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To cite this version:

Sylvestre Njakou Djomo, Igor Staritsky, Berien Elbersen, Bert Annevelink, Benoit Gabrielle. Supply costs, energy use, and GHG emissions of biomass from marginal lands in Brittany, France. Renewable and Sustainable Energy Reviews, 2023, 181, pp.113244. 10.1016/j.rser.2023.113244 . hal-04300031

HAL Id: hal-04300031
https://hal.inrae.fr/hal-04300031

Submitted on 20 Jul 2024

Supply costs, energy use, and GHG emissions of biomass from marginal lands in Brittany, France

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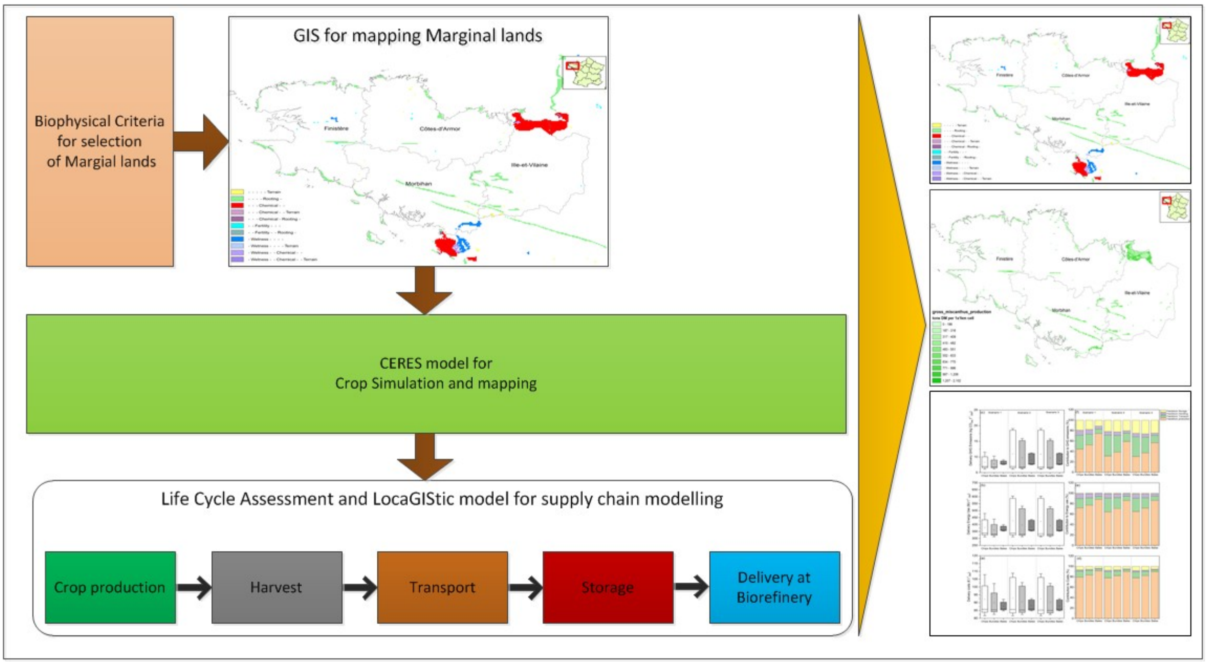
Graphical Abstract



Abstract

Growing energy crops on marginal lands is an option to increase current bioresources while avoiding the food vs fuel dilemma. Yet, little is known about the extent and characteristics of marginal lands, and about how growing energy crops on such lands will impacts productivity, supply chains, and the environment. This study combined a geographic information system, a crop growth model, life cycle assessment, and a logistics model to *(i)* quantify and map marginal lands *(ii)* estimate the yields of miscanthus grown thereon *(iii)* assess the impact on supply chain and the environment of miscanthus from marginal lands in Brittany. Three miscanthus harvest forms (chips, bundles, and bales) and three logistics scenarios (no storage, one storage point, and two storage points) were studied. It showed that 57544 ha of marginal lands are available in Brittany and that rooting (55%) and salinity (34%) were the dominant marginality factors of these lands. Miscanthus yields on these lands varied from 0 to 21 t DM ha^{-1} y^{-1}, depending on marginality constraints. Despite the low energy use (311 to 604 MJ t^{-1} DM) and GHG emissions (6 to 19 kg $CO_{2\text{-eq}}$ t^{-1} DM), the delivery costs were too high (81 to 108 € t^{-1} DM). Bales were the cheapest and most environmental-friendly biomass form, as was the logistics configuration with no storage point. Sourcing biomass from marginal lands offers a solution for sustainable biofuel production in Brittany. However, economic incentives are needed to encourage production on marginal lands given the high delivery costs of biomass.

Keywords: Marginal lands, miscanthus, supply chain management, logistics, costs, energy use, GHG emissions

Preprint published in Renewable and Sustainable Energy Reviews, with the following DOI: 10.1016/j.rser.2023.113244

1. Introduction

Europe still relies on fossil fuels as the main energy resource to support its economy, but the use of fossil fuels contributes to climate change and air pollution. Climate change and energy insecurity are challenges faced by many countries around the world, and the war in the Ukraine has raised awareness for these issues. The latest Intergovernmental Panel on Climate Change (IPCC) assessment report concluded that sustained GHG emission reductions are needed to prevent global temperatures from rising by more than 2 ºC above the pre-industrial levels by the end of this century [1]. The even more stringent goal of keeping global warming under the 1.5 ºC limit requires drastic actions: a lower total carbon budget of about 400 to 600 Gt of CO_2, leading to a 45% emission reduction target 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 to 32% by 2030 and to reduce GHG emissions by 40% relative to the 1990 levels by 2030 [3]. Besides these targets, the EU has ambitions to build a carbon neutral future by 2050. Biomass is an important resource in terms of material and energy provision in the context of the transition to a circular bioeconomy and to a renewable energy system [4].

Among the various biomass feedstocks, perennial energy crops (PECs) are the most relevant candidates for biomaterial and bioenergy production because of their fast growth, high yields, high carbon storage potential, favourable energy density, and their high cellulose and hemicellulose contents. In addition to facilitating the realisation of renewable energy targets, PECs provide the means to alleviate pressures on agricultural and forest residues and to help the agricultural sector transition into a more diverse market-driven industry, while improving its environmental footprint and stimulating the local and regional economies [5, 6].

PECs such as miscanthus (*Miscanthus giganteus*) are characterised by a long occupation of land, continuous biomass production with a variable cycle of 15-20 years, little soil disturbance, and continuous carbon addition to soils [7-10]. Like many other PECs, miscanthus tolerates low fertility soils and can grow on a wide range of marginal lands − i.e. lands having biophysical constraints, which in the aggregate are too severe for a sustained production of food or feed [11] − in Europe. Growing miscanthus on marginal lands avoids competition for land resources with food crops. Miscanthus is seen as a carbon neutral feedstock because the CO_2 that is released during its production, harvesting, transport, processing and combustion has been previously captured from the atmosphere through photosynthesis [12-14]. Bioenergy from miscanthus can even become a negative emission technology if carbon capture and storage is applied at the biorefinery level [15]. Aside from the climate benefits, miscanthus provides ecosystem services as co-benefits, such as wildlife habitat, erosion control, and requires far less herbicides and fertiliser [7, 9, 16, 17]. PECs in general also offer opportunities for strengthening the local economy [18, 19]. Their benefits are spatially varied depending on the properties of land cover, soil types and the adopted management practices [20]. Marginal circumstances will cause lower yields for all crops, but a perennial crop like miscanthus is likely to cope better with these limitations than most food and feed crops, which have too low yields to make the production economically viable [21]. Worldwide, interests for developing marginal lands-based biomass production at large scale are increasing, and the use of PECs may be the best approach to lowering the supply chain costs of biomass [22, 23]. Consequently, assessing the extent and characteristics of marginal lands, and gaining insights into the supply chain economics and their environmental impacts is essential to determining the feasibility of a biorefinery plant relying on bioresources from marginal lands.

Previous studies have used different working definitions, methods, land cover inventories, and assumptions to assess the global [24, 25], continental [11, 26, 27], and national potentials [28, 29] of marginal lands. Despite the large differences in marginal land estimates, all these studies point to their substantial potential. Some of these studies are not spatially explicit and do not estimate the productivity of PECs on these lands [24, 30]. Other works combined geographic information systems, crop models, and multi-factor analyses to show that the total biomass output from marginal lands depends on location, land area, marginality constraints, and the types of PECs grown thereon [24, 29, 31, 32]. Finally, a few studies have evaluated the impacts on hydrological systems, water quality and GHG emissions of growing PECs on marginal lands [33, 34]. Besides land and feedstock availability, costs and sustainable biomass mobilisation and supply are prerequisites for large-scale deployment of biorefineries relying on these bioresources.

Studies on supply chains and biomass logistics have, until now, dealt with model development [35], evaluations of economic and environmental impacts [36], and optimisation of biomass resources from agriculture, forestry and processing industries [37-39]. Concerning the supply chain models, deterministic and stochastic optimisation models have been developed and used to locate feedstock sourcing, address uncertainty in biomass supply, find optimal supply chain design, and to incorporate traffic congestion and emissions from logistics operations [35, 40-43]. They show that transport and handling activities represent between 20 and 50% of biomass delivery costs and that high supply chain costs are important barriers for biomass deployment and commercialisation. The logistical arrangements, biomass harvest forms, storage types, and transport distances affect the supply costs, energy use and GHG emissions [44].

Knowledge of the sustainability of marginal land-based biomass is indispensable to guide policy making regarding the use of these lands. Unfortunately, little information exists in literature on the economic and environmental impacts of PECs from marginal lands. In addition, the trade-offs between economic and environmental aspects of biomass logistics operations have not been studied yet [45]. Bioenergy producers need to know the types and quantities of marginal land-based biomass available by location to make an effective use of these bioresources. They also need to know the economic and environmental impacts of the logistics required for supplying this biomass to biorefinery. The interface between supply chain issues and biorefining is of great relevance because the question of how biorefinery systems are implemented is crucial to the success of biorefinery projects [46]. The main goals of this study are to quantify marginal lands in Brittany (France) and to assess the supply chain economic and environmental impacts of sourcing biomass from these lands. This study first estimates and maps the potential marginal lands in Brittany; it then assesses the productivity of miscanthus on these lands. Finally, it quantifies the supply chain costs, energy use, and GHG emissions of miscanthus from marginal lands.

2. Materials and methods

2.1. Study area

Brittany (48° N; 30° W) is the westernmost region of France, covering about 27200 km^2. The region is composed of four departments: 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 12 ^{o}C. The majority of soils in Brittany are deep silty clay loams and the main vegetation cover types are forests, pastures and croplands. Agriculture is one of the dominant economic activities in the region. It occupied 1.7 Mha lands in 2017 and represented 4.1% of the total employment in Brittany [47]. Livestock breeding is the primary agricultural activity in the region and animal feed production centres on wheat, fodder maize, and alfalfa grass (temporary and permanent grasslands) [47]. PECs production currently represent a minor but steadily growing part (0.04%) of the total biomass production in the region [48].

2.2. Description of the CERES-EGC and the LocaGIStics models

The CERES-EGC model [49] was used to simulate miscanthus growth and yield on marginal lands. It derives from the CERES suite of models implemented in the Decision Support System for Agrotechnology Transfer (DSSAT) software package [49]. This process-based model simulates carbon, nitrogen, and water dynamics in agro-ecosystems, and the growth and development of miscanthus with a step size of one day[50]. Crop development proceeds through nine growth stages based on heat unit accumulation from planting to harvest, and leaf numbers are calculated during vegetative growth stages. Carbon assimilation is computed as a function of incoming solar radiation, leaf area index, plant population, the canopy extinction coefficient, and radiation use efficiency. Assimilated carbon is then partitioned to various plant parts, including leaves, rhizomes and roots. Simulated plant growth responds to variation in management practices, soil properties (e.g., soil water-holding capacity, organic matter content, temperature, and nutrient availability), and meteorological conditions. Management inputs required for model execution include planting density, cutting dates, fertilizer/irrigation application rates and dates. Daily minimum and maximum temperature, solar radiation, wind speed, and precipitation are also required to run the model. More information about this model can be found in Gabrielle et al. [50] and El Akkari et al. [51], which detail the adaptation to miscanthus and the validation using data from field trials across France and the UK.

LocaGIStics [52] is a regional supply chain model that simulates the supply of biomass from fields to a biorefinery or to an energy conversion plant. It consists of different modules that can be connected to form a complete supply chain. Each module represents an operation or process (e.g., transport, or drying) and is independently constructed with a set of inputs and outputs. Data on costs, energy use, and GHG emissions common for all operations and processes are gathered into individual modules as well. These modules were first constructed in a spreadsheet and imported into the model. The same is true for the biomass production module, which is simulated using the CERES-EGC model and imported into the LocaGIStics model for supply chain assessment. In LocaGIStics, biomass moves from one module to the next one via connectors. The strength of this model is its flexibility and ability to model multiple types of feedstocks, logistical sourcing options (e.g., direct transport from the field to the plant, or using intermediate collection points) and conversion processes. Its geospatial features allow it to determine the transport distance based on biomass availability maps. The tool handles both single and multiple modes of transport, and can assist the user in the design and analysis of multiple delivery chains to find the optimal solution.

2.3. Identification and mapping marginal lands in Brittany

Marginal lands in Europe were identified according to the method of Elbersen et al. [11]. This approach builds on other land evaluation systems for agronomic suitability, including previous work to identify areas of natural constraints [53]. Eighteen biophysical factors were clustered into six broader factors and used for the classification of severe growth limitation. These factors include: *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 unfavourable soil texture), and *vi)* adverse terrain conditions (steep slopes, flooding risks). Data used for identification of marginal lands originated from different sources [11]. The marginal land units were identified with biophysical factors within the 20% margin of the threshold value of severity. This also allowed mapping 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 while areas where specific natural constraints were alleviated by agronomic improvement measures (e.g., fertilisation drainage) were excluded.

2.4. Miscanthus growth simulation and mapping

Miscanthus was chosen as the most suitable PEC for Brittany, in line with recent work on the development suitable biomass crops for marginal land in Europe [9]. The suitability of Brittany for the growth of miscanthus is further confirmed by the fact that there are already 800 hectares of miscanthus established in the region [54] Prior to using CERES-EGC to simulate of miscanthus growth, it was calibrated and tested by comparing its outputs to field observations from seven long-term trials in France and the United Kingdom. The trials involved various treatments for miscanthus in terms of fertiliser input rates and harvesting window (autumn vs late winter) in both countries [51]. The model was run over the Brittany region on the 1067 simulations units (i.e., polygons), resulting from the overlay of the EU soil map, the latest Corine Land Cover maps and administrative limits (counties – see ref. [6] for more details). As a first step, miscanthus was assumed to be cultivated on current croplands in Brittany without requiring that they be classified as marginal. To integrate the identified marginal lands in the crop modelling, we overlaid the marginal land map [11] 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 kg N ha^{-1} based on a combination of agronomic and economic modelling [51] and no limitation for P/K availability in soils. To account for the main marginality factors (rooting constraints and salinity), CERES-EGC was modified as followed: rooting constraints were related to a reduction in the soil water holding capacity, while a 30% reduction in miscanthus yields was assumed to account for the moderate effect of salinity on this crop [55]. The yields and GHG emissions for miscanthus crop over the simulation units were exported as a shape file and imported into the LocaGistics model where polygon maps were made.

2.5. Miscanthus supply chain and scenarios description

To optimize the supply chain performance of miscanthus from marginal lands, three delivery scenarios were developed (Fig. 2). Each of these scenarios represents a specific configuration of the biomass supply chain and consists of the following activities: biomass production, harvesting into different forms (bundles, chips, or bales), loading, transport, unloading, and optional storage at intermediate collection points (ICP), transport, and delivery at the biorefinery plant. Scenario 1 assumes that the three biomass forms are collected from miscanthus fields and transported directly to the biorefinery over a round-trip distance of 20 km. Thus, storage prior to processing occurs only on the premises of the biorefinery. Scenario 2 considers that after field collection, the biomass is first transported to one ICP where it is stored for a while and delivered later on demand to the biorefinery, where it is directly processed (so no more storage). The distance from this one ICP to the biorefinery gate was calculated to be 62 km (round-trip) by using the travel time platform within QGIS. In scenario 3, the biomass is first transported from the fields to one of two distinct ICPs, depending on their proximity to the fields, and later transported as required to the biorefinery plant. For this scenario LocaGIStics sets a round-trip supply distance of 62 km from ICP1 to the conversion point and of 125 km from ICP2 to the same conversion point was calculated (Fig 2). In all scenarios, the LocaGIStics model prescribes the optimum number of fields required to meet the total biomass demand of the biorefinery (i.e., 40 kt DM per year), and the assignment of farms to storage locations in scenarios 2 and 3. The cheapest biomass is collected first, and this continues until the total biorefinery demand is met. This means that the collection from the ICPs only starts when there is no cheaper biomass in the vicinity of the biorefinery. A storage capacity of 15 kt DM y^{-1} is assumed for the ICP in scenarios 2 and 3 [56]. It is further assumed that the ICPs can store biomass for three months until requested by the biorefinery plant. Although each ICP could dry or further process the biomass into pellets or briquettes, neither the drying nor the pre-processing processes were considered in this study. A biomass supply of 40 kt DM y^{-1} is assumed in all scenarios. This supply level has been shown to be financially feasible in a small/medium scale bioenergy facility [57]. Since miscanthus feedstock is sold by mass, a functional unit of 1 ton of dry matter (t DM) delivered to the biorefinery plant was used [58]. The supply costs, energy use, and GHG emissions of each scenario were thus normalised to this functional unit. 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

The supply chain costs of biomass plant-gate delivery were estimated using an activity-based costing approach. This method uses activities to trace the direct and indirect costs associated to biomass supply chains. A number of cost factors were distinguished in the biomass production costs: land costs, capital costs, labour costs, fertilizer costs, rhizome costs, planting costs, pesticide/herbicide costs, and harvesting costs. Items such as land costs, labour costs, and capital costs are independent of management intensity levels, while fertilizer, pesticide and seed costs are directly linked to production figures, hence independent of the land area considered. Biomass production costs were annualised and normalised to 1 t 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 were obtained by dividing the loader cost (€ h^{-1}) by the loader throughput (t DM h^{-1}). Transportation costs also included both fixed and variable costs and were computed as the sum of fixed costs and the product of variable costs and transport distance. A round-trip transport distance and a 1% biomass loss rate for transport to the biorefinery plant were assumed. Storage costs included the construction and operational costs of the storage facility, land costs, machine costs, and insurance costs. The total supply chain delivery costs were calculated by summing the costs of the supply chain components, namely biomass production, harvesting, handling, transport and storage. These supply chain components were built into a cost calculation spreadsheet and incorporated into the LocaGIStics tool.

The analysis accounted for the direct and indirect energy inputs for miscanthus production, harvest, handling, transport and storage. The direct energy input for a given farm activity was calculated as the product of its fuel consumption (l h^{-1}) and the heating value of the fuel (MJ l^{-1}), divided by the work capacity (ha h^{-1}). The indirect energy inputs related to farm equipment (e.g., tractor, harvester, sprayer, etc.) were computed by multiplying the mass of the equipment (kg) by its embodied energy (MJ kg^{-1}) and dividing by the product of equipment lifetime (h) and work capacity (ha h^{-1}) of the equipment for a given operation. For farm inputs (e.g., rhizomes, fertilisers, herbicides etc.), the indirect energy use was calculated by multiplying the embodied energy (MJ kg^{-1}) of the farm input by the input rates (kg ha^{-1}). Diesel consumption during biomass transport was based on vehicle fuel economy of the truck, the transport volume as well as the transport distance, while the indirect energy inputs related to truck production were calculated in the same manner as for the indirect energy inputs associated with farm equipment. The energy consumption during biomass storage accounted for both the direct energy consumed to construct the storage facility and the indirect energy related to materials used to construct the storage facility. The total energy inputs were calculated as the sum of all direct and indirect energy inputs of the supply chain activities.

As for the energy consumption, the direct and indirect emissions associated with production, harvest, handling, transport and storage were considered in the computation of supply chain GHG emissions. Direct GHG emissions associated with direct energy inputs were estimated as the product of fuel consumption (l h^{-1}), fuel heating value (MJ l^{-1}), and fuel carbon intensity (kg CO_2 MJ^{-1}), divided by the work capacity (ha h^{-1}). The indirect GHG emissions attributed to farm equipment were estimated by multiplying the embodied carbon dioxide of the equipment (kgCO_2 kg^{-1}) by the weight of the equipment (kg) and divided by the product of equipment lifetime (h) and work capacity (ha h^{-1}) of the equipment. The indirect GHG emissions associated to farm inputs were computed as the product of embodied carbon dioxide of the farm input (kg CO_2 kg^{-1}) and the input rates (kg ha^{-1}) for a given farm activity. Soil carbon sequestration and N_2O emissions were simulated by means of the NCSOIL model [59], a nested module in CERES-EGC. NCSOIL simulates CO_2 exchange between the soil-plant system and the atmosphere via the net photosynthesis and soil organic mineralization processes. The variations of soil organic carbon stocks associated with miscanthus production were also obtained from these simulations and averaged over their 20-year timeframe. Annual soil organic carbon change was converted to CO_2 equivalents by multiplying their value by 3.6 (the ratio of the molar mass of CO_2 to that of carbon). The simulation of N_2O emissions accounted for both the nitrification and denitrification processes [60]. Soil emissions of N_2O were converted to CO_2 equivalents using a GWP_{100} (i.e., the relative global warming potential over 100 years) of 298 [61]. Note that no indirect land use change was considered in this study because the cultivation of PECs on marginal lands will not lead to displacement of food and feed crops. For each field, the GHG emissions from agricultural activities (Soil organic carbon stock change, field emissions, CO_2 emissions from farm inputs, farm equipment, and the CO_2 from fuel burning), handling, transport, and storage were summed up to estimate the supply chain GHG emissions of miscanthus marginal lands. The data used to estimate costs, energy use and GHG are shown in the supplementary material.

2.7. Sensitivity analysis

A sensitivity analysis was carried-out by altering some parameters by a certain percentage relative to their baseline values, and the effects of these changes on the outcomes of the study were calculated. Miscanthus production costs, energy use, and GHG emissions were varied by ±15% relative to the baseline case. Transport distances, storage capacity and storage duration were also varied by ± 20%, relative to the baseline. Finally, the influence of truck configuration on costs, energy use and GHG emissions was assessed by choosing other truck types (e.g., 4 axle semi-trailer vs 2 axle rigid truck vs 5 axle semi-trailer).

3. Results

3.1. Yields and carbon sequestration of miscanthus on marginal land in Brittany

About 57544 ha (i.e., 3.3% of the region's total utilizable agricultural area) were identified as biophysically marginal. Rooting constraints resulting from low rootable soil volumes 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. Salt affected lands were mostly located near the coastlines (Fig. 3). The current land cover of these marginal lands were primarily temporary grasslands (65%) and permanent grasslands (35%). Ile-et-Vilaine was the department with the largest area of marginal lands (32695 ha), followed by the Morbihan (13231 ha), the Finistère (7770 ha), and the Cote d'Armor (3848 ha).

Miscanthus yields on these marginal lands as simulated by CERES model varied from 0 to 21 t DM $ha^{-1}y^{-1}$ (with an average of 9 t DM $ha^{-1}y^{-1}$), depending on marginality constraints, climate, and soil quality (Fig. 4). These yield levels highlighted the low agronomic potential of marginal lands. Overall, this suggests that miscanthus could grow on marginal lands over long time periods (the 20-year simulation timeframe) in Brittany. Saline soils showed lower yields than stony soils, which suggested that some marginality factors were more severe for miscanthus production than others. Yields were lower in the Morbihan department compared to the other departments due to its higher share of salt-affected soils in the former. The total collectable biomass from these marginal lands amounted to 518 kt y^{-1} (8.9 PJ y^{-1} of energy). Ile-et-Vilaine had the highest biomass potential because of both its larger share of marginal lands and higher yields of miscanthus (Fig. 4). Growing miscanthus on marginal lands in Brittany resulted in modest soil carbon sequestration in most sites (with an average gain of 0.54 t C $ha^{-1}y^{-1}$). However, some sites were a small sink while other were a source of carbon, and there was a substantial inter-site variation in carbon sequestration rates (from -1.45 to 1.29 t C ha^{-1}y^{-1}, where a negative number implies a soil organic carbon). The main variation factors involved differences in soil moisture, marginality constraints and available nutrients, as well as biomass productivity. Overall, these data suggest that miscanthus can sequester carbon despite poor soil conditions in marginal lands thanks to its efficient use of nutrients and water, as well as its tolerance to stress.

3.2. Feedstock production costs, energy use and GHG emissions

The production costs of miscanthus varied from 53 to 104 € t^{-1} DM depending on crop yields and harvesting methods. Baling involved additional operations such as mowing and windrowing which resulted in production costs 7 to 11% higher than bundles and chips. Farm-gate costs varied depending on the harvest forms ranging from 53 to 95 € t^{-1}DM for chips, from 55 to 98 € t^{-1}DM for bundles, and from 59 to 104 € t^{-1} DM for bales (Fig. 5a). Energy use and GHG emissions followed a similar pattern, with bales consuming more energy and emitting more GHGs than bundles and chips. The farm-gate energy use ranged from 199 to 354 MJ t^{-1}DM for chips, 204 to 363 MJ t^{-1}DM for bundles, and from 242 to 430 MJ t^{-1}DM for bales (Fig 5b). Assuming an energy density of 17 GJ t^{-1}DM for miscanthus, the net energy gains ranged from 38 to 84 MJ for every MJ of fossil energy inputs, depending on biomass harvesting forms. With regard to climate change, growing miscanthus on marginal lands in Brittany resulted in low GHG emissions because soil organic carbon sequestration offset GHG emissions from agricultural activities. The GHG emissions ranged from -65 to 116 kg CO_2 t^{-1}DM for bales, they varied from -70 to 111 kg CO_2 t^{-1}DM for bundles, and between -71 and 110 kg CO_2 t^{-1}DM for chips (Fig 5c). The agricultural activities that contributed most to the production costs were establishment of the miscanthus fields, followed by harvesting and land rent, respectively (Fig. 5d). Harvesting was also the second contributor to total energy use (38 to 49% share), after establishment (45 to 55%, see Fig. 5e); however, it became the main contributor to GHG emissions in the baling case (Fig 5f).

3.3. Supply areas, delivery costs and environmental impacts

Fig. 6 shows the locations of both the biorefinery plant and storage points (at the ICPs), the road network, and the biomass supply areas for each of the studied scenarios. Biomass availability around the ICPs in the Finistère and Morbihan departments was lower than that around the ICPs in the Ille-et-Vilaine department. Assuming a 100% availability for the biomass produced, supplying a 40 kt DM y^{-1} biorefinery required different collection distances for the different scenarios analysed in this study (see section 2.5). The amount of biomass delivered to the biorefinery ranged from 40006 to 40013 t DM y^{-1}, depending on the scenario (Tab. 1). Due to small losses in the logistics chain, the quantity of biomass delivered to biorefinery in each scenario was slightly higher than the demand.

The total delivery costs varied from 3.5 to 3.7 M€ y^{-1}, depending on the biomass harvest form and scenario (Tab. 1), while energy use ranged from 14.1 to 16.5 TJ y^{-1} and GHG emissions varied from 300 to 411 tCO_2 y^{-1}. Substantial differences existed in the delivery costs, energy use, and GHG emissions of the different biomass harvest forms. The delivery costs ranged from 81.5 to 108.5 € t^{-1}DM for chips, 82.4 to 102.8 € t^{-1}DM for bundles, and 84.6 to 92.6 € t^{-1}DM for bales depending on the supply chain scenario (Fig 7a). Because the cheapest source of biomass is selected first in LocaGIStics, the estimates represented the minimum delivery costs of a given biomass form to the biorefinery. The delivery energy use ranged from 311.5 to 604.4 MJ t^{-1}DM for chips, 312.4 to 532.1 MJ t^{-1}DM for bundles, and from 352.7 to 437.3 MJ t^{-1}DM for bales (Fig 7b). Thus, the configuration of logistics impacted the net energy gains by 29 – 37% depending on the biomass harvest form. The GHG emissions varied from 6.1 to 19.1 kgCO_2 t^{-1}DM for chips, 6.2 to 15.8 kgCO_2 t^{-1}DM, for bundles and 7.5 to 11.3 kgCO_2 t^{-1} DM for bales (Fig 7c). As for the costs, these estimates represented the minimum energy use and GHG emissions to deliver miscanthus biomass to the biorefinery. Bales had lower delivery costs, energy use and GHG emissions than both chips and bundles because of their high bulk density, which reduced the number of truckloads and amount of storage needed (Fig 6). The volume limit of the transport vehicle was reached for bundles and chips before the payload weight limit. Thus, more trips and storage volume were necessary to deliver the required biomass quantity to the biorefinery.

As expected, the delivery costs, energy use, and GHG emissions increased from scenario 1 to 3 for all biomass forms due to the additional transport distance and storage needed to supply biomass to the 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. The variations in delivery costs, energy use, and GHG emissions across the logistics scenarios suggest that optimal biomass supplying chains from marginal lands are site-dependent. The breakdown of costs shows that feedstock production and transport dominated delivery costs, with shares ranging from 79 to 90% and 4 to 12%, respectively, followed by storage (3 to 6%) and handling (2 to 3%). Transport even became the main contributor to supply chain GHG emissions for chips and bundles in scenarios 2 and 3 (Fig 7d-f).

3.4 Sensitivity analysis

The sensitivity of the results to key assumptions made above was tested. Varying feedstock production costs, energy use, and GHG emissions by 15% relative to the baseline resulted in a 13% change in the delivery costs, 10% change in energy use, and 9% in GHG emissions across all scenarios. When the transport distances were changed by 20% relative to the baseline, delivery costs varied by 2%, the energy use by 6% and the GHG emissions by 6% in all scenarios. This means that biomass from marginal lands can be transported on relatively long distance without increasing the delivery costs significantly. Sensitivity to truck configurations showed that larger trucks resulted on average in a 34% reduction in delivery costs compared to smaller trucks. Similar trends were observed for the energy use and GHG emissions. A 20% change in storage duration had only minor effects (≤ 1%) on costs, energy use, and GHG emissions.

4. Discussion

4.1. Yields and carbon sequestration of miscanthus on marginal land in Brittany

This study estimates that about 57544 ha of marginal lands are available in Brittany, representing 3% of the agricultural lands in Brittany. Estimates of regional and global marginal lands have been carried-out using different approaches. Cronin et al. [62] combine a global fuzzy model with climate scenarios to show that under different climate scenarios, the global area that is available and suitable for energy crops changed substantially over the past century. Although the approach used in this study corresponds to current climate conditions, it maps well and provides good estimates of marginal lands available for energy crop production in Brittany. Whether these marginal lands were unused for several years and therefore classified as low-risk areas (i.e., low indirect land use change), in the logic of the recently revised Renewable Energy Directive that prescribes no use for at least 5 years, remains to be determined.

An average yield of 9 t DM $ha^{-1}y^{-1}$ was simulated for miscanthus on marginal lands in this study, which corresponded to the yield levels (7 to 10 t DM ha^{-1} y^{-1}) for moderately suitable marginal land categories according to Milbrandt et al. [32]. The yield range in this study (0 to 21 t DM $ha^{-1}y^{-1}$) is consistent with that observed for miscanthus on low quality lands in France (3 to 23 t DM ha^{-1} y^{-1} [63]). However, it corresponds to only a third of the range of potential yields (i.e. 15 to 50 t DM $ha^{-1}y^{-1}$ of miscanthus on good lands in Europe [64, 65]. Uncertainties exist regarding the yield levels of energy crops on marginal lands [5]. Yields on these lands vary considerably depending on soil properties (nutrient levels, bulk density, pH), marginality constraints (salinity, sodicity, stoniness), management (fertiliser, irrigation), land use history, and type of crop grown thereon [66]. Management practices targeting the marginality constraints (e.g. removing stones from stony fields or irrigating salt affected fields) can improve the yields of PECs on marginal lands [67]. Similarly, advances in breeding techniques could improve the yields of miscanthus on such lands [68]. Whether breeding can produce new miscanthus varieties that are economically viable when grown on marginal lands remains a topic for further research. Similar to biomass yields, soil organic carbon stocks and GHG fluxes are site-specific and reflect the long-term balance between organic matter inputs from vegetation and losses due to decomposition, erosion, and leaching. Limited information on soil carbon sequestration under miscanthus grown on marginal land is currently available in the literature. Mi et al. [23] report that miscanthus could sequester 0.46 t C ha^{-1} y^{-1} on marginal lands in China, in agreement with the estimate (0.54 t C ha^{-1} y^{-1}) of carbon accumulation rate under miscanthus in this study. Carbon accumulation rates under miscanthus on fertile croplands range from 0.42 to 3.80 t C $ha^{-1}y^{-1}$ [69]. The effect of PECs like miscanthus on building-up soil organic carbon is particularly large in marginal lands with low soil organic carbon levels [7, 70, 71]. However, if miscanthus is established on land that already has high soil organic carbon levels, such as long-abandoned land with dense shrubs and/or forest vegetation coverage, this may lead to a serious decline in soil organic carbon. In these situations, it is very difficult to build-up carbon again in a short period of time [71-73]. In addition to carbon storage, growing PECs like miscanthus on marginal lands may also provide shelter for various bird species, mammals, and invertebrates [74, 75].

4.2. Farm-gate and delivery costs, energy use, and GHG emissions

This study shows that Brittany has enough marginal lands for the production of lignocellulosic biomass for at least 10 small-scale biorefinery plants with a capacity of 40 kt y^{-1}. However, the high production costs of miscanthus on marginal lands may discourage farmers to grow this crop on their lands. The farm-gate costs (53 to 104 € t^{-1}DM) in this study agree well with ranges of 56 to 120 € t^{-1} DM for miscanthus production on marginal land in the literature [12], but they are higher than the range (63 to 102 € t^{-1} DM) reported for lignocellulosic feedstocks grown on croplands in Europe [76]. The delivery costs of miscanthus biomass to the biorefinery in this study ranged from 81 to 108 € t^{-1}DM, depending on the yields and biomass harvest form. Factoring in farmers' profits, Simon et al. [77] reported delivery costs ranging from 100 to 120 € t^{-1}DM for miscanthus and from 95 to 115 € t^{-1} DM for cereal straw in France. The delivery costs in this study surpassed the delivery costs of lignocellulosic energy crops from croplands (58 to 103 € t^{-1}DM [78]) and those of forest residues (44 to 77 € t^{-1}DM [79]) in Europe. Consequently, PECs from marginal lands may not be cost-competitive without improvements in feedstock yields, harvesting efficiency, and logistics. Since miscanthus is efficient in increasing soil organic carbon content on marginal lands [80], the economic valuation of such C sequestration is necessary to improve its economic competitiveness. Government policies such as imposing a tax on farm-gate GHG emissions or providing incentives via subsidies could also boost the economic viability of PECs from marginal lands.

Concerning the energy efficiency, reported farm-gate energy gain for miscanthus on croplands in the literature range from 36 to 98 MJ per MJ of energy inputs [81, 82]. Even though the farm-gate energy gains in this study (38 to 84 MJ for every MJ energy inputs) are hampered by logistics energy requirements, energy gains at the biorefinery gate still range between 27 and 53 MJ per MJ energy input. Consequently, miscanthus from marginal lands could be as energy efficient as miscanthus from regular cropland. Similar to the net energy gain, the logistic requirements increased the supply chain GHG emissions of miscanthus from marginal lands. To comply with the current EU RED sustainability criteria [3], the GHG emissions of solid biofuel should be under 34 gCO_2 MJ^{-1} [3]. The delivery GHG emissions, which ranged from 6.1 to 19.1 $kgCO_2$ t^{-1} (i.e., 0.35 to 1.12 gCO_2 MJ^{-1} assuming a low heating value of 17 GJ t^{-1} for miscanthus), represented only 1% to 3% of the current emission limits set by the EU for solid biofuels. Thus, miscanthus sourced from marginal lands has the potential to lessen the dependence on an unstable fossil fuel supply and to mitigate some undesirable aspects of fossil fuel production and use, notably GHG emissions. However, without substantial subsidies and other economic incentives marginal lands-based miscanthus can hardly compete with other bioresources and with fossil fuels.

Miscanthus was selected as the suitable crop for cultivation on marginal lands in Brittany based on the mapping proposed by Von Cossel et al. [9]. However, many other crops, including herbaceous and woody crops can also be cultivated on these marginal lands. While it is agreed that there is no one size fits all crop, miscanthus has many valuable characteristics that will favour its use not only as a 'model crop' for cultivation on marginal lands, but also as a sustainable feedstock for biorefinery in Brittany and in Europe at large. This study contains a relatively high degree of spatially explicit details regarding production locations and transport network, and biomass demands. The spatial resolution of biomass supply is relatively coarse and can be improved. While adding details may encourage a clearer preference for a particular production location, which maybe of interests to industry stakeholders, it is not expected to alter the merit of the supply chain costs of this study.

An important uncertainty is the effect of climate change on crop yields on marginal lands. Plant response to elevated CO_2 concentrations, together with projected variation in temperature and precipitation will determine future crop yields in general. CO_2 fertilisation can increase crop yields considerably due to enhanced carbon assimilation rates as well as improved water-use efficiency [83, 84]. Whether miscanthus yields on marginal lands will increase under elevated atmospheric CO_2 concentrations will depend on the availability of additional inputs such as nitrogen [85]. Indeed, adequate supply of nutrient is needed to sustain additional growth under elevated CO_2 concentrations. However, crops are constrained by nutrient availability in marginal lands and additional growth might be limited.

5. Conclusion

This study is a first of its kind to combine a geographical information system, a crop growth model, life cycle assessment, and a logistics model to assess the extent and characteristics of marginal lands in Brittany, and to explore the possibility of supplying biomass from these marginal lands to local biorefineries. It shows the spatial distribution of marginal lands across Brittany and estimates the yields of miscanthus on these lands. It highlights that crop cultivation, and transport dominated the supply chain costs, energy consumption and GHG emissions. It estimates that at least 81 € t^{-1} DM were required to deliver miscanthus biomass to biorefinery though the GHG emissions were only 3% of the current emission limits set by the EU for biofuels. Biomass supply in the form of bales was more cost efficient and environmentally friendly compare to its supply in the form of chips. Also, the direct supply of biomass to biorefinery was cheaper and less polluting than having to store it first at the ICP. Consequently, harvest forms and logistic configurations influenced the delivered costs, energy consumption and GHG emissions of biomass from marginal lands. Overall, the study showed that sourcing biomass from marginal lands provides net energy gains and has low GHG emissions but at a relatively high cost compared to PECs grown on good soils. Thus, more aggressive policies and incentives to foster low-carbon technologies are needed to encourage Brittany's farmers to grow perennial energy crops on marginal lands. Although the results shown here cannot be generalised to other regions of France because of differences in marginality constrains, agronomic, climate and soils conditions, the methodology presented here to map out marginal lands, assess yield potentials, delivery costs and environmental impacts has relevance beyond France and could be applied to other regions of the world where suitable data are available.

Acknowledgement: This work has received funding from the European Community's Horizon 2020 (H2020) as part of the MAGIC project under the grant number 727698.

Declaration of competing interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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TABLE AND FIGURE LEGENDS

Tab. 1: Quantity, supply chain costs, energy use, and GHG emissions of miscanthus from marginal lands

Biomass forms	Scenarios											
	Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3	Sceneraio 1	Scenario 2	Sceneraio 3
	Amount (t DM y^{-1})			Costs (€ $year^{-1}$)			Energy use (MJ $year^{-1}$)			GHG emissions (kg CO_2 $year^{1}$)		
Chips	40009	40006*	40008**	3620143	3659629	3666692	14716097	16371025	16458573	316679	410893	415074
Bundles	40012	40009*	40013**	3558554	3585142	3591887	14142974	15333125	15404748	300415	368463	371734
Bales	40011	40008*	40010**	3501838	3515604	3515368	14827680	15193575	15271937	324374	348940	351473

* some amounts (9277 tDM for chips ; 9463 tDM for bundles ; 9815 tDM for bales) of biomass originated from ICP1 to biorefinery in addtition to that from the fields, ** some amount (12192 tDM for chips ; 12139 tDM for bundles ; 12139 for bales) of biomass come from ICP1 and ICP2 to biorefinery in addition to the one from fields, no biomass from ICPs in scenario 1 ; collected felds were 106 in scenario 1, 103 fields in scenario 2, and 100 fields in scenario 3 to supply annual biomass demand of the biorefinery. ICP = intermediate collection point.

Fig. 1: Map of Brittany and its department

Fig. 2: Supply chain design, components and configurations for the three investigated scenarios (ICP = intermediate collection points)

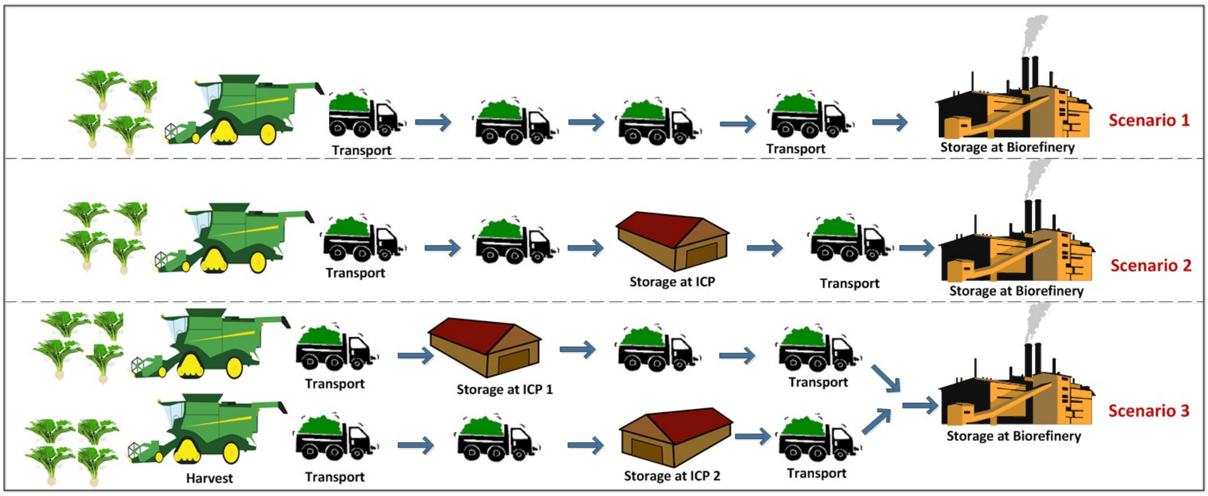

Fig. 3: Distribution of marginal lands in Brittany. The different colour on the map represents the marginality constraints.

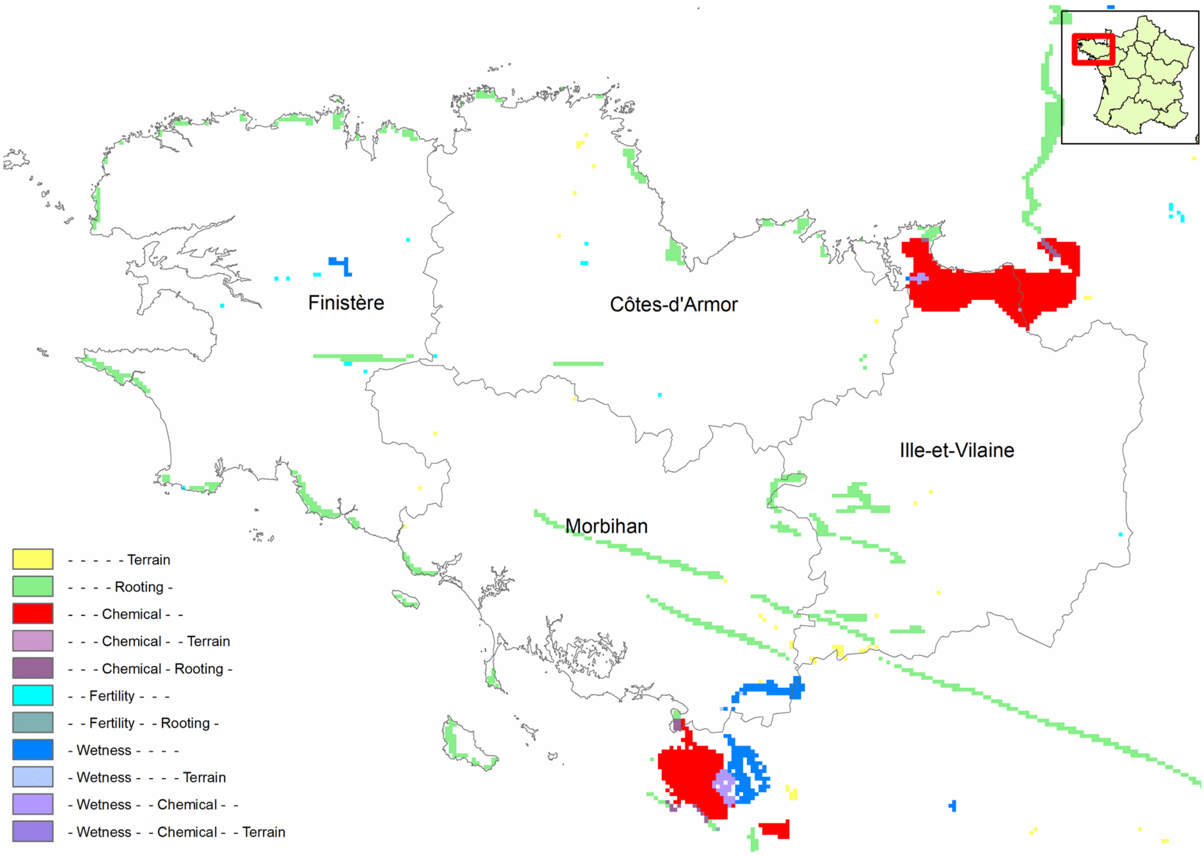

Fig. 4: Distribution of miscanthus yields on marginal lands in Brittany

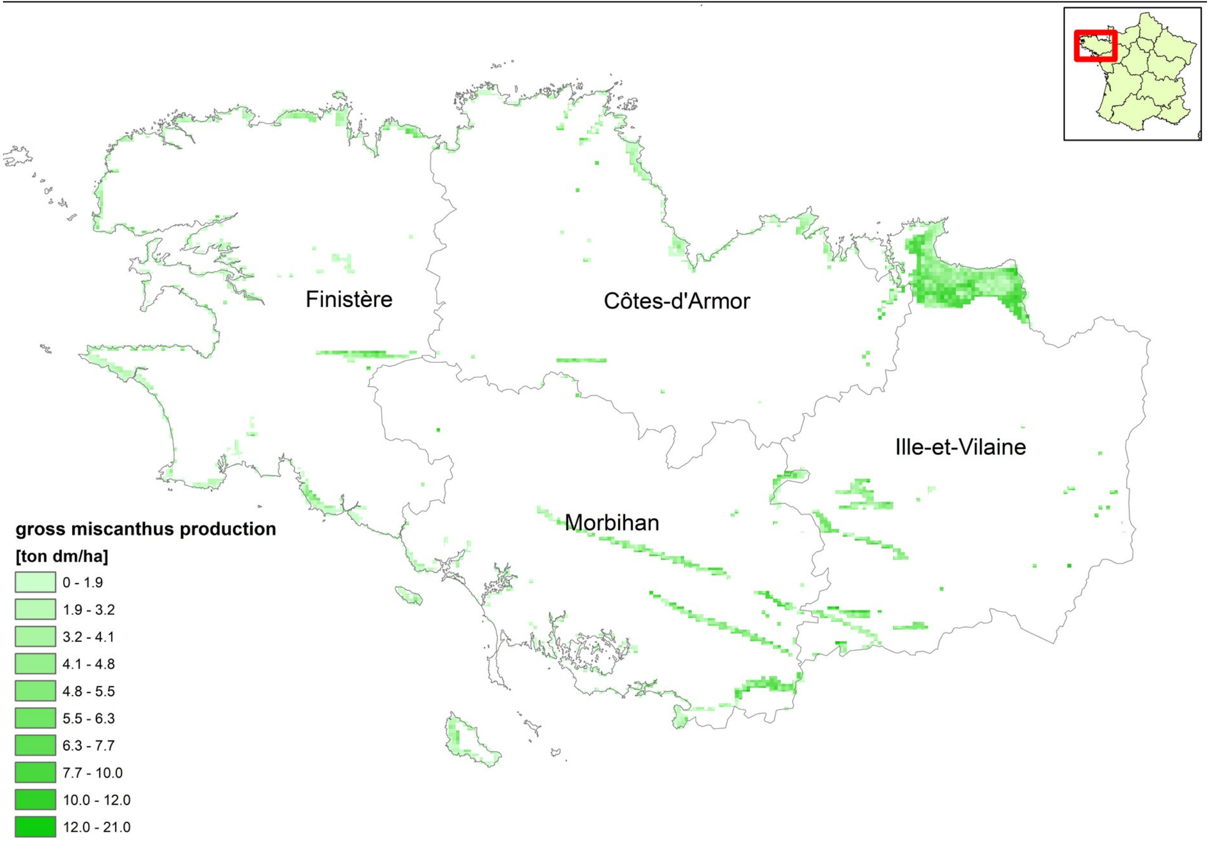

Fig. 5: Miscanthus production costs, energy use, and GHG emissions (bottom panels) as well as the breakdown of average production costs, energy use and GHG emissions (top panels).

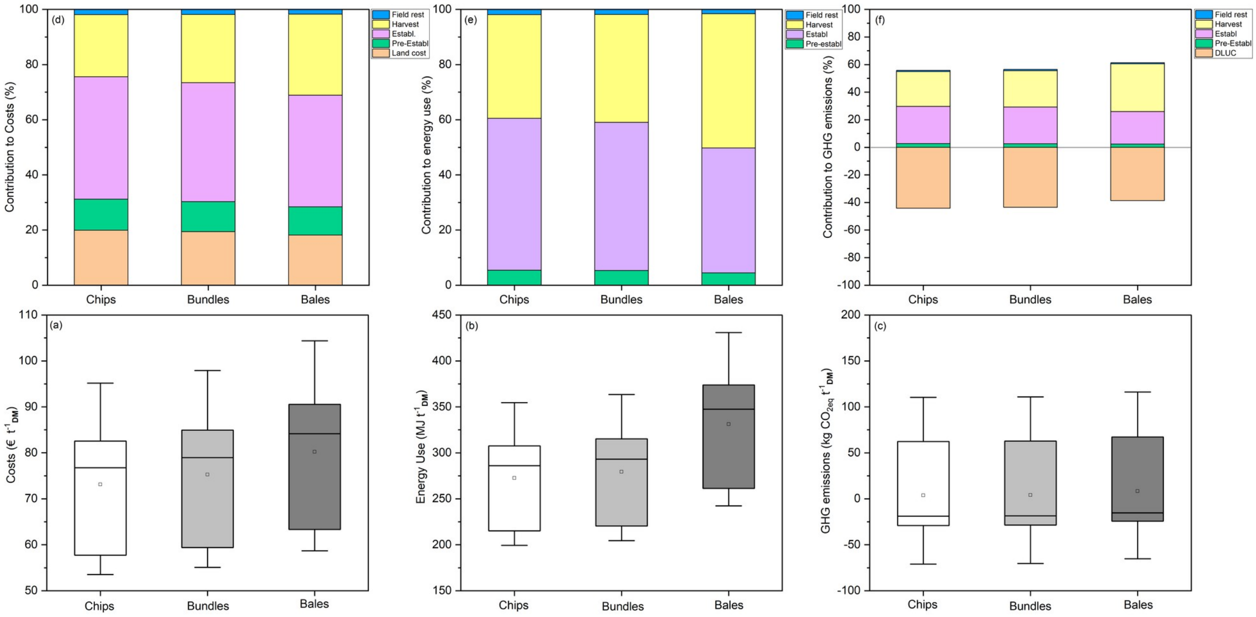

Fig. 6: Location of biorefinery and storage points in the different scenarios

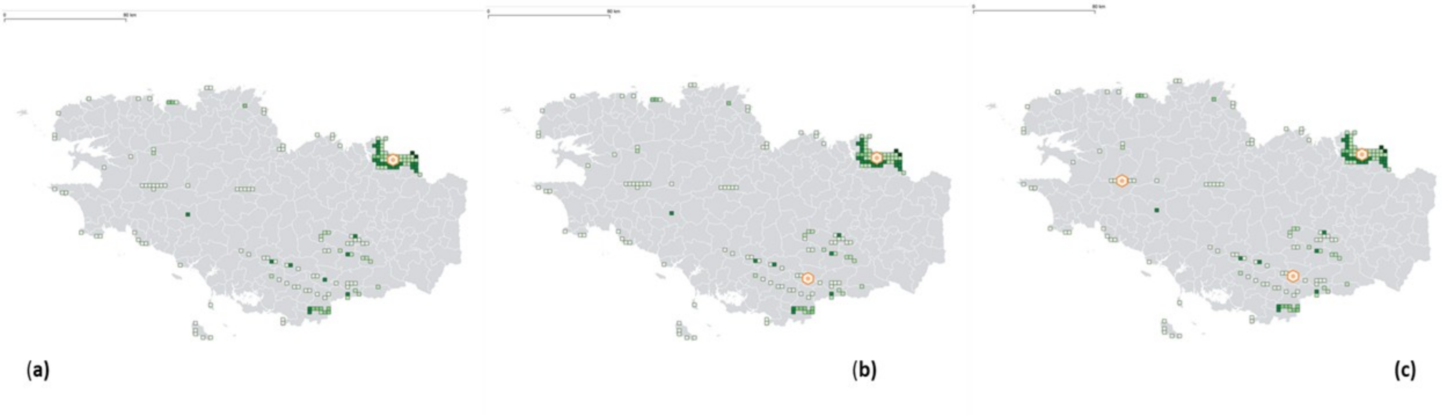

Fig. 7: Supply chain costs, energy use and GHG emissions (bottom panels) as well as the breakdown of the average supply chain costs, energy use and GHG emissions (top panels)