthus in addition to current production levels, without changes in agricultural practices. This additional biomass from marginal lands could enhance the future bio resources potential of the region.

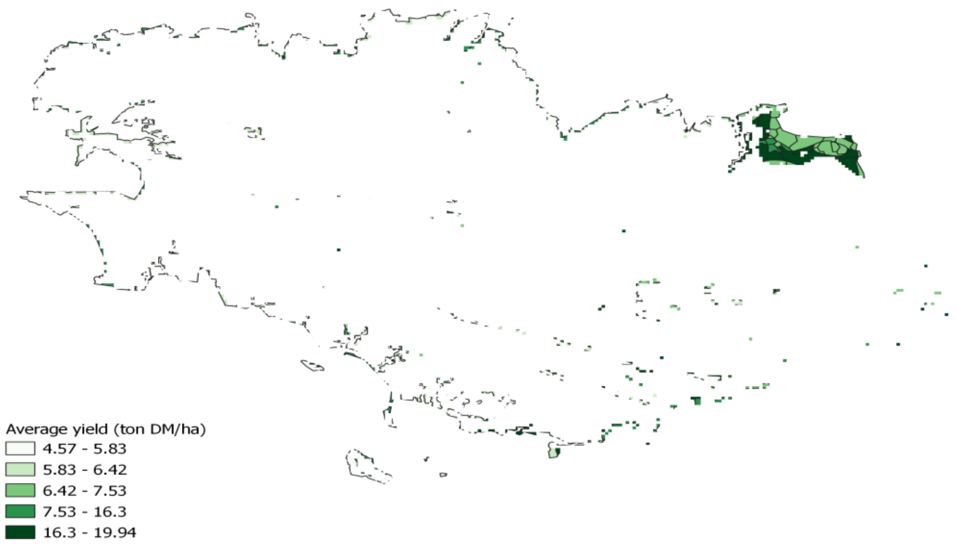

Fig 4. Miscanthus yields on marginal lands in Brittany

3.3 Feedstock production costs, energy use and GHG emissions

3.3.1 Feedstock production costs (farm gate)

The production costs varied from 53 to 104 € tDM^{-1} depending on the yields and harvesting methods (Fig 5a). When harvested as chips, miscanthus production costs ranged from 53 to 95 € tDM^{-1}, while the production costs varied from 55 to 98 € tDM^{-1} when harvested as bundles, and from 59 to 104 € tDM^{-1} if harvested as bales (Fig. 5a).

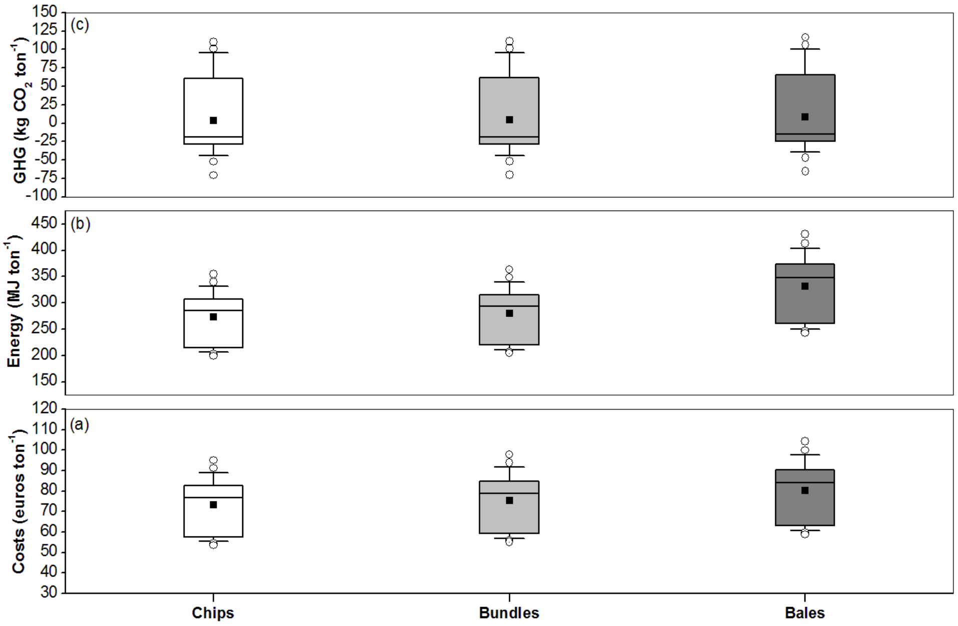

Figure 5. Farm gate costs, energy use, GHG emissions of miscanthus biomass forms (harvested as chips, bundles or bales).

The average farm-gate costs of miscanthus chips (73 € tDM^{-1}) and bundles (75 € tDM^{-1}) were 6.3% and 8.8% lower than the costs of bales (80 € tDM^{-1}), respectively (Fig 5a). The high costs of bales relative to bundles and chips were due to the extra operations of mowing and windrowing preceding the baling operation. A breakdown of the average production costs highlights the importance of harvesting, which was the 2nd largest cost component after establishment, regardless of the biomass form. Land rent ranked 3rd in the breakdown of production costs (Fig. 6a).

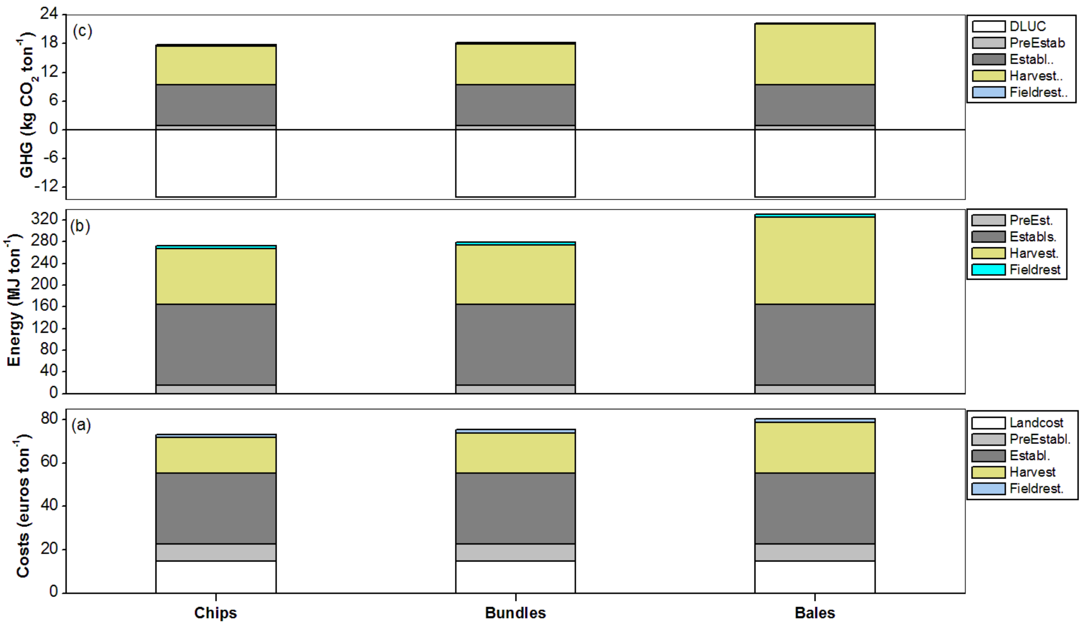

Fig 6. Contribution of different management activities to the production costs, energy use, GHG of chips, bundles and bales. DLUC: direct land-use changes (the white segment on plot 6c corresponds to the soil C sequestration rates simulated by CERES-EGC following miscanthus establishment).

3.3.2 Feedstock energy use (farm gate)

The energy use for the production of miscanthus on marginal lands ranged from 199 to 430 MJ ton^{-1}, regardless of the biomass form. Harvesting miscanthus as chips required 272 MJ tDM^{-1} (199 to 354 MJ ton^{-1}), while 279 MJ ton^{-1} (204 to 363 MJ tDM^{-1}) was needed to harvest it as bundles, and about 331 MJ tDM^{-1} (242 to 430 MJ tDM^{-1}) was consumed when it was baled (Fig 5b). Bales thus consumed more energy compared to chipping or bundling because two extra actions (mowing, windrowing) are required to complete this activity. As for the costs, harvesting (38-49%) was the 2nd most contributing activity to the feedstock energy use, after establishment (45-55%), whereas pre-establishment (4-5%) was the third most energy consuming activity. Field restauration (1-2%) contributed only little to the feedstock energy use (Fig 6b).

3.3.3 Feedstock GHG emissions (farm gate)

The cultivation of miscanthus on marginal lands in Brittany resulted to modest GHG emissions in some cases, and the average net GHG emissions ranged from 4 to 8 kg CO_2 tDM^{-1} depending on the yield and harvesting method (Fig 5c). As for the energy and cost analysis, baling resulted to higher GHG emissions relative to the other harvesting systems. GHG emissions for the baling case ranged from 65 to 116 kg CO_2 tDM^{-1} depending on the biomass yield, while they varied from -70 to 111 kg CO_2 tDM^{-1} for the bundling case, and between -71 to 110 kg CO_2 tDM^{-1} for the chipping case, depending on yields, soil types and marginality constraints (Fig 5c). The CERES-EGC model consistently simulated large soil C sequestration following the establishment of miscanthus, which reduced the GHG emissions incurred during production stage of miscanthus. In terms of harvesting options, chips and bundles contributed similarly to the establishment phase, but baling incurred larger emissions (Fig 6c).

3.4 Feedstock delivery costs, energy use, GHG emissions

3.4.1 Feedstock delivery costs (biorefinery gate)

The total biomass delivered to the biorefinery plant ranged from 40,099 to 40,186 ton $year^{-1}$, depending on the biomass and scenario studied. In all studied scenarios, the amount of biomass delivered to the plant in each scenario was slightly higher the demand, due to small losses in the logistic chain **(Tab. 1)**.

Tab. 1 Total amount of biomass delivered, total delivery costs, energy use and GHG emissions of each scenario.

Biomass forms	Scenarios											
	SC 1	SC 2	SC 3	SC 1	SC 2	SC 3	SC 1	SC 2	SC 3	SC 1	SC 2	SC 3
	Amount (ton $year^{-1}$)			Costs (€ $year^{-1}$)			Energy use (MJ $year^{-1}$)			GHG emissions (kg CO_2 $year^{1}$)		
Chips	40,099	40,036*	40,186**	3,641,769	4,364,015	4,564,021	19,745,901	42,969,621	49,482,497	428,792	1,983,289	2,452,266
Bundles	40,099	40,036*	40,186**	3,726,379	4,448,491	4,648,815	20,018,577	43,241,868	49,757,765	446,836	2,001,306	2,470,350
Bales	40,099	40,036*	40,186**	3,925,272	4,647,071	4,848,139	22,096,530	45,316,547	51,838,229	611,645	2,165,855	2,635,517

* some amount (9,277 ton) of biomass originated from icp1 to biorefinery in addition to that from the fields, ** some amount (12,196 ton) of biomass come from icp1 and icp2 to biorefinery in addition to the one from fields, no biomass from icps in scenario 1 ; collected fields were 106 in scenario 1, 103 fields in scenario 2 and 100 fields in scenario 3 to supply annual biomass demand of the biorefinery.

Biomass losses were more important in scenario SC2 than in other two scenarios. The total delivery costs varied from 3,641,769 to 4,848,139 € y^{-1}, depending on the harvesting and storage scenarios. Short distance (< 20 km) transport of biomass in the form of chips was much cheaper than with bundles or bales, regardless of the storage scenario, suggesting that this densification strategy was optimal for this range of distances (Fig.7). The same applied to energy use, which ranged from 1,9745,901 to 51,838,229 MJ y^{-1}, and for GHG emissions, which varied from 428,792 to 2,635,517 kg CO_2 y^{-1}. The delivery costs, energy use, and GHG emissions increased from scenario 1 to scenario 3 due to the extra distance and storage of biomass required to supply biomass to the biorefinery. In terms of harvest form, costs ranged from 91 to 114 € tDM^{-1} for chips, 93 to 116 € tDM^{-1} for bundles, and 98 to 121 € tDM^{-1} for bales (Fig 7a). Despite requiring lower transport and storage volumes, high-density biomass forms such as bales were not economically viable because of their larger capital and operating costs. On average, baling incurred an additional cost of at least 6 € tDM^{-1} relative to both chips and bundles, suggesting that the extra costs incurred for baling the biomass did not offset the avoided costs due to reduction in number of trucks delivery.

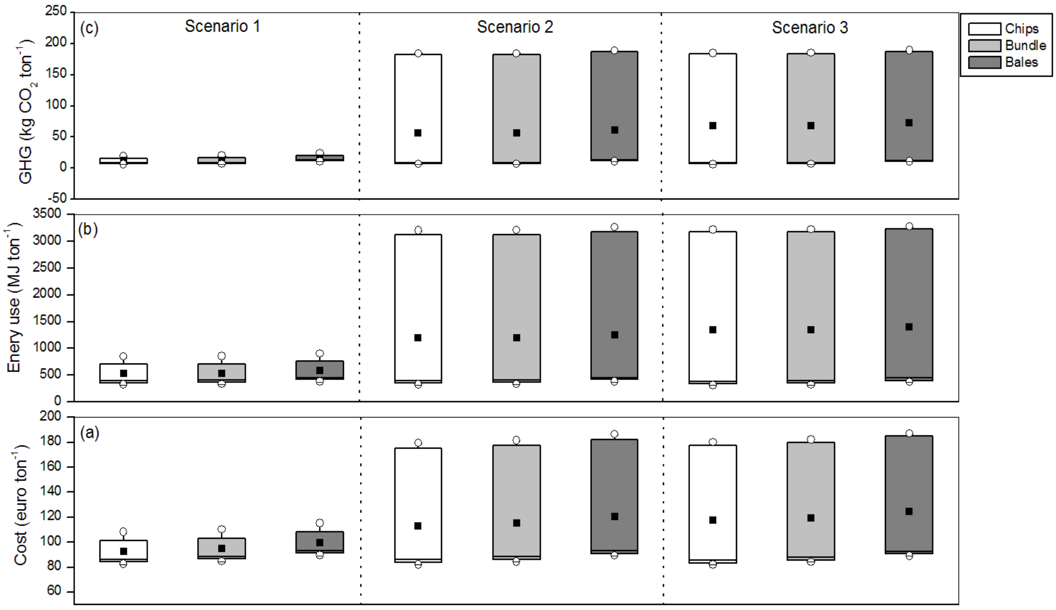

Fig. 7 Delivery costs, energy use and GHG emissions of the different forms of miscanthus harvested (as chips, bundles or bales).

3.4.2 Feedstock delivery energy use and GHG emissions (biorefinery gate)

The energy use ranged from 492 to 1,231 MJ tDM^{-1} for chips, 499 to 1,238 MJ tDM^{-1} for bundles, and 551 to 1,290 MJ tDM^{-1} for bales, depending on the logistics scenarios (Fig. 7b). With regard to GHG emissions, the estimates varied from 10 to 61 kg CO_2 tDM^{-1} for chips, from 11 to 62 kg CO_2 tDM^{-1} for bundles, and from 15 to 66 kg CO_2 tDM^{-1} for bales (Fig. 7c). As for the economic analysis, the energy consumption and GHG emissions increased drastically from scenario 1 to scenario 3 for all biomass forms, suggesting that the increase in collection distance had significant influence on energy consumption and GHG emissions of the supply chain. With regard to specific biomass form, delivering biomass as bale was slightly more energy intensive and emit more GHGs than delivery biomass as chips or bundles. On average, the extra energy consumption for the bale case was 33 MJ tDM^{-1}, while the extra GHG emissions were 3 kg CO_2 tDM^{-1}, relative to both chips and bundles. Overall, the wide range of delivery costs, energy use, and GHG emissions suggest that logistics are site-dependent and vary substantially in function of biomass forms, supply chain components and configurations.

3.4.3 Contribution Analysis

The contribution of the different logistics components are show in Fig 8 a-c. It appeared in scenario 1 that feedstock production dominated the total delivery costs (62-80%), followed by transport (11-30%) and storage

(5-7%), depending on the biomass forms and scenario assessed. However, the contribution of the feedstock production decreases in scenarios 2 to scenario 3 while that of the transport increase as results of increasing distance between scenario 1 and scenario 3. This confirmed the influence of transport distance on feedstock delivery cost. Transport activity, became the most contributing activity to total energy consumption and GHG emissions in the scenarios 2 and 3 (Fig. 8b-c), in line with increasing distance for collecting the biomass. Importantly, we noted that the contribution of transport to total energy consumption and GHG emissions was lower for bales than for both chips and bundles in all scenarios. This latest findings highlight the effects of reduced number of truck-deliveries to total energy consumption and GHG emissions of miscanthus supply chain. However, these effects were not so large as to reverse ranking between the three biomass delivered forms (i.e., bales becomes more energy efficient and less polluting than chips and bundles).Handling represented only a small fraction (<3 %) of the total delivery costs (Fig 8a). As the collection distance increased in scenarios 2 and 3, the share of transport increased drastically and this stage became the main contributor to both the energy use (69-73%) and GHG emissions (81-90%) (Fig 8b-c). Consequently, transport can be a major logistics component for supply chains characterized by a long collection distance. It even appeared as a major hindrance for sourcing biomass from marginal land, causing a 20% increase in the worst-case scenario (SC3) relative to the 'local' one (SC1). The share of the different logistics components also differed for the different biomass forms, with the highest share estimated for bales and the lowest share computed for the chips (Fig 8a-c).

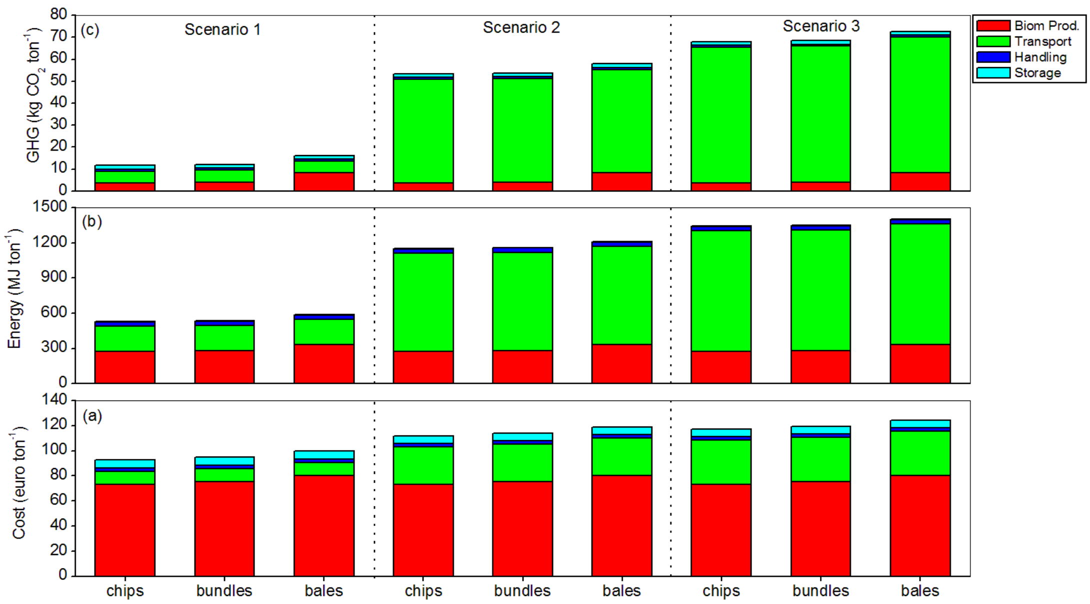

Fig 8. Contribution of the different element of the logistic chain to the delivery costs, energy use, and GHG emissions of miscanthus biomass forms (chips, bundles, and bales).

4 Discussion

4.1.1 Availability of marginal lands to grow an industrial crop

Lignocellulosic biomass is one of the most promising renewable alternatives to fossil fuels for the production of biobased products such as chemicals, materials, fuel and energy. Marginal lands are seen as a solution to land scarcity and as an ideal way to meet growing global demands for lignocellulosic biomass. Using a biophysical approach we showed that marginal lands account for only 3% (or 57,784 ha) of the agricultural lands in Brittany. Although small, this estimate still represents a non-negligible fraction of lands for the production of biomass for biorefining purposes in France. The fact that France is a major agricultural country in Europe may explain the little amount of marginal lands available in Brittany, because most lands are already used for agriculture. The findings of [15, 34] that France is not among the European countries with large amount of marginal lands is consistent with the small amount of marginal lands simulated here for Brittany. However, the choice of this region is still relevant given that it is one of France's region with the largest area cropped to miscanthus so far [40].

A deeper understanding of the exact location and the characteristics of lands regarding their unused abandonment and degradation status is limited and eventually determines which part of these lands can really be used for the production of low-ILUC biofuels, as defined in the Recast Renewable Energy Directive [41]. The focus in this study was on marginal lands as these have a higher chance to become unused/abandoned and degraded and therefore, more likely to be used for low-ILUC biomass production in the near future. Furthermore, current yielding capacity on these lands is already low, which implies that the ILUC effects of establishing miscanthus for bioenergy is very limited. Nonetheless, it was not assessed as part of this study whether marginal lands in Brittany are already unused or will become unused in the near future. This can be expected because of the low yielding capacity of these marginal lands but there are many more factors that determine the eventual future use/abandonment of food and feed production and the attractiveness of establishing miscanthus production on it [14, 42]. Also, no attention was paid in the study to the current biodiversity status in these marginal lands and the presence of other ecosystem services and how these are altered by the introduction of perennial biomass cropping [43]. In future research it is recommended to assess the impacts of miscanthus on the wider ecosystems services present, and stimulate those land uses which are economically viable and deliver positive effects on both biodiversity conservation and GHG mitigation. The results from this study are a first step in this direction, but do not deliver this full understanding yet.

4.1.2 Miscanthus yields on marginal lands

There is a growing interest to establish miscanthus on marginal lands to meet ever-increasing global demands of bioresources. Studies have shown that miscanthus requires less nutrients and is stress resistant, hence can be successively deployed on marginal lands [5]. Despite the unequal distribution of marginal lands and variation in miscanthus yields in the different departments of Brittany, we showed that each department of Brittany has sufficient marginal lands and biomass output to supply a biorefinery plant of 40 kton y^{-1} biomass inputs, if a yield of 9 ton ha^{-1} y^{-1} is assumed. Reported yield estimates of miscanthus on marginal lands in China range from 2 to 32 tDM ha^{-1} y^{-1} [30]. In Europe, simulation studies show that miscanthus can reach 15 to 19 tDM ha^{-1} y^{-1}, depending on marginality constrains and climate conditions [43]. The yields simulated in Brittany are generally within the ranges found in literature in Europe for miscanthus, but are lower than those obtained in China [30]. In fact yield of 32 tDM ha^{-1} y^{-1} on marginally land is unlikely under European conditions. Current yields on marginal lands are also much lower than yields of miscanthus on good soils [44, 45]. Yields ranging from 10 to 30 tDM ha^{-1} y^{-1} have been obtained on good soils in Europe [9, 46]. Increase in yields on marginal lands may be achieved by selecting and growing new genotypes that are more adopted to marginal circumstances. Yield improvements may also be realised by taking measures that reduce some marginality constraints before establishment of miscanthus on marginal lands. These measures may give higher yields, but may also add to the cost of production which will endanger the economic viability and may have adverse effects on ecosystem service present.

4.1.3 Miscanthus production Costs, Energy, GHG emissions (farm gate)

The economic aspects of miscanthus production and utilisation as bioresources for biorefinery has been evaluated in several studies[47-49]. These studies are often region dependent due to contributing local factors affecting the outcomes of the analysis. In this study, we computed production costs of miscanthus ranging from 53 to 104 € tDM^{-1} depending on yields, marginality constraints, agronomic and conditions. The lower range value of our cost estimate agree well with that of miscanthus production (56 € ton^{-1}) on marginal lands in Germany[8]. The lower range value of our cost estimate is also in accordance with the average production costs of miscanthus on "regular" (non-marginal) croplands (64 € tDM^{-1}) in France [50], suggesting that miscanthus from marginal lands may, in general, be more expensive that miscanthus on non-marginal lands. Estimates of production costs of miscanthus (63 to 102 € ton^{-1} [20]), and short rotation woody crops (49 to 130 € ton^{-1} [51]) on croplands in Europe vary substantially across countries and studies because of different calculation methods, labour, land prices and management. Consequently the production costs of miscanthus from marginal lands computed in France cannot be compared directly to production costs of miscanthus from non-marginal lands outside France for the reasons above. They are also in agreement with the range in costs estimates of miscanthus (63 to 102 € ton^{-1} [20]), and short rotation woody crops (49 to

130 € ton^{-1} [51]) production on croplands in Europe. Despite the low yields achieve by miscanthus on marginal lands, its production on marginal lands are comparable to those pertaining to regular croplands in Europe. With regard to climate change mitigation, growing miscanthus on marginal lands in Brittany will result in carbon sequestration in most cases, but not in all of them. As shown in Fig 6, the conversion of marginal lands with high soil organic carbon content inevitably results in GHG emissions, and should be avoided as much as possible. The literature on environmental impacts of miscanthus production on croplands with fertilizer inputs shows values ranging from 300 – 1,210 MJ ton^{-1} for energy use [52, 53] and from -82 – 33 kg CO_2 ton^{-1} for GHG emissions [52]. Our estimates of energy use are in some cases, slightly higher than those reported in literature, while our estimates GHG emissions are accordance with the range values (-82 – 33 kg CO_2 ton^{-1}) reported by Brandao et al. [52]. Overall, our assessment shows that 2nd generation biofuels in Brittany, be limited by the supply of biomass but more by the costs of converting this feedstock into biofuels and the transportation costs in scenario 2 and scenario 3.

4.1.4 Miscanthus Supply Chain Costs, Energy, GHG emissions (Biorefinery gate)

We showed that each of the departments of the Brittany region has enough marginal lands for the production of cellulosic biomass for a small to medium-scale biorefinery plant. The delivered costs of miscanthus from marginal lands in Brittany ranged from 91 - 121 € ton^{-1}. Given the lack of studies on supply chain costs of lignocellusic biomass from marginal lands in France or Europe, data on the supply chains of both miscanthus and straw from croplands were used as proxy for comparison. Simon et al. [54] calculated delivery costs ranging from 100 to 120 € ton^{-1} for miscanthus and from 95 to 115 for straw in France, using production costs of 90 € ton^{-1} for miscanthus and 85 € ton^{-1} for straw, and further assuming a transport cost of 0.18 € tDM^{-1} km^{-1} and transport distance of 58 to 168 km. Our estimates of delivery costs of miscanthus from marginal lands are slightly higher than those from Simon et al. [54] because our estimates does not include profit margin unlike in Simon et al. [54]. In Europe, the supply chain costs of biomass woody crops range from 58 to 130 € ton^{-1} [55], again in agreement with this study. These findings suggest that the supply chain costs of miscanthus from marginal lands in Brittany is slightly more higher than the price of lignocellulosic biomass from agriculture in France. These estimates are also much higher that the delivered costs of forests biomass which vary from 44 to 77 € ton^{-1} [56]. This is because forest biomass has higher density than agriculture feedstocks, resulting in mass-limited transportation rather than volume-limited transportation (miscanthus is volume-limited because of its lower density), and therefore lower transportation costs. Another explanation of lower delivery costs of forest residues relative to both miscanthus and energy crops is that both miscanthus and energy crops must be established and managed, and the involved activities have consequences on the production costs and thus the supply chain costs. With regard to environmental performance, energy use ranged from 45 to 511 MJ ton^{-1}

[57] while the GHG emissions varied from -1.7 to - 9 CO_2 tDM^{-1} [58] in the literature. These estimates are lower than our estimates for miscanthus from marginal lands. They are also much lower than estimates for biomass from agriculture (including marginal lands), confirming the environmental competitiveness of forest biomass over agricultural biomass.

Past studies have claimed that PECs from marginal lands are feasible or attractive only when accompanied with economic incentives such as subsidies[59]. Our analysis shows that the supply chain costs of miscanthus from marginal lands in Brittany are substantially larger than those of PECs on croplands, especially when considering the extra transport required when scaling up the supply. The cost of production miscanthus from marginal lands falls in the upper range of those of growing PECs from cropland, and may still be competitive provided the transportation distance does not exceed 50 kms. They have the advantage of mitigating ILUC risks, compared to PECs grow no cropland, and this may justify the allowance of specific subsidies – bearing in mind that some forms of those, such as fixed costs payment independent of the biomass yields, may be inefficient [60]. In this study, we considered the supply of biomass to a single biorefinery plant and from a single biomass source. In practice the supply chains of biomass may be more diverse (to include croplands, marginal lands, or forest products), and offer more degrees of freedom in terms of performance optimization. This can also be more complex and challenging as they contain a great number of dependent variables that interact to determine the final costs of feedstock. A better understanding of the biomass supply including the amount, locations, quality, and shape/forms is the key element for the success.

5 Conclusion

Sourcing biomass from marginal lands is urgently needed to support the broader effort to increase the development of biorefinery industries. We combined a GIS, a process-based crop model (CERES-EGC), and the LocaGIStics model to assess the potential of marginal lands in Brittany, simulate biomass yields on these lands, and to assess the delivery costs, energy use and GHG emissions. Our assessment showed that marginal lands represent only 3% of the total agricultural lands in Brittany. The most prominent marginality factors were stoniness and salinity. Miscanthus demonstrated sufficient yields on these lands to be economically viable, although these could be further improved if suitable genotypes become available. Our analysis also showed that logistics (i.e. transport, handling and storage) play an important role in the supply chain of biomass from marginal lands, as they contributed 20% to 80% of the the delivery costs, depending on the supply chain configuration and transportation distance. The same went for energy use and GHG emissions. It is therefore essential that the transport, handling, and storage activities are operated and managed in an efficient manner in order to improve supply-chain performance. Storage at intermediate collection points (ICPs) resulted in higher deliver costs, energy use, and GHG emissions relative to field storage because of the additional costs and transport involved. However, these ICPs help addressing the disadvantage of field storage (e.g. high dry matter losses0, and ensure continuous biomass supply at the biorefinery plant throughout the year. Given that 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 region studied here – will not suffice to answer the demand a large-scale biorefinery such as a lignocellulosic 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 into account.

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