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Agro-energy supply chain planning: a procedure to evaluate economic, energy and environmental sustainability

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Abstract

The increasing demand for energy and expected shortage in the medium term, solicit innovative energy strategies to fulfill the increasing gap between demand-supply. For this purpose it is important to evaluate the potential supply of the energy crops and finding the areas of EU where it is most convenient. This paper proposes an agro-energy supply chain approach to planning the biofuel supply chain at a regional level. The proposed methodology is the result of an interdisciplinary team work and is aimed to evaluate the potential supply of land for the energy production and the efficiency of the processing plants considering simultaneously economic, energy and environmental targets. The crop simulation, on the basis of this approach, takes into account environmental and agricultural variables (soil, climate, crop, agronomic technique) that affect yields, energy and economic costs of the agricultural phase. The use of the Dijkstra's algorithm allows minimizing the biomass transport path from farm to collecting points and the processing plant, to reduce both the transport cost and the energy consumption. Finally, a global sustainability index (ACSI, Agro-energy Chain Sustainability Index) is computed combining economic, energy and environmental aspects to evaluate the sustainability of the Agro-energy supply chain (AESC) on the territory. The empirical part consists in a pilot study applied to the whole plain of Friuli Venezia Giulia (FVG) a region situated in the North-Eastern part of Italy covering about 161,300 ha. The simulation has been applied to the maize cultivation using three different technologies (different levels of irrigation and nitrogen fertilization: low, medium and high input). The higher input technologies allow to achieve higher crop yields, but affect negatively both the economic and energy balances. Low input levels provides, on the average, the most favourable energy and economic balances. ACSI indicates that low inputs levels ensure a more widespread sustainability of the agro-energy chain in the region. High ACSI values for high input levels are observed only for areas with very high yields or near the processing plant.

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Introduction

The increasing demand for energy and expected shortage in the long term, solicit new energy strategies to fill the increasing demand-supply gap (European Commission, 2009; Tenerelli and Carver, 2012). European Commission intends to implement these strategies in a contest where the environmental and social goals are considered as well. A sustainable strategy must be addressed to achieve these three main goals: i) guarantee the security of the energy market; ii) minimize the environmental impact; iii) avoid the social consequences of energy shortage (United Nations, 1987). The biomass produced from the agriculture sector represents a potential renewable source of carbon-neutral material for the production of bioenergy (Ragauskas *et al*., 2006). The current debate on the sustainability of energy crops is focused on some controversial points: competition with food and fodder crops for fertile lands (Cassman and Liska, 2007), with other human activities for water resources (Service, 2009) and their effects on the direct and indirect land use change (Fargione *et al*., 2008; Searchinger *et al*., 2008; Di Lucia *et al*., 2012). Hence, it is important to evaluate the potential supply of the energy crops cultivated in some dedicated areas of the EU territory; this will require to evaluate the appropriate crops with the best energy performance (to maximize net energy yield), the environmental conditions to achieve the best performance of the land use (soil, fertility, water supply, climate, crop rotation, etc.), the compatibility among food, fuel and social acceptance goal. The intensification of agriculture production could lead to severe consequences such as soil erosion and compaction, nutrient leaching, pesticide spreading and biodiversity loss. These considerations suggest to adopt the crop biomass production strategy, following an integrated agro-energy supply chain (AESC) approach that will solve simultaneously the economic, energy and environmental balances (Pimentel, 2003; WWI, 2006; Muller, 2008). This drives to a network approach that will integrate the activities of agents operating at different levels of the AESC: producers, processors and consumers, sequentially connected by the complementarity of the chain operations (Boehlje *et al*., 2003; Christopher, 2005; Rosa, 2008; Sexton *et al*., 2009). The AESC management requires to analyze the problems inherent production, processing, logistics (harvesting, transport and storage), marketing and channel diversifications, and the most efficient organization in order to coordinate the vertical integration and impose the hierarchical decisions to the member (Menard and Valceschini, 2005), in an environment characterized by the asymmetric distribution of information among partners and contingent risks caused by production and markets (Epperson and Estes, 1999). For this purposes, the spatial distribution of biomass and supply must be compatible with the demand and costs (production, processing, transport and distribution) (Grassano *et al*., 2011; Tenerelli and Carver, 2012). This paper proposes an integrated and interdisciplinary approach to planning the biofuel supply chain at a regional level aimed to evaluate the potential use of the land for the energy production and side effects, to supply the existing processing plants and accomplish with the economic, energy and environmental targets. The problem of biomass allocation is dealt by integrating the territorial and climatic information in a crop simulation model (*MiniCSS*; Rocca and Danuso, 2011). The approach is based on the simulation of agricultural and environmental variables affecting crop yields, production technologies and related costs. Moreover, this methodology uses an optimized product flows from the farm to collecting points and processing plants and evaluates the risk caused by price volatility. At first, the dynamic crop simulation takes into account the climate variability; in later stages the results are used in a routine to optimize transports along the existing road network. Finally, the procedure produces for the whole biofuel chain a global suitability index. This index combines economic, energy and environmental results to evaluate the sustainability of bioenergy crops on the territory. The purposes of this research are: i) to analyze the effects of the interaction between pedo-climatic events, affecting the variability of crop yields and their energy balance; ii) to optimize the biomass hauling from field to collecting points and processing plants, with maximization of the return by assuming a cooperative organization; iii) to optimize the performance of the AESC by considering simultaneously the economic, energy and environmental balance.

Materials and methods

The agro-energy chain is composed by the rural territory, the collecting points, the processing plants and the roads connecting all these points. Biomass is produced in farm parcels, transported and stored in intermediate collecting centres and transformed in biofuel by processing plants. At first, the procedure requires the definition of the production system with pedo-climatic description. The choice of the crop and related agricultural technique is addressed to make a crop growth simulation in specific areas of the territory (Figure 1). The analysis of the road graph detects the minimum paths between the parcels and the conversion plants, in order to optimize the biomass transport from farm to collecting points and to processing plant. In the conversion phase the economic value of biofuel and co-products and their costs are calculated; it is also estimated the energy balance. Finally the economic, energy and environmental balance of the AESC are calculated and used to elaborate a composite index of the crop sustainability of the territory (ACSI, Agro-energy Chain Sustainability Index, explained in detail later). This procedure takes into account five sources of variability: soil characteristics and availability, climate, road network, agricultural techniques and crop. The first three factors are site-specific for the territory and are a part of variability that is to be considered, but independent from the farmer choices. The latter two are the variability sources directly controllable by agronomic choices and so are optimizable.

Study area

The procedure was applied to a study area represented by the whole plain of the Friuli Venezia Giulia (FVG) region, North-Eastern Italy (Figure 2). It consists of about 295,000 parcels of arable land, for a total area of about 161,300 ha. The spatial position of the parcels was defined using the geo-referenced database of the regional census of agricultural activities performed in 2009 with a map scale 1:2000 provided from Friuli Venezia Giulia Region. The parcels were classified in 140 homogeneous classes, according to their pedological and climatic conditions. The vectorial method has been used to represent all spatial information in this paper.

Pedo-climatic classification

Pedological and climatic conditions play an important role in agricultural activities, substantially determining crop yields. The soil classification was made considering texture, permeability, cation exchange capacity and the available water content (Figure 3, left panels). These data were obtained from thematic maps provided by the Regional

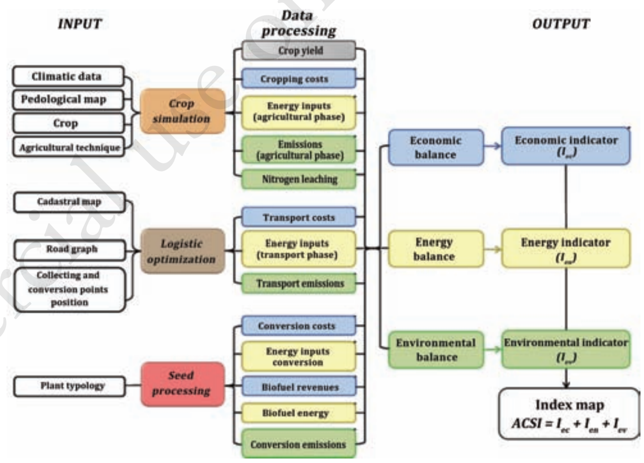

Figure 1. Procedure framework (inputs, data processing and outputs).

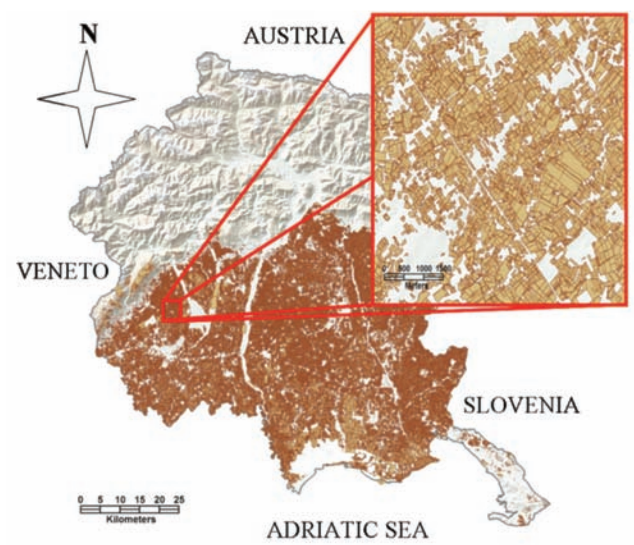

Figure 2. Cadastral map of the study area.

Agency for Rural Development (ERSA). Each map, in turn, classifies the specific variable into three classes. The combinations of these spatial information resulted in 22 soil types came out of the 81 potentially possible combinations (Table 1).

The meteorological data for 17 meteo stations were provided by OSMER FVG (OSservatorio MEteorologico Regionale). From these historical data and for each meteorological station, the climatic parameters for the weather generator *Climak 3* (Danuso, 2002; Rocca *et al*., 2012) were estimated and used to generate series of 100 years. Generated meteo data were then spatialized using the Voronoi method, associating to each parcel the meteo data of the nearest station (Figure 3, right panel). The historical and generated meteorological series con-

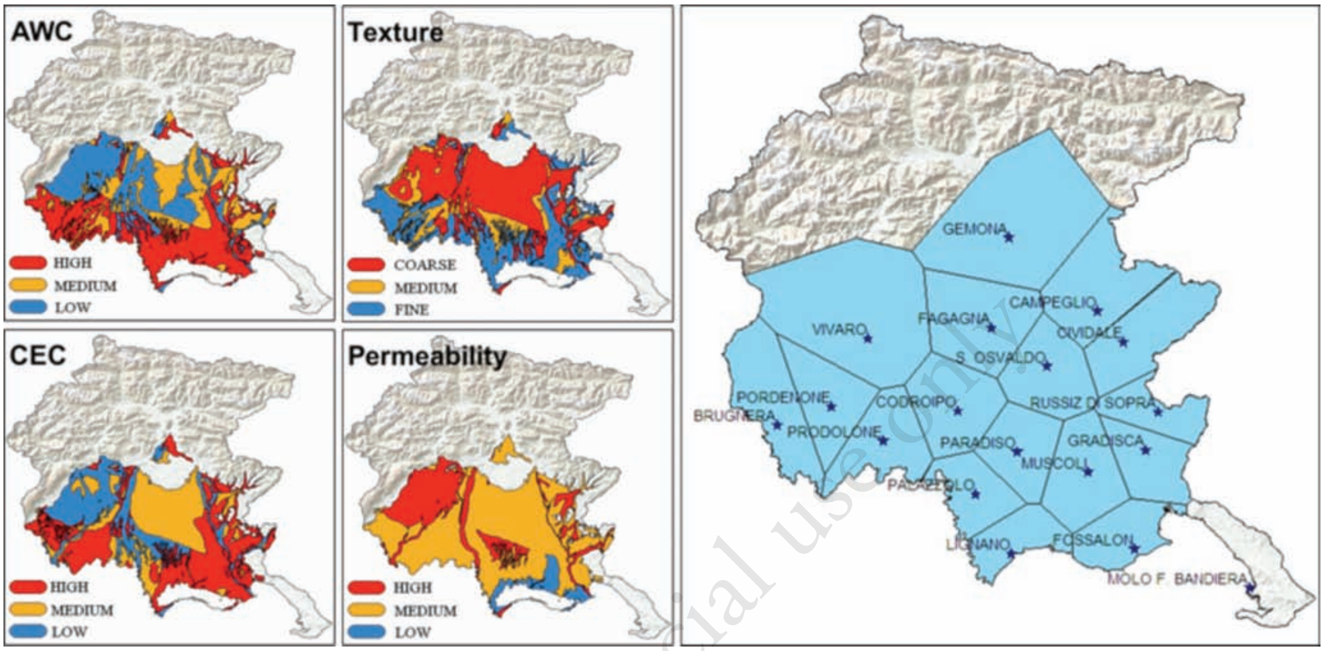

Figure 3. Thematic maps of soil features (on the left): available water content (AWC), cation exchange capacity (CEC), texture and permeability. On the right, Voronoi spatialization of the meteorological series.

Table 1. Soil types in the study area and their features, classified using the available soil traits.

Soil code	Number of parcels	Total area (ha)	Available water content	Cation exchange capacity	Texture	Permeability
S1	16,018	5991	Low	Low	Medium	High
S2	15,725	7597	Low	Low	Coarse	Medium
S3	21,018	10,335	Low	Low	Coarse	High
S4	382	144	Low	Medium	Medium	Medium
S5	45,955	19,441	Low	Medium	Coarse	Medium
S6	3815	3850	Low	Medium	Coarse	High
S7	7137	4404	Medium	Low	Medium	High
S8	1978	1315	Medium	Low	Coarse	High
S9	810	888	Medium	Medium	Medium	Medium
S10	45,031	19,341	Medium	Medium	Coarse	Medium
S11	6836	3046	Medium	Medium	Coarse	High
S12	2561	1273	Medium	High	Fine	Medium
S13	16,647	9575	Medium	High	Medium	Medium
S14	8048	3774	Medium	High	Coarse	Medium
S15	1565	498	Medium	High	Coarse	High
S16	4828	2471	High	Low	Medium	High
S17	22,998	13,365	High	Medium	Fine	Medium
S18	993	644	High	Medium	Medium	Medium
S19	9781	13,485	High	High	Fine	Low
S20	51,819	31,380	High	High	Fine	Medium
S21	8426	4498	High	High	Medium	Medium
S22	2808	3973	High	High	Coarse	Medium

sist of daily records of rainfall, solar radiation, minimum and maximum air temperature and reference evapotranspiration.

Generated meteo series of 100 years allow to completely propagate the effect of climatic variability to the simulated crop production.

The combination between soil types (22) and climate conditions (17) produced 140 pedo-climatic typologies. A spatial query assigned to each parcel a specific soil-weather combination.

Crop simulation

Crop simulations for each parcel were performed using the model *MiniCSS*. This is a generic, daily step, dynamic crop simulation model, able to perform annual or multi-annual simulation. *MiniCSS* has a modular structure; each module represents a different part of the cropping system. The phenological and crop growth module simulates the development based on Growing Degree Days (GDD). This module also simulates biomass accumulation and crop yield using the radiation use efficiency approach. The model considers the reduction of the potential rate of growth due to the presence of stress conditions (non-optimal temperature, water shortage and lack of nitrogen). The module for soil dynamics carries out, with a mono-layer cascade approach, the simulation of soil water content considering maximum and actual evapotranspiration, runoff, infiltration, percolation and drainage into groundwater. The soil water reserve increases with rainfall and irrigation. Furthermore, it simulates the dynamics of soil organic matter with an implementation of the *RothC* model (Coleman and Jenkinson, 2008) and the nitrogen dynamics of soil, considering the fractions of nitrogen as nitrate and ammonium. The NH_4^+ concentration in the soil can increase due to the mineralization of organic matter or to nitrogen fertilization. The management module generates the cropping practices (sowing, irrigation and fertilization) as events, using an internal decisional strategy. The economy module simulates the crop economic accounting, assuming all the inputs; capital (seed, fertilizer, pesticide, fuel and machinery) and labor are supplied in outsourcing, allowing to explicit all components of production cost. The energy module estimates the energy balance considering both direct and indirect energy inputs required for each agricultural practice. It uses an LCA (Life Cycle Assessment) approach (Brentrup *et al*., 2001; 2004) and the parameter for the energy accounting are derived from the Ecoinvent database 2.1 (Nemecek and Kägi, 2007). *MiniCSS* has been calibrated and validated for different energy crops and for the soil water and nitrogen dynamics (Rocca and Danuso, 2011; Rocca *et al*., 2011).

The simulation requires, as inputs, the following information:

- soil parameters and generated weather data derived from previous land classification;
- crop parameters: to test the procedure those of maize crop were chosen;
- agricultural technique: three input levels were imposed by modifying the maximum water stress tolerated by the crop and the level of nitrogen fertilization (Table 2).

One hundred simulations per parcel were performed, one for each year of the generated weather series. The model outputs taken into account were the mean of the crop yield (*CY*, $t \cdot ha^{-1}$ of grain with 14% moisture content), the agronomic costs (*AC*, $€ \cdot ha^{-1}$) and the energy inputs required in the agricultural phase (*AE*, $GJ \cdot ha^{-1}$).

Biomass transport optimization

The transport optimization problem is addressed to search for the shortest way to carry out the biomass from the field (each parcel of arable land on the territory) to the processing plant. It is important to underline that, due to the small sizes of the fields in the study area, it is strategically important to collect all the products in specific intermediate collecting points. This ensures reduced transport costs for the farmers and an increase of their bargaining power in the supply chain. Therefore, biomass transport includes two steps: the first one, from the field to the collecting point, is covered by using the farm trailer pulled by the tractor; the second step from the collecting point to the processing plant, is carried out with truck (assuming the weight more than 32 t). For this study, 53 collecting points (Figure 4), already operative in the study area, were considered. Economic costs and energy input were calculated, separately, for both transport phases; their values were then referred per hectare for each single parcel.

The application of the Dijkstra's algorithm (Dijkstra, 1959) to the road graph (regional technical map of FVG - scale 1:5000) allows to minimize both the paths of the two transport steps (Figure 4). The road graph has excluded the highways because their access is forbidden to the considered means of transport (*e.g.* tractor) or too expensive for the length of hauling. The transport costs (*TC*, $€ \cdot ha^{-1}$) were calculated according to the market prices and in relation to the road distance (Km). The energy consumption during the transport phases (*TE*, $GJ \cdot ha^{-1}$) was calculated using coefficients of energy consumption estimated by the software *SimaPro* v7.2.4 on the basis of Ecoinvent database 2.1 (Nemecek and Kägi, 2007).

Processing phase

For the purpose of the AESC it was considered the maize trans-

Table 2. Agronomic treatments as considered in the maize crop simulations.

	Input level		
	High	Medium	Low
Tolerated water stress (% of easily available water)°	20	50	80
Total amount of N fertilization (kg ha^{-1})	300	175	75
Number of N fertilizer application	3	2	1

°A tolerated water stress of 50% means that automatic irrigation starts only when the 50% of the easily available water has been depleted. For example, in a soil type S1 (see Table 1) in the area of Codroipo, the seasonal amount of irrigation water applied, considering a water tolerated stress of the 50%, is roughly 110 mm.

Figure 4. Collecting points (small circles), processing plant (big circle), road network (continuous lines) and biomass collecting areas on the study area.

formed into ethanol using a dry-mill plant and the DDGS (Dried Distillers Grains with Solubles) process. The biofuel yield (BY, L · ha^{-1}) obtained from a single parcel is determined from the crop yield (CY) and calculated as:

$$BY = CY \times Kb$$

where Kb is the crop yield to biofuel conversion coefficient (398 L · t^{-1}).

Processing costs (CC, € · ha-1) were calculated proportionally to the total biofuel production of the parcel, using the yield previously determined with simulation, and referred per hectare (Table 3, according Siemons *et al*., 2004). The co-product value ($CopV$, € · ha^{-1}) was estimated assuming a profit from DDGS sale of 0.15 € · L^{-1} of biofuel (Siemons *et al*., 2004) and referred to the hectare. The energy outputs from biomass processing include the fuel energy of the produced biofuel and the energy equivalent values for co-products that are typically used for aims different from energy commodities. The energy inputs are the energy costs of the conversion of crop to biofuel. The energy content of the produced biofuel (BE, GJ · ha^{-1}) was estimated using the coefficients proposed in the review of Hill *et al*. (2006) (Table 3). Other coefficients from the same paper were used to calculate the energy required to convert corn into biofuel and to assign co-product credits ($CopE$, GJ · ha^{-1}) as follows. For DDGS it was used an *economic displacement* concept using which it was calculated the energy required to generate the products for which DDGS serve as a substitute in the marketplace.

Agro-energy chain sustainability index

The proposed index combines economic, energy and environmental aspects useful to determine the sustainability of bioenergy crop supply chain. The ACSI was defined as:

$$ACSI = w_{ec}\, I_{ec} + w_{en}\, I_{en} + w_{ev}\, I_{ev}$$

where:
I_{ec} economic indicator (0-1)
I_{en} energy indicator (0-1)
I_{ev} environmental indicator (0-1)

w_{ec}, w_{en}, w_{ev} are the weights of each indicator that take values between 0 and 1 and their sum is one. The assignment of the weights should be decided by decision makers, according to the goals they want to achieve or can be subjected to a negotiation among the stakeholders. There is also the opportunity of not considering some aspects of the proposed index giving a weight equal to zero to the corresponding indicator.

The values of the economic indicator (I_{ec}) were obtained from min-max normalization of the threshold prices (TP, € · L^{-1}), calculated for each parcel. Threshold price is the sale price of the biofuel (without taxes) that allows to balance chain costs and revenues:

$$TP = ChC \mid BY$$

where ChC is the chain cost (€ · ha^{-1}). All the elements that compose chain cost are explicated in the formula:

$$ChC = AC + TC + CC + CopV$$

Therefore I_{ec} takes into account costs and revenues of the phases of production, transport and conversion of the biomass (revenues from the sale of biofuel). The normalization of the threshold prices considers, at the same time, the values for all the three agricultural techniques. It also takes into account the value direction assigning the minimum score to the largest values of the threshold price and the maximum score to the smallest one. Smallest thresholds are indeed indicative of greater suitability. Energy sustainability indicator I_{en} derives from the normalization of the energy chain balance (EnB, GJ · ha^{-1}) for each parcel. Also in this case, the normalization was obtained with min-max method considering jointly the values for the three agricultural techniques. In this case, greatest indicator values are associated to greatest values of energy balance which represent the more sustainable situations. Chain energy balance was defined as:

$$EnB = BE + CopE - AE - TE - CE$$

In the procedure it was attempted to represent the complexity of the agro-energy system as much as possible. However, at present, it does not consider environmental aspects (emissions) and I_{ev} indicator is not calculated yet. Therefore, for economic and energy indicators the assigned weight was the same (0.5) in order to give them the same importance. To verify that indicators have the same influence on the composite index the F-test between their variances was performed (Nardo *et al*., 2005).

Table 3. Coefficients used to calculate revenues, costs, energy inputs and outputs of the maize processing phase.

Coefficient	Unit	Value	Source
Coproduct value	€ · L^{-1} biofuel	0.15	Siemons *et al*., 2004
Conversion costs	€ · L^{-1} biofuel	0.28	Siemons *et al*., 2004
Energy content biofuel	GJ · L^{-1} biofuel	21.26	Hill *et al*., 2006
Coproduct credit	GJ · L^{-1} biofuel	4.31	Hill *et al*., 2006
Conversion energy	GJ · L^{-1} biofuel	12.73	Hill *et al*., 2006

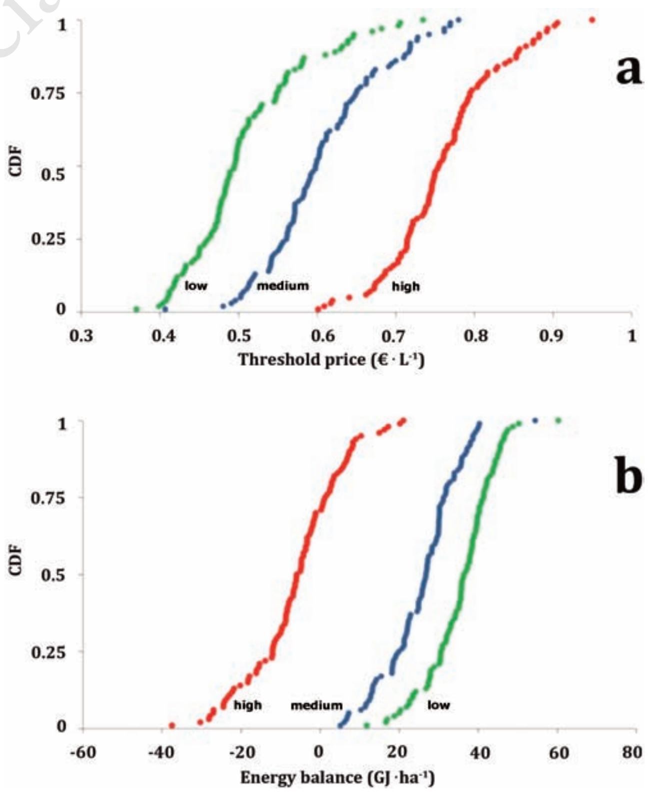

Figure 5. Variability of the maize crop simulations in a single parcel with three input levels (high, medium and low). Empirical cumulative distribution functions (CDF) are shown for the simulated threshold prices (a) and the energy chain balances (b). The crop simulations, for all the input levels, are performed using the same one hundred years generated weather series.

Results and discussion

The effects of the climatic variability on the productions and consequently on the threshold price and on the energy chain balance are shown for three input levels in Figure 5. The simulations were made on a single parcel with defined pedological and climatic features. Each curve represents the empirical cumulative distribution function of the values of 100 simulations for different annual climatic conditions.

The low input agricultural technique allows to obtain more favourable threshold prices and energy balances in comparison with other input levels. At the same threshold price, the low input curve shows the largest number of simulations (years) under this value. Assuming the final price of the biofuel without taxes equal to 0.70 €·L^{-1}, almost the 100% of the low input simulations generate a threshold price less lower than this value; with the medium input the value decreases to the 90% and with high input technique below the 20%. With the lowest input technique the cumulative function for energy balance shows the highest value.

The crop yields, threshold prices and energy chain balances for the study area are shown in Figure 6. The statistics for the same variables and for the three agricultural theses are presented in Table 4. The high input levels ensure the maximum crop yields everywhere, but negatively influence the agronomic costs and, consequently, the threshold prices, making them less convenient. They also require the highest energy consumption leading to the lowest energy balance per hectare. The dispersion of the values of threshold price and energy balance extends increasing input level.

The spatial distributions of I_{ec}, I_{en} and ACSI are shown in Figure 7 and the relative statistics in Table 5. *F*-test between the indicator variances did not detect significant differences at 0.05 P-level so, they have the same influence on the composite index, assuming their equal

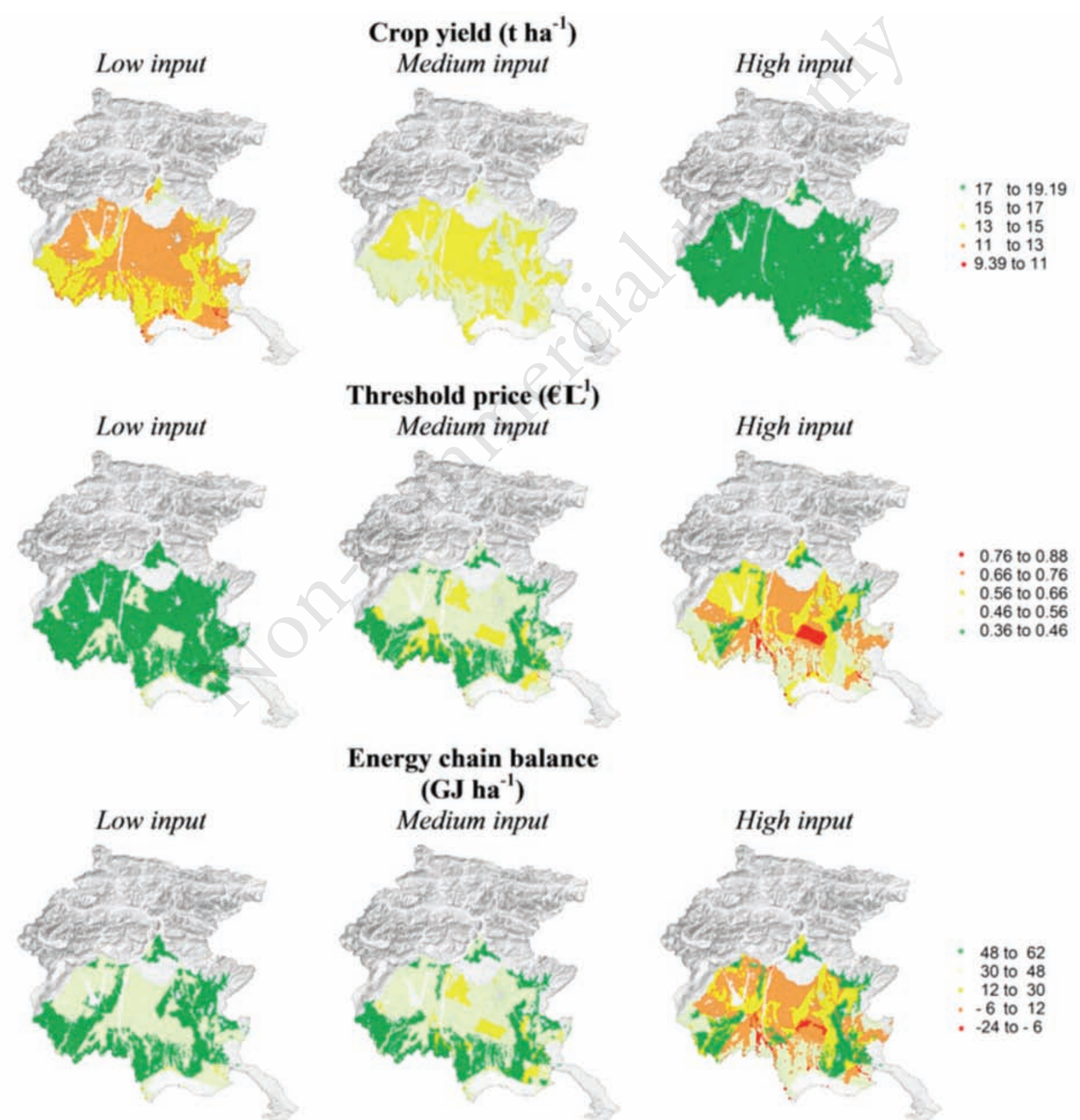

Figure 6. Spatial distribution of the simulated maize yield, relative threshold price and energy chain balance.

weight. The indicators and the composite index take greater values for low input levels. The dispersion of the values of I_{ec}, I_{en} and ACSI is larger for the highest levels of treatment. The total area in which indicators and the final sustainability index have more favourable values, close to one, increases progressively proceeding from high to low input. High ACSI values for high input levels are observed for areas with very high yields or near the processing plant. ACSI indicates that for the FVG region low inputs levels ensure widespread agro-energy chain sustainability.

Conclusions

The results of this pilot study in Friuli Venezia Giulia Region suggest that the chain performance greatly depends on the biofuel final prices that affect the producer decisions to cultivate maize and this will determine the quantity of product that is related to scale economies in production, transport and processing. Low input maize management techniques let to reach a widespread sustainability in all the FVG in economic and energy terms.

Table 4. Results for the simulated maize yield, relative threshold price and energy chain balance for three input levels.

	Low input				Medium input				High input			
	Min	Max	Mean	CV %	Min	Max	Mean	CV %	Min	Max	Mean	CV %
Crop yield (t ha^{-1})	9.39	15.35	12.73	7.70	12.74	16.78	15.03	4.78	16.18	19.19	18.07	3.13
Threshold price (€· L^{-1})	0.36	0.62	0.43	8.30	0.39	0.74	0.51	11.66	0.43	0.88	0.62	15.07
Energy chain balance (GJ ha^{-1})	22.27	62.49	46.86	13.70	9.06	61.66	41.05	24.13	-24.29	57.44	21.05	91.15

CV, coefficient of variation.

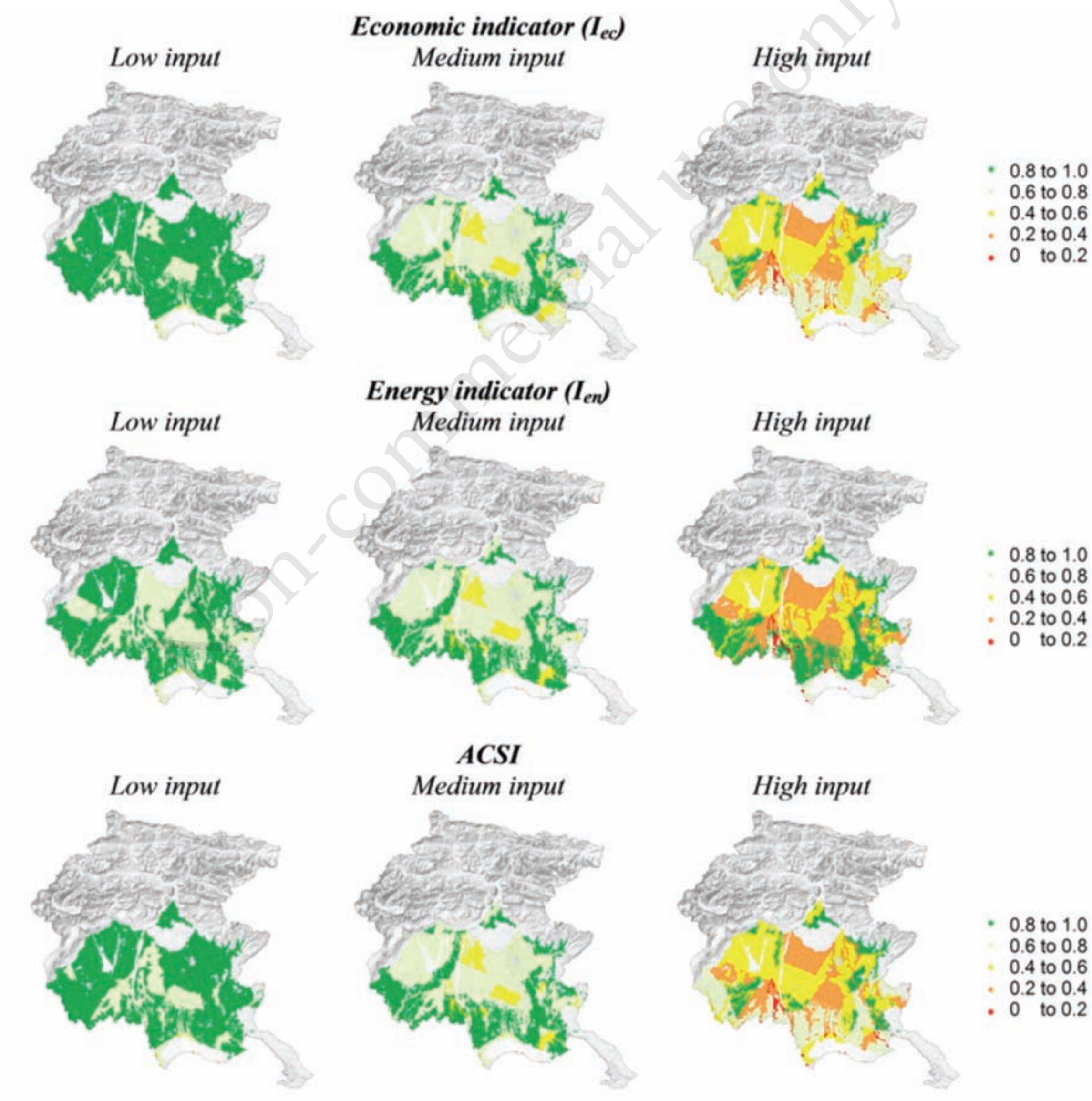

Figure 7. Spatial distribution of the values of economic indicator (I_{ec}), energy indicator (I_{en}) and Agro-energy Chain Sustainability Index (ACSI) calculated for the maize crop. At present, ACSI does not include environmental indicator (I_{ev}).

Table 5. Statistics for the economic indicator (I_{ec}), for the energy indicator (I_{en}) and for the Agroenergy Chain Sustainability Index (ACSI) for three input levels of maize crop. Larger values indicate better suitability. The distribution of the study area within the indicator classes it is also reported.

	Indicator properties				Total area for each indicator class (ha)				
High input	Min	Max	Mean	CV %	0-0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1
I_{ec}	0.00	0.87	0.51	35.80	1379	40,989	62,282	45,517	11,120
I_{en}	0.00	0.94	0.52	42.34	1766	56,025	43,994	13,082	46,421
ACSI	0.00	0.91	0.52	39.05	1379	44,079	59,193	42,332	14,305
Medium input	Min	Max	Mean	CV %	0-0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1
I_{ec}	0.28	0.96	0.73	15.72	0	254	16,460	92,807	51,767
I_{en}	0.38	0.99	0.75	15.14	0	31	15,540	88,368	57,349
ACSI	0.33	0.98	0.74	15.36	0	31	15,650	89,095	56,512
Low input	Min	Max	Mean	CV %	0-0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1
I_{ec}	0.50	1.00	0.88	8.01	0	0	258	28,763	132,266
I_{en}	0.54	1.00	0.82	9.03	0	0	258	68,731	92,299
ACSI	0.52	1.00	0.85	8.45	0	0	258	41,365	119,665

CV, coefficient of variation.

High input levels gives their best results only in well-defined suitable land.

In this study maize, one of the most common energy crops, is considered. However, the procedure allows the comparison of alternative energy crops in a specific territory. In this sense, the future evolution of the procedure will be based on: i) the comparison of the performance of different energy crops on the same territory; ii) the identification of the optimal use of the agricultural techniques to maximize the energy balances for each parcel (production problem); iii) the optimal distribution of the collecting points in the territory (logistic problem); iv) the optimal coordination among the agents operating at different levels of the chain to improve the AESC performance (organization problem); v) the reduction of the threshold prices and costs to expand the area of crop cultivation and supply for processing plants (efficiency of the AESC problem).

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