Integrated design and sustainable assessment of innovative biomass supply chains: a case-study on miscanthus in France

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Abstract

Cost-efficient, environmental-friendly and socially sustainable biomass supply chains are urgently needed to achieve the 2020 targets of the Strategic Energy Technologies-Plan of the European Union. This paper investigated technical, social, economic, and environmental barriers to the development and innovation of supply chains, taking into account a large range of parameters influencing the performances of biomass systems at supply chain scale. An assessment framework was developed that combined economic optimization of a supply chain with a holistic and integrated sustainability assessment. The framework was applied to a case-study involving miscanthus biomass in the Burgundy region (Eastern France) to compare alternative biomass supply chain scenarios with different annual biomass demand, crop yield, harvest timing and densification technologies. These biomass supply chain scenarios were first economically optimized across the whole supply chain (from field to plant gate) by considering potential feedstock production (from a high-resolution map), costs, logistical constraints and product prices. Then sustainability assessment was conducted by combining recognized methodologies: economic analysis, multi-regional input-output analysis, emergy assessment, and life-cycle assessment. The analysis of the case study scenarios found that expanding biomass supply from 6 000 to 30 000 tons of dry matter per year did not impact the profitability, which remained around 20€ per ton of biomass procured. Regarding environmental impacts, the scenario with the lowest feedstock supply area had the lowest impact per ton due to low economies of scale. Mobile briquetting proved to be also a viable economic option, especially in situations with a considerable scattering of the crop production and expensive transportation logistics. By highlighting hot-spots in terms of economic, environmental and social impacts of biomass supply systems, this study provides guidance in the supply chain optimization and the design of technological solutions tailored to economic operators as well as other stakeholders, such as policy makers.

Keywords Miscanthus, economic optimization, Emergy Assessment, Multi-Regional Input-Output Analysis, Life-Cycle Assessment, logistics

1. Introduction

Two recent pieces of legislation in Europe, the Renewable Energy Directive [1] and the Fuel Quality Directive [2], will have considerable impacts on the deployment of bio-energy in Europe over the next decade. These directives set targets for the renewable content and the greenhouse gas (GHG) abatement of transport fuels, which were communicated in 2009 by the European Commission [3] and its subsequent updates. A rapid 'transformation of our entire energy system' and the development of competitive and affordable low-carbon technologies are warranted, according to the SET-plan. In this policy document, biomass was ascribed an overall 14% share for the energy mix of the EU by 2020, an increase from 6% in 2010. This implies a more than two-fold increase within a very short timeframe, creating a unique opportunity to develop bioenergy while also posing a formidable challenge in terms of feedstock supply. Biomass production and supply are the key components of the economic and environmental performance of bio-based value chains [4]. Accordingly, the SET-plan puts an emphasis on sustainability assessment for current and upcoming feedstock sources, and calls for the development of technologies that broaden the feedstock base and maximize the economic and environmental efficiency of the entire biomass supply chains. It also flags the need to manage and develop human and social capital, to increase the sustainability and facilitate a continuous improvement of these chains. Innovative techniques for crop management, biomass harvesting, storage and transport offer a prime avenue to increase biomass supply while keeping costs down and minimizing adverse environmental impacts [5].

Dedicated energy crops are projected to provide a large proportion of the biomass feedstock needed to fuel bioenergy development in the coming decades [6]. Among such crops, the perennial C4 grass miscanthus is a promising candidate due to its high yield potential and low requirements for soil tillage, weed control, and fertilization, combined with a long cultivation period [7, 8]. It is currently primarily used as a solid fuel for combustion, on a relatively small scale (i.e. annual biomass supply under 10 kt.year^{-1}). Some case-studies of miscanthus production at plot or farm scale have been described, but mostly focus the agricultural production phase and ignore the downstream logistics, which can be complex. The aspects of the miscanthus production that have been studied include, cultivation methods [9], the socio-economic or environmental performance of the production system [10, 11], and the environment life cycle assessment of hypothetical supply chains to produce energy from miscanthus biomass[12, 13]. In contrast, larger-scale bioenergy pathways, such as those on 2nd generation, lignocellulosic feedstock, have only been studied hypothetically, considering aspects such as logistical challenges [14, 15]. Environmental assessment of large-scale of several feedstock have considered the impact of land-use or greenhouse gases emissions reductions policies [4, 15], or trade-offs and competition between biofuel and food production [16, 17] using ecosystem and/or economic modeling. Such studies have aimed to estimate the land requirements, energy yields and associated economic and environmental impacts of new bioenergy pathways [18]. However, such large-scale analyses have large source of uncertainties, mainly due to the diversity of cultivation technologies, large variations in yields, and different transport contributions [19, 20]. These factors vary greatly between cases and largely influence the sustainability of biomass supply chains. Thus, it appears necessary to examine on a case by case basis how supply chains can be optimized and their sustainability assessed, but using an integrated assessment framework.

In addition to the economic optimization of the bio-based value chain, its impact on the regional economy may be assessed in a Multi-Regional Input-Output (MRIO) analysis. It generates information about socio-economic impacts of biomass supply chains, such as economic value added, and job creation, directly and indirectly related to the activities involved in a system [21]. Using the same kind of input data, not expressed in monetary units but in biophysical units, the environmental assessment can be conducted under the same framework. Life-cycle assessment (LCA) is commonly used as a flexible tool to answer a wide variety of different policy-relevant questions [22]. It considers both direct and indirect use of resources throughout the supply chain, and emissions to the environment. It outputs a set of indicators representative for the diverse range of environmental issues relevant to bioenergy pathways. However, LCA draws system boundaries around anthropogenic processes (resource extraction, refining, transportation, etc.) and does not consider the energy provided by natural phenomena and, usually, human labour. These latter aspects can be considered by Emergy assessment (EmA) [23]. Both methods are largely based on the same type of inventory data (i.e., accounting for energy and material flows), but apply different theories of values and system boundaries since their scopes differ. In EmA, in fact, all forms of energy, materials and human labour that contribute, directly or indirectly, to a production process are evaluated using a common unit. EmA is particularly suited for assessing agricultural systems since the method accounts for the use of freely available natural resources (sun, rain, wind and geothermal heat), as well as marketable goods and services.

Sustainability assessment of biomass supply chains should address economic, social and environmental aspects. However, these three dimensions are seldom combined and there is a need for models and methodologies, which integrate the main factors that influence biomass supply chains performances and sustainability in a consistent and comprehensive manner [24]. A recent study on wood-based value chains proposed such a multi-criteria analysis [25], but only partially integrated the various dimensions of sustainability. Here, we have combined the above methodologies into an integrated framework for sustainability assessment, encompassing economic, environmental and social criteria in relation to a bioenergy project. The development and test of a new 4-step framework was the overreaching objective of this manuscript. The framework was applied to optimize and assess a currently-operating supply chain in Burgundy, as well as potential, innovative variants involving an expansion of biomass demand based on supply area or crop yield, or alternative harvesting dates and biomass densification technologies. All scenarios are defined based on economic optimization of transportation and storage.

2. Materials and methods

2.1. The existing miscanthus supply chain at Bourgogne Pellet

Bourgogne Pellets (BP) is a farmers' cooperative comprising about 350 members based in the municipality of Aiserey in the Burgundy region of Eastern France. In 2015, the supply area of BP covered 400 ha of miscanthus, scattered across arable land in an approximately 70 km radius around Aiserey. The supply chain operated by BP includes six stages, namely agricultural production, harvest, handling, transport, storage and processing, and produces biomass feedstock products in a range of forms – chips, bales and pellets. Each year, the scale of production and type of product vary in response to the miscanthus yields and demand for different products.

Miscanthus is a perennial crop with a life span of about 15 years thanks to rhizomes, which store starch, proteins, and other nutrients during winter, allowing for a regrowth in spring. From year 2 to year 15, the plantation is mature and the above-ground biomass is harvested once a year. In the BP supply-area, the biomass is harvested as loose *chips* or as compressed *bales* with either short or long piece sizes, denoted *short bales* (6-10 cm) and *long bales* (10-40 cm), respectively. This allows a diversity of end-uses beyond energy purposes (mulching, livestock bedding, bio-material). Harvested products are either directly transported to the pelleting facility at BP, or stored at intermediary storage prior to transport to the BP facility. All long bales and a portion of short bales are then processed as pellets, that will be sold on the market together with chips and the remaining short bales. More detailed data on the case-study may be found in Morandi et al.[10].

Technical and economic data about the inputs and outputs for each operation within the full supply chain were collected from field trials, direct interviews with farmer and private companies involved in the supply chain, modeling and technical documentation. When no specific data were available, data were taken from national and European databases or from scientific literature (Table 1).

Table 1 Type of data collected and associated sources

Data	Field Trials	Interviews	Model calculations	Technical documentation	Database & literature
Miscanthus fields geographical location		x	x		
Crop management		x			
Inputs		x			
Yields			x		
Biomass losses and emissions			x		x
Operation costs	x	x			
Material & infrastructure prices & maintenance		x		x	
Manpower	x	x			
Operation efficiency	x	x		x	
Energy consumption	x	x		x	
Material & infrastructure description		x			x

2.2. Defining simplified scenarios to explore specific logistics features

Ten supply chain scenarios were defined to consider the influence of keys variables (demand variations and alternative logistic solutions to supply the BP facility) on sustainability indicators (Table 2).

Table 2 Overview and main characteristics of studied scenarios

Cases	Supply-chain scenarios	Key parameters	Unit	Value
Baseline	Scenario 1	Fertilization	kg.ha^{-1}	0
		Harvest time	-	Spring
		Harvest techniques	-	Chips, Bales S, Bales L
		Yield	t DM.ha^{-1}	14.83
		Demand	t DM.y^{-1}	6 000
		Processing	-	Pelletization
		Capacity of pelletization.	t FM.h^{-1}	1.9
Alternative demand	Scenario 2	Demand	t DM.y^{-1}	8 000
	Scenario 3	Demand	t DM.y^{-1}	12 000
	Scenario 4	Demand	t DM.y^{-1}	30 000
Alternative yield	Scenario 5 Minimum	Yield	t DM.ha^{-1}	12.53
	Scenario 6 Maximum	Yield	t DM.ha^{-1}	16.68
Alternative harvest	Scenario 7 Autumn	Fertilization	kg.ha^{-1}	67
		Harvest time	-	+ Autumn
		Harvest techniques	-	+ Shredder
		Yield Autumn	t DM.ha^{-1}	18.69
Alternative processing	Scenario 8 Briquette 1	Processing	-	+ Briquetting
		Capacity	t FM.h^{-1}	0.5
	Scenario 9 Briquette 2	Processing	-	+ Briquetting
		Capacity	t FM.h^{-1}	1.0
	Scenario 10 Briquette 3	Processing	-	+ Briquetting
		Capacity	t FM.h^{-1}	1.5

The baseline (Scenario 1) corresponds to the existing supply chain, with its current annual demand, production area, practices and infrastructures. However, yields were based on estimated for mature miscanthus crops [26] to get rid of the variability due to the various ages of fields within the supply-area (from 2 to 7 years-old in Burgundy). Scenarios for alternative demand, numbered from 2 to 4, represent expansion of supply from 6 000 ha to 30 000 ton dry matter per year (t DM.y^{-1}) based on a model of the potential miscanthus area expansion (see section 2.3.1).

Six additional scenarios, numbered from 5 to 10, represent alternative yields, harvesting and processing logistics. They all assume the same supply area as baseline (i.e. Scenario 1). Scenarios for alternative yields (Scenario 5 and Scenario 6) are based on extreme values estimated for the Burgundy region with a statistical model derived from a meta-analysis of miscanthus yields [26]. The model was calibrated with local on-farm yields and integrates the effect of crop aging on yields. A scenario for alternative harvest timing (SCENARIO 7) involved the possibility of harvesting part of the miscanthus crop in autumn. Data for harvesting green miscanthus in autumn were taken from field trials conducted in Italy using a shredder to cut the field instead of a silage harvester [27]. A fertilizer input rate was adjusted to compensate for the higher nitrogen exportation compared to the spring harvest of miscanthus. In the baseline scenario we only considered the possibility of producing pellets. However, miscanthus may also be processed as briquettes [15], which are similar to pellets but with a larger diameter (Ø75 mm instead of 8 mm for pellet). A mobile briquetting unit may reduce the need to transport bales as briquettes can be sold directly from intermediate storages. This option involves the transport of the briquetting press to the intermediate storage point where briquetting takes place. It leads to the production of a fourth end-product, briquettes, in addition to chips, short bales and pellets. Scenarios numbered from 8 to 10 differ according to the capacity of the briquetting unit.

For all 10 scenarios we considered energy production as the only market opportunity for miscanthus-based products. All miscanthus crops were harvested, possibly stored in an intermediary storage point and eventually transported to the BP facility. Product outputs were expressed in tons of dry matter per year (t DM.y^{-1}) at this stage. Then part of the production (all the long bales and part of the short bales) is processed as pellets. After this final processing stage, product outputs were expressed on the basis of the energy content of the biomass (in GJ), based on lower heating value (Table 3).

Table 3 Main characteristics of end-products for the Bourgogne Pellets case-study

End-products	Chips	Short bales	Pellets	Briquettes
Moisture content (% H_2O)	16	12	9	10
Lower Heating Value (GJ per ton Fresh Matter)	14.7	15.6	16.0	16.0

2.3. 4-step assessment framework

A 4-step framework (Figure 1) was developed to design, optimize, assess and compare the the existing biomass supply-chains and the alternative scenarios. Step 1, named Potential feedstock production, determines the potential volumes of the various feedstock that can be produced from different geographical locations. Step 2, named Economic optimization, optimizes the economics (profitability) of the biomass supply chain from production to facility gate from with respect to harvest techniques, transport, storage and processing options. The last two steps perform a sustainability multicriteria multiscale assessment (SUMMA) introduced by Ulgiati et al. [28], which integrates the multiple sustainability assessment methodologies. Step 3, named Individual assessments, assesses the socio-economic and environmental impacts of the optimized supply chains using: Economic analysis, Multi-Regional Input-Output (MRIO) Analysis, Emergy Assessment (EmA) and Life-Cycle Assessment

(LCA). Step 4, named Integrated assessments, integrates the indicators result from step 3, to identify "hotspots" and assess the relative sustainability of scenarios.

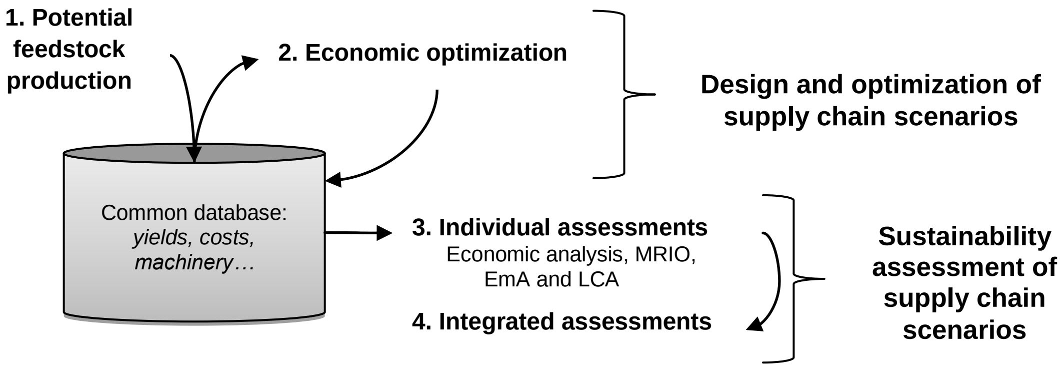

Figure 1 Four-step framework for assessing the overall impacts of existing biomass supply-chains and to compare alternative scenarios

2.3.1. Potential feedstock production

A spatially-linked explicit location model [29] was produced showing the geographic locations within the BP supply area that meet the required criteria for miscanthus production (e.g. slope and size of the field and its distance to the farmstead). The criteria were derived from interviews with farmers. A Boosted Regression Tree data mining method was applied to relate the location of the actual miscanthus fields and the farmers' criteria, resulting in a spatially explicit model that predicts the probability of establishing miscanthus on any given land parcel. This probability was calculated for all the land parcels of the supply area of BP, i.e. within a radius of 70-km around the facility. The proposed areas of miscanthus production for each scenario resulted then from the overall demand for feedstock, the current areas of miscanthus, and the probability of establishing miscanthus on each given land parcel. Miscanthus yields were averaged across all land parcels of the study area to facilitate the economic optimization.

2.3.2. Economic optimization

The operation and configuration of a supply chain depends on crop yields, current and extended market demand, and technology. To evaluate all supply chains scenarios in a consistent manner, a model of an economically optimized supply chain was used as a proxy for designing the supply chain logistics. The economic optimization was undertaken using a general optimization model used for strategic planning of biomass supply chains [30]. The model is based supply chain network with nodes for biomass production, harvesting, storage and processing, and product flows between the nodes. The model identifies the supply chain configuration that optimizes overall profit depending on constrains for production, storage capacity, demand, costs and, sales prices. The model is run for a period of one year with a monthly time series. The optimization process resulted in a description on how much miscanthus is harvested in each municipality for each product (chips, short and long bales), how long it is stored locally, how it is transported to BP, and the mix of final products.

Transport configuration was based on the shortest-path transport distances via the real road network, and transport cost per ton of each product (chips and bales). Loading and unloading costs are included in the transport cost. Chips are more expensive to transport due to their lower density, but they have lower harvesting costs than bales. Thus, harvesting as chips will only be economically viable for municipalities close to the BP facility. In addition, limited storage capacity will also influence the quantity harvested as chips, as specific storage infrastructures are needed to store chips. By contrast, storage for bales is available in local warehouses in each municipality and can be used for free for a few months after harvesting, but extended storage incurs a storage cost. There is at the BP facility for chips and bales (3 silos that can be used for both), and four warehouses with limited capacity for intermediate storage of chips.

Overall supply chain costs include agricultural production, harvesting, transport including loading and unloading, storage and pelletizing. Income was based on the sales of the final products (chips, short bales and pellets) as bulk from the plant, at a price based on estimates provided by BP. Precise demand data was not available, so no limit was placed on the maximal demand of the final products. As chips and short bales are sold locally with a requirement on regularity, the demand for these products was assumed to be uniform throughout the year.

2.3.3. Individual assessments

As already described, the Multi-criteria assessment (SUMMA) includes different methodologies with their respective indicators (Table 4).

Table 4 Indicators used in the SUMMA diagram

Methodology	Indicator (Short name)	Unit
Economy	Supply cost (Cost)	€
MRIO	Total economic activity (Eco. Activity)	k€
	Value added	k€
	Employment	people
	Multiplier effect (Mult. Effect)	dimensionless
EmA	Emergy Unit Value (UEV)	seJ
	Renewability (Renewability)	%
	Labour input (Labour)	%
	Emergy Unit Value w/o labour (UEV w/o)	seJ
LCA	Climate change (CC)	kg CO_2 eq
	Freshwater ecotoxicity (FET)	CTUe
	Human toxicity, cancer effects (HT)	CTUe
	Land use (LU)	kg C deficit
	Water resource depletion (WRD)	m^3 water eq

2.3.3.1. Economic Analysis

The economic analysis was an integrated part of the optimization model described above, with the optimization based on maximizing the overall profit for BP. We used the total supply cost up to the plant gate per ton dry matter of harvested product as an economic indicator in the assessments (Table 4). This cost excludes the cost of pelletizing at the plant, but includes all other cost components as described in the previous section. While this analysis focuses on BP's economic performance from a micro-level perspective, the Multi-Regional Input-Output Analysis will analyze the impacts of BP activity in the whole economy at a macro-level perspective.

2.3.3.2. Multi-Regional Input-Output Analysis

Input-Output (IO) analysis has been used to estimate macro-economic impacts of industries within the national or regional economy [21]. This analysis estimates how the economy would grow as a consequence of a change in the final demand of goods and services from a macroeconomic perspective [31]. The IO analysis was initially focused on one unique region or country. However, during the last decades, international trade has become more and more important, implying that economic analyses cannot be focused on one region only but should consider the global world. In order to do this, several organizations and projects have been producing harmonized Input-Output tables that connect the production of goods and services from one sector in one country to other sectors and countries that require these good [31]. This way, the IO framework is expanded to a Multi-Regional Input-Output (MRIO) analysis, which was used to estimate the socio-economic impacts in this case study. Under this framework and by considering four MRIO indicators (Table 4), it is possible to identify the activity sectors and countries that will benefit from the supply chain in terms of economic stimulation and job creation.

The goods and services demanded along the different supply chain scenarios as well as the activity sectors among the economy that would provide these goods and services have been identified to run the analysis for estimating both direct and indirect socio-economic impacts from a macro-economic perspective. The analysis also included the so-called induced effect, which estimates the socio-economic impacts derived from the expenditures made by the workers using part of their salary. In this case study, the salaries and wages, as well as the social contribution, were estimated based on the working hours required in each agriculture operation and on the data published by Eurostat for the French Agriculture sector in 2011. The salaries earned by the workers were assumed to be partially spent in other goods and services, generating a new final demand and, therefore, new socio-economic effects. A tendency of workers to save 5% of their net salary, and an average expenditure in goods and services similar to the France-wide average in 2011 was assumed. The final demand was defined considering the activities occurring each year, from the planting to the removal of miscanthus crop and, to consider the time effect, the net present value of all costs along the whole miscanthus cycle was calculated and used to estimate the socio-economic impacts. The discount rate was assumed to be 4% per annum. Altogether, direct, indirect and induced socio-economic effects for each year contributed to the total economic activity generated by BP expressed in k€. Value added expressed in k€ is defined as the value of gross output less intermediate inputs. Employment represents the number of jobs supporting; both full-time and part-time. Finally, to understand how the global economy would expand as a result of BP activities, the multiplier effect, which is a proportionality factor of much the economy will change in response to the final demand derived from BP activities was calculated. More details about the MRIO analysis can be found in de la Rúa and Lechón [32].

2.3.3.3. Emergy Assessment

Emergy Assessment (EmA) is a thermodynamics-based methodology that estimates the environmental support provided by nature and society to the system under study. As defined by Odum [23], emergy is the available solar energy necessary, directly and indirectly, to make a product or a service. All inputs (energy and matter) required to produce a product or to sustain a system are converted, by using their respective UEV (Unit Emergy Value), into the common unit of solar equivalent joules (seJ). Then, the total emergy of a system is given by the sum of all emergy in the inputs. For this study, all input flows to the supply chain were divided into two main categories: renewable inputs (of local as well as global origin) and non-renewable inputs. Renewable inputs are generated by planetary processes (e.g. solar radiation, rain, wind, geothermal heat). Non-renewable inputs are from internal storage of the system (e.g. soil and locally supplied minerals) or non-renewable inputs bought from outside the system.

Under this framework four emergy indicators were considered (Table 4). The UEV of the supply chain for the total production of chips and bales at the BP storage was calculated as the total emergy per ton dry matter of products (i.e., chips and long and short bales). Renewability was calculated as the proportion of total emergy that is renewable emergy. The labour indicator was calculated as the percentage of emergy required to support the human labour force (further referred as labour) involved directly or indirectly in the supply chain. Finally, UEV w/o labour is calculated omitting labour in the total emergy. More details about the Emergy Assessment can be found in Morandi et al. [10]

2.3.3.4. Life Cycle Assessment

The Life-Cycle Assessment (LCA) is a standardized methodology to assess potential environmental impacts associated with all the stages of a product's life, from-cradle-to-grave. LCA considers the emissions of pollutants to the environment and the use of resources and infrastructures. We used the methodology recommended in International Life Cycle Data handbook [33] to calculate impacts. Fluxes are then converted into potential impacts based on impact characterization factors for inventoried substances relative to a reference substance (such as CO_2 for the global warming potential). In this study we present 5 impact categories. Climate change potential (expressed in kg CO_2

eq.) is mainly influenced by carbon- and nitrogen-based emissions. Two impact categories are mainly influenced by chemical inputs and infrastructures: freshwater ecotoxicity (CTUe) and human toxicity, cancer effects (CTUh). Finally two impact categories are mainly influenced by resource use: land use (kg C deficit) and water resource depletion (m^3 water eq.).Reactive nitrogen emissions during miscanthus farming were estimated using the CERES-EGC model [34]. The model takes into account soil, climate and management conditions that influence N emissions. Values refer to the average for miscanthus in Burgundy. Reactive nitrogen emissions from the final removal of from the field were based on measurements performed at Grignon, France [35]. Pesticides and phosphorus emissions were calculated following recommendations from Nemecek and Kägi [36].

2.3.4. Integrated assessment

The Sustainability Multicriteria Multiscale Assessment (SUMMA) is an integrated assessment introduced by Ulgiati et al. [28] that takes into account several complementary methodologies used to assess the sustainability performance of a system. Each methodology is applied according to its own rules and the respective indicators are calculated. All results are combined together to provide a comprehensive picture of the sustainability assessment of the system. The main characteristic of the SUMMA method is that all the assessment methodologies draw on a common data inventory. In this application, we combined the indicators derived from economic analysis, MRIO analysis, EmA and LCA listed in Table 4. A spider diagram was used to present the combined indicator set each supply chain scenario. Each indicator was normalized against the highest from amongst the scenarios studied, such that the highest value is assumed to represent the preferres outcomes. Here we assume that higher labour input, as measured by EmA, was preferable, as was a higher employment rate. Profit and Climate change indicators were used to compare all 10 scenarios by means of impact per GJ product including the pellet production.

3. Results

3.1. Integrated assessment of alternative demand scenarios

Figure 2 potential biomass feedstock production from land identified to be suitable for miscanthus production in each municipality of the supply area, in this case for Scenario 4. It shows a rather scattered distribution of potential miscanthus production within the BP supply.

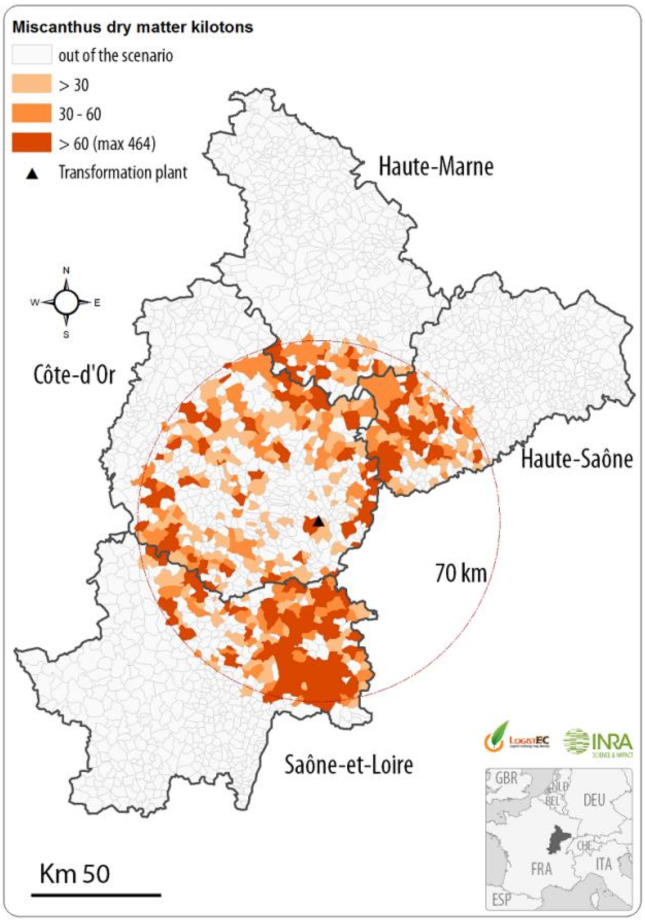

Figure 2 Map of potential feedstock supply for each municipality in the supply area of the BP facility, considering a potential miscanthus demand of 30 000t DM per year (scenario 4)

The economical optimization of the baseline scenario and alternative demand scenarios (Scenarios 1 to 4), simulating current and expanded miscanthus production, led to four different scenarios in terms of product quantities and costs (Figure 3). While pellets remained the main product for all scenarios, the contribution of chips decreased from scenarios 1 to 3. In terms of absolute numbers, the quantity of chips sold was about the same. The combination of a limited storage capacity and need for regularity of supply (not deviating more than 25 % between months), lead to a hard constraint on the quantity of chips that could be sold since chips have to be stored throughout the year. With sufficient storage capacity or when allowing for a larger variation in the demand, the share of chips would have been higher in scenarios 1-3. In scenario 4, the share of chips increased in comparison to scenario 3 due to an increased storage capacity. The variation in the quantity of short bales produced was more erratic and mainly resulted from overall storage limitations. Upscaling biomass production generated an approximately constant profit across scenarios due to slight variations in the share of each end-product to cope with the variations of costs. Scenario 2 was slightly more preferable than other scenarios thanks to a higher share of pellets, which are sold at a higher price than the other end-products. When expanding biomass production, cost savings due to economies of scale in processing were offset by increased transportation costs.

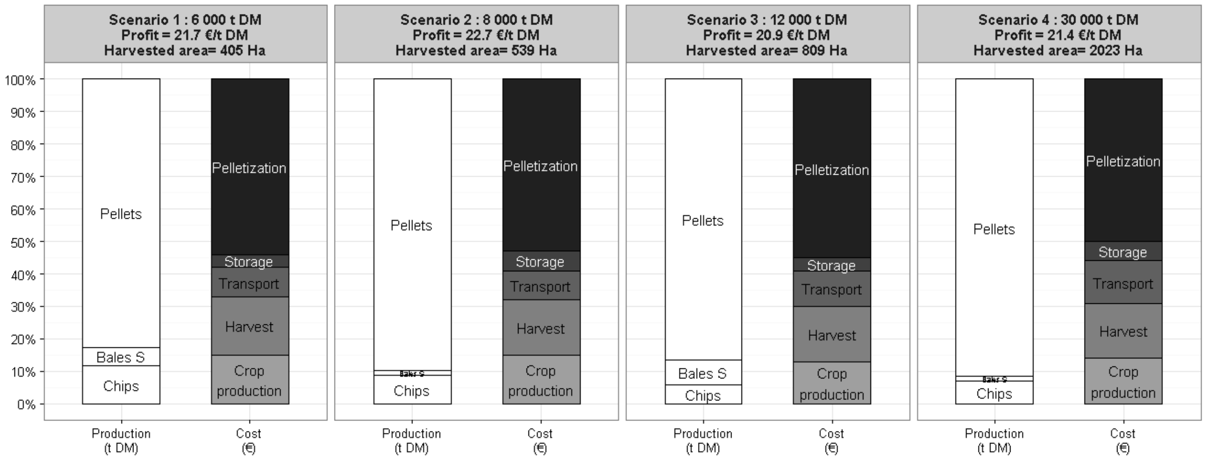

Figure 3 Relative share of the amount of each end-products sold and relative share of costs for each stage of the supply chains in Scenarios 1 to 4, when simulating an expansion in the annual biomass production from 6 000 to 30 000 t DM.

Figure 4 compares scenarios 1 to 4 based on the combined indicator results from the different sustainability assessment per ton of biomass dry matter stored at BP facility (prior to pelletization). For all 14 indicators, except supply costs and the MRIO multiplier effect, Scenario 1 produced the most preferred result, and hence was the reference against which other scenarios were normalised. For the remaining MRIO indicators, only Scenario 2 differed from the other scenarios. In addition, supply chain performance decreased with increasing biomass demand for all environmental impacts, as assessed by EmA and LCA. For supply costs and land use Scenario 3 was as preferable to Scenario 1 thanks to a higher relative share of bales, which require less storage.

The largest variations among the scenarios occurred with the EmA indicators, with scenario 1 differing strongly from the others due to a better performance concerning resource use. Increasing both biomass supply and collection area required extra inputs (i.e., more machinery, diesel and human labour) relative to the baseline scenarios, and this reduced the use of natural resources. In emergy terms, in fact, this means that the weight of the external inputs in the total emergy required by the system, is bigger than the weight of the natural resources. However, the fraction of emergy related to input of labour only made up around 1% of the total emergy flow for all scenarios so this variation was not so relevant when comparing scenarios each other.

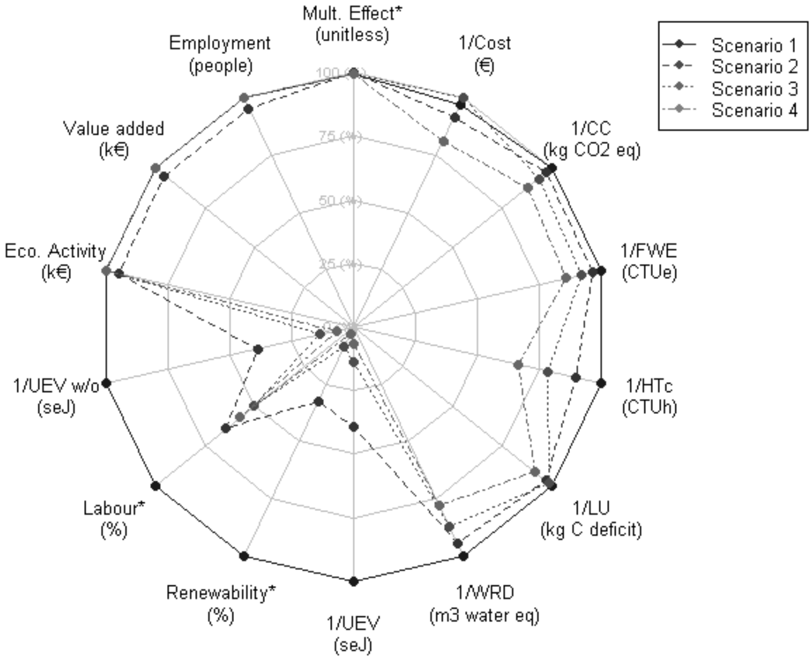

Figure 4 Spider diagram of Scenarios 1 to 4 displaying the value of indicators relative to their maximum value across the four scenarios. Some of the indicators were inverted so that large values be preferable. All impacts are calculated per t DM stored at the BP facility, except for those indicators with a ‘*’ symbol. For more details about the indicators see Table 4.

The MRIO indicators were very similar across all scenarios and only scenario 2 showed lower socio-economic performances. The multiplier effect amounted to 2.44 for scenarios 1, 3 and 4, and 2.45 for scenario 2. As explained before, the multiplier effect measures how the economy will be stimulated in response of the demand of goods and services by final consumers. When final consumers acquire 1 unit (measured in monetary terms) of the products provided by BP, the total economy will produce 2.4 units, dedicating 1 unit to the final consumer and 1.4 to the intermediate demands.

Through the MRIO, it is possible to identify the regions where the impacts will occur. This issue is of high importance when using the results for public investments or plans that aim at stimulating the national economies. For all impact categories, more than 70% of the total benefits were located in France. Concerning job creation, China would indirectly benefit from BP activities, keeping in the country 6% of the total employments generated by its activity. It is also possible to identify the activity sectors and the countries that will be most stimulated by the analysed system. The highest impacts are due to four activity sectors: “Electrical and Optical Equipment”, “Agriculture, Forestry and Fishing”, “Electricity, Gas and Water Supply” and “Inland Transport”, all located in France.

3.2. Integrated assessment of alternative yield, harvest and processing scenarios

In the assessed supply area (i.e. the baseline, Scenario 1), production and harvesting costs per unit of product increased as yield decreased (Figure 5, Scenario 5). This was due to the need for more land parcels for miscanthus cropping. Transportation costs also went up due to a different spatial distribution of fields in the feedstock scenarios, with slightly higher costs as more land parcels are needed and they tended to be more distant from the BP facility. Land rent was disregarded, but it is still worth noting that the profit per GJ remained positive even when crop yield was reduced substantially. Regarding the climate change impact, high yield appeared preferable: maximizing yields (Scenario 6) lead to an increase in profit and to a reduction in the impacts provided since it did not involve additional agricultural inputs.

Introducing the possibility of additional autumn harvesting (Scenario 7) led to increased production when collecting biomass from the same fields as in the baseline scenario, due to the higher yields per hectare obtained with this management (Figure 5). This came with additional costs due to the need for extra fertilizer inputs, but these costs did not undermine the increase in profit per GJ of biomass harvested. Moreover, autumn harvesting entailed a large reduction in storage costs, and even a slight reduction in transportation costs due to lower needs for handling at intermediate storages. Spreading the harvest over two periods would almost eliminate the need for costly storage at the municipality level, after the month of June. It also changed the distribution of the final products, making possible to exclude the sale of short bales, which was the least profitable option. This is inevitable in the baseline scenario due to storage limitations. Autumn harvesting can be considered as an economically viable alternative, especially if storage is a limiting factor and/or comes at considerable cost. However, including autumn harvest led to an increase in the climate change potential of biomass, due to the need for extra fertilizer inputs.

As shown in Figure 5, briquetting (Scenarios 8 to 10) reduced the total costs and drastically increased the profit of the supply chain. Looking closer at the various cost components (not shown), it appears that briquetting reduced the transport, but increased storage costs. As mobile briquetting occurs in intermediary storage, often located far from the BP facility, more bales had to be stored in farmsteads after the month of June. About 1/3, 2/3 and 3/3 of harvested crops were used to produce briquettes in Scenarios 8, 9 and 10 respectively. The profit results may be over-estimated since the cost of transporting the briquettes to the BP facility was not included due to the lack of specific data on this potential market. Profits also depended on the briquettes sales price, here assumed equal to the pellets price. This price may be over-estimated, but, nevertheless, briquetting can be seen as an interesting option. Determining whether briquetting should entirely substitute pellet production or remain more limited would require more detailed analysis taking into consideration the investment capacity of BP and the amortization of existing infrastructure through a capital budgeting analysis. The option of using mobile briquetting should be considered as an alternative to a central pellet production facility, at least for areas without an existing pelletization facility. Mobile briquetting appears a viable economic alternative, especially in situations with a considerable scattering of the crop production and expensive transportation logistics as in this case study. Including briquetting at intermediate storage points appeared an environmental-friendly option to meet an expanding demand of biomass. The most environmental-friendly briquetting option is the one presented in scenario 10, featuring the largest throughput of the briquetting press, followed by those considered in scenarios 9 and 8 (with smaller throughput). Unlike other end-products, increasing briquette production reduces the impact per GJ, thanks to the economy of scale for machinery and its transport from one storage point to another.

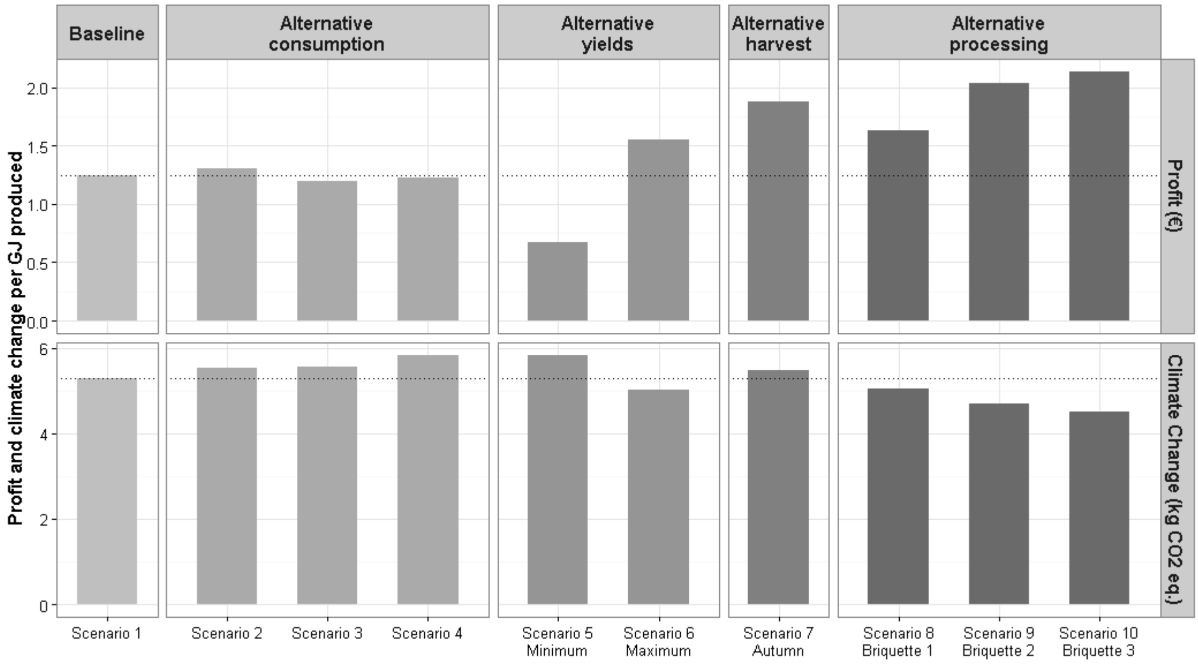

Figure 5 Profit and climate change potential per GJ produced in each scenario, including the pellet processing. Dotted line corresponds to baseline

4. Discussion

4.1. Limited economies of scales

The economical optimization of the BP supply chains indicates that revenue outweighs costs for all scales, ranging from 6 000 t DM to 30 000 t DM per annum and corresponding to an increasing collection area from around 400 ha to 2 000 ha. By considering the assumptions on prices and costs, chips, bales, pellets and briquettes all contributed to a positive margin of the whole supply chain. Land rent was disregarded, while costs were estimated based on what was assumed as necessary costs within each scenario, and not on the actual expenses for the BP facility.

Increasing the annual biomass supply from 6 000 t DM to 30 000 t DM yielded economies of scale with respect to the processing at the BP facility (i.e. pelletization). However, although the cost of processing pellets decreased as the scale of operations increased, both transportation and storage costs increased correspondingly. These effects balanced out so that the profit per ton remained approximately constant, at 20 € per t DM. Regarding environmental impacts, the scenario with the lowest feedstock supply has the lowest impacts, whether expressed per t DM or per GJ at BP facility and whether including or not the pelletization process. This is due to the trade-off between the increased impacts of the transportation stage and the economies of scale in the processing facility, which applied costs as well as environmental impacts. The contribution of biomass transportation to the environmental impacts became so large it could not be offset by the savings incurred in the biomass processing phase. Such discrepancy between the optimum size of biomass supply chain from the economic and environmental standpoints has also been observed [37]. In this study, this phenomenon is mainly due to the specific spatial distribution of the miscanthus fields. Similar to perennial biomass crops in general, miscanthus focuses the attention of the scientific and environmentalist communities since they represent a good trade-off between productivity, input level and adaptability to marginal lands. Their cultivation is then promoted on the basis that these crops can produce energy with a low impact on food production and on the environment, when established on marginal lands where food production is less effective [38]. Thus, the advantage of miscanthus appears to lie in its ability to be grown on marginal lands. The definition of "marginal land" is relative on each specific context and territory and it generally amounts to the less productive and accessible fields [39]. The second factor that explains the scattered spatial pattern of miscanthus production lies in the fact that the area cropped to miscanthus on each farm is quite limited (making up around 2.5% of the farm area). The financial risks are still too high due to the fact that the energy market is not mature yet (see section 4.4.). Miscanthus production is then distributed among several farmers, each of them having a limited area of their farm planted to this crop, and mostly on the fields they consider marginal within their farmland [29]. Therefore, miscanthus is not systematically concentrated in lands that can be described as marginal regarding the whole supply area but also marginal regarding each farmland. In total, this induces scattered spatial distribution patterns for miscanthus fields in the supply area.

This study concludes that it would have been beneficial from economic and environmental stand points that miscanthus fields be less scattered overall. This pattern seems to stem from the high risk that farmers associate with growing miscanthus given that markets are currently uncertain. Assuming these markets would be more mature in the near future due to bioenergy development, it would be interesting to revisit this conclusion from the point of view of the food versus fuel competition, which may also warrant a scattered spatial distribution to prevent miscanthus from infringing on food crops. Considering that the spatial location optimization of miscanthus fields based on economic and environmental indicators might offset other benefits of this crop, one solution could be to limit the size of the transformation facilities or to develop intermediate densification options as illustrated by the mobile briquetting scenarios.

4.2. Rethinking the densification options

Optimization by maximizing profit resulted most feedstock being harvested as bales, pelletized, and sold at a high price, similarly to other case-studies [40]. About 80-90% of the feedstock was converted to pellets, which decreased transport and storage costs since pellets are denser than bulk chips or bales. Chips quantity was also constrained by limited storage capacities. However, the modelling showed that increasing storage capacity would increase the amount of chips produced and improve the company's profit. Despite their low density, chips emerged as another option to improve logistics through reduced harvesting costs, providing a relatively short transportation distance to the facility.

Processing biomass throughout the year requires substantial storage capacity, whether for bales, chips or pellets. Miscanthus, in fact, is traditionally harvested within a single, narrow time window (in March and April) and this entails costs for dedicated storage facilities, which will inevitably tend to be high. Despite this, chips seem to have a further potential and the increasing storage capacity at BP facility appears to be beneficial since, in general, more feedstock can be transported directly to the facility, avoiding intermediate storage and additional handling. At the same time, relying on storage facilities at farms that are otherwise idle represent a favourable utilization of local resources. This also holds for the use of farmers' own machinery to handle the biomass, at times (*e.g.* in winter) when it is under-utilized. The drawback is that the use of small scale storages and the use of farmer's machinery increase the number of handling operations and it tends to be rather expensive and less efficient compared to a more "streamlined" supply chain with a centralized storage and dedicated machinery.

Mobile briquetting is currently unavailable at BP and, .as previously described, both cost and price assumptions are uncertain. Still, mobile briquetting appears to be a viable economic alternative, especially in situations with a considerable scattering of the miscanthus fields and expensive transportation logistics.

4.3. The importance of crop yields

Crop production and harvesting costs are inversely related to biomass yields as already underlined in many studies [41, 42]. For a given quantity of miscanthus, a yield reduction will increase these costs due to the need for more area to produce it, while a yield increment will reduce the same costs. Reduced yields will also typically slightly increase transportation costs, as feedstock has to be collected over a wider supply area to obtain the same biomass output but the calculated profit per GJ remained positive, even when yields were reduced quite substantially. As often found [43], the environmental impacts per GJ of biomass delivered at the BP facility decreased with increasing yield. In general, increasing yields per unit area through more input-intensive agricultural practices comes at the cost of higher environmental burdens on ecosystems locally, but reduces the land footprint of biomass. Therefore, there is a trade-off between land-use and environmental impacts per unit area, especially when the latter may exceed acceptable limits (e.g., through water pollution). It often implies that the total impact on the environment increases and this may contribute to create unacceptable burdens to the environment. However, since whatever the management scenarios, the use of inputs in the management of miscanthus is lower than in other arable crops [44, 45] and the indicators calculated in the case studies on a hectare basis may help address this potential trade-off.

Introducing the possibility of additional autumn harvesting increased the profitability of the supply chain. Furthermore, BP could seek a second crop to process that could be harvested in-between the winter and autumn miscanthus harvesting to further reduce storage and handling costs. However, this option was not addressed nor elaborated in this study.

4.4. Lessons learned from applying the integrated assessment

The strong relationship observed between environmental performance and the biomass collection area may be considered as a general tendency. However, it is unclear to which extent it was influenced by the economic optimization and the assumptions about market demand for each product. When scaling up biomass supply, limiting the share of chips and bales in favor of pellets was favorable from the economic point of view because pellets were more profitable overall. However, the conclusion on environmental performance was not so clear-cut because all scenarios involved a similar volume of chips with close characteristics in terms of collection area. On the contrary, expanding the production of both bales and pellets lead to an increase in transport and storage needs, resulting in lower performances per t DM. Overall, under our assumptions, the potential economies of scale generated by increaing the biomass supply volume and hence its collection area were outweighed by the extra transportation and storage incurred. When ramping up production, care should be therefore taken to ensure that increased transportation costs will not dominate over the reduced production cost at the facility.

The results of the economic optimization for the different scenarios, indicating a positive economic result, are based on specific assumptions about market prices for energy products supplied by BP. Markets for woody pellets have expanded in France in the latest years and prices above 150 $ per ton for industrial pellets have been reported for 2015 [46].· These assessments are partly at odds with the current focus of BP on non-energy markets and the downscaling of its processing operation due to insufficient sales. It seems that markets for miscanthus chips and pellets, as well as bales for energy production, are immature and need to be secured.

The environmental performance of supply chains lead to conclusions similar to those of the economic analysis, since reduced costs is related to lower resource consumptions and thus lower impacts. However, at supply chain level, while the sales made it possible to maintain the profit, the environmental impact per ton of miscanthus produced increased with increasing biomass supply regardless of the functional unit (ton DM or GJ). This confirms that transportation distance is a key issue in the sustainability of biomass supply chains, and that local sourcing should be favored. In case biomass is not available locally, low-cost densification options such as decentralized briquetting emerge as the optimal choice.

The framework proposed in this study is intended as a set of instruments aiding to navigate the potential complexities of supply chain design, and providing quantitative examples of the consequences of agronomic or technological choices. It is not a decision-support system per se, not having been packaged into a user-friendly software or modeling system. It is far from offering all the modeling options that would be required by users (e.g. bioenergy project developers). Still, it may be applied to new supply chains, pending the provision of detailed information for the various steps of the supply chains, and for the yield potentials of energy crops. Elaborating a database with both accurate and comprehensive information on these supply chains is therefore the first step to take in the assessment, and probably the most crucial one. The common database put together for the BP case-study provides a good template for such purpose, along with subsets of data, which may be considered generic. The methods themselves rely for some on commonly-used software packages or databases, which may readily be put to use in new case studies.

5. Conclusions

The economical optimization of the BP supply chain, indicates that revenues from the sale of end-products outweigh costs for all levels of production, ranging from 6 000 t DM to 30 000 t DM annually. However, it assumed the market for end-products could be expanded, which does not reflect the current state of the biomass crop sector in the region where BP operates. Farmers were advised to be careful and limit the number of miscanthus fields, as uncertainty in sales and immature markets has appeared to be an issue. However, considering current practices, expanding biomass supply lead to higher environmental impacts per ton produced. The transportation distance remains the key issue in this outcome. In the context of biomass energy crops being grown in marginal lands, expanding the demand inevitably leads to more scattered plots and thus longer transport distances. Mobile briquetting appeared as a viable economic alternative, which reduces the environmental impact at supply chain scale. A more secure biomass energy market could allow such investment. Secondly, there appeared a trade-off between land-use and environmental impacts per unit area. Higher yields would allow lower impacts per unit of energy produced, assuming it does not involve the use of additional agricultural inputs. In the context of competition for land between food and energy production, the question of intensifying energy crops should be revisited: can the slight increase of climate change impact, associated with autumn harvesting be considered ‘acceptable’ to allow more biomass production on a limited land area? Including other uses of land (food crops, protected zones) and their interplay with biomass production in supply expansion scenarios would make it possible to consider these trade-offs. By tackling important challenges, such as collecting high quality data to analyze, the various components of the supply chain, coupling complexes modeling and integrating sustainability indicators into a common framework, this study provides benchmarks for innovative biomass supply chains. Models and dataset are available on demand to design and improve other supply chains. Moreover, being based on commonly recognized methods the developed sustainability accounting framework, it could be replicated and serve as a reference for further studies aiming at improving the sustainability of biomass supply chains.

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