Optimal energy performance on allocating energy crops

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OPTIMAL ENERGY PERFORMANCE ON ALLOCATING ENERGY CROPS

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Abstract

There is a variety of crops that may be considered as potential biomass production crops. In order to select the best suitable for cultivation crop for a given area, a number of several factors should be taken into account. During crops' selection process, a common framework should be followed focusing on financial or energy performance. Combining multiple crops and multiple fields for the extraction of the best allocation requires a model to evaluate various and complex factors given a specific objective. This paper studies the maximization of total energy gained from the biomass production by energy crops, reduced by the energy costs of the production process. The tool calculates the energy balance using multiple crops allocated to multiple fields. Both binary programming and linear programming methods are employed to solve the allocation problem. Each crop is assigned to a field (or a combination of crops are allocated to each field) with the aim of maximizing the energy balance provided by the production system. For the demonstration of the tool, a hypothetical case study of three different crops cultivated for a decade (*Miscanthus giganteus*, *Arundo donax*, and *Panicum virgatum*) and allocated to 40 dispersed fields around a biogas plant in Italy is presented. The objective of the best allocation is the maximization of energy balance showing that the linear solution is slightly better than the binary one in the basic scenario while focusing on suggesting alternative scenarios that would have an even optimal energy balance.

Keywords: optimization; decision support; allocation tool; dispersed fields; energy balance.

Nomenclature	**Abbreviations**

C	Number of Crops	EoE	Efficiency of Energy
F	Number of Fields	EI	Energy Input (GJ)
b	Decision Variable (Binary)	EO	Energy Output (GJ)
sa	Decision Variable (Linear)	BP	Binary Programming
eb or EB	Energy Balance	LP	Linear Programming
aeb	Unit Area Energy Balance		
a	Area		
t	Threshold area		

1. INTRODUCTION

Energy demand is rising constantly across all sectors, driven by population growth and changing lifestyles (Mekhilef, Saidur, Safari, Mustaffa, 2011). In the agricultural sector, efforts have focused both on reducing the total energy consumed in agricultural practices (Tuomisto, Hodge, Riordan, Macdonald, 2012) but also on rendering the agricultural sector a producer of renewable energy (Demirbas, 2008). It is noteworthy that the agricultural and forestry sector was responsible for 2.15% of the total energy used in Europe in 2009 (FAO, 2009). However, during the same year, bioenergy production accounted for the 52% of the total European renewable energy production, with the respective number for the worldwide bioenergy production rising up to 74% (FAO, 2009). There are several ways to produce energy from biomass, starting from direct combustion and moving on to more complex and integrated processes such as biorefining, i.e. the refining of raw materials that come from various biomass sources (Yaman, 2004). Manufacturing of biofuels is a way of processing biomass which is of particular interest due to its economic and environmental benefits (Sarkar, Ghosh, Bannerjee, Aikat, 2012). The cultivation of energy crops and the use of agricultural residues are the main sources of biogas products (Hossain, Liu, Du, 2016). Compared to biorefining process, biogas refers to a mixture of gases coming from the resolution of raw materials that are connected to various biomass sources.

There are many studies regarding the conversion of this type of biomass in biogas (Rodriguez, Alaswad, Benyounis, Olabi, 2017;Chiumenti, Boscaro, Da Borso, Sartori, Pezzuolo, 2018). Biogas that comes from grasses has specific constraints that should be taken into consideration. Grasses have high lignocellulosic content and a quite complex structure. Before this type of biomass inserted in the anaerobic digester it should be conditioned in order to the degradation will be accelerated given that the microorganisms will have wider surface area to act. This conditioning process will play crucial role for the quality of the extracted biogas.

As the biogas industry is constantly evolving, adding value to biomass, transforming it to biofuels, biochemicals and other relevant products (De Bhowmick, Sarmah, Sen, 2018), the strategic planning of the production process become particularly important. It is necessary to examine the total energy balance and related energy costs of cultivating the crops involved (Parajuli et al., 2015; Peter, Helming, Nendel, 2017). In addition, in many countries there are no large areas available for cultivation and agricultural production systems consist of many dispersed and significantly smaller fields. The need for strategic planning is more crucial in these complex agricultural systems, where a number of crops have to be allocated to different fields, in order to increase resource efficiency and minimize the costs involved and ensure biodiversity (Busato, Sopegno, Berruto, Bochtis, Calvo, 2017).

Focusing on the energy costs involved in the production of a single crop, Sopegno et al. (2016) introduced a computational tool for the appraisal of the energy requirements of the cultivation of *Miscanthus giganteus* in individual fields including all in-field and transport operations (Sopegno et al., 2016). An analysis of production system and energy balance of two energy crops was made by Angelini, Ceccarini, Nassi o Di Nasso & Bonari (2009). Gemtos, Cavalaris, Karamoutis, Tagarakis, and Fountas (2013) made a wide range of experiments in Greece in order to assess the energy analysis of three energy crops and estimate their energy balances. Behera (2015) made an energy self-sufficiency evaluation of multiple farming systems. Busato, Sopegno, Berruto, Bochtis, and Calvo (2017) developed a web-based tool for the estimation of various energy indices in multiple-crop production systems, such as energy input (EI), energy output (EO), energy balance (EB) and energy return of investment (EROI). Moreover, Rodias, Berruto, Bochtis, Busato, and Sopegno (2017) proposed another detailed computational tool focusing on the energy cost estimation (by using indices such energy input, energy output and efficiency of energy (EoE)) of multiple-crop and multiple field production systems.

Even though there is enough research that includes multiple crop and multiple field production systems, it is highly important to incorporate the appropriate crop-to-field allocation under certain objectives, field features, and operating constraints. There are many reasons to cultivate multiple crops in a large group of fields, such as biodiversity, various harvesting time, field operations management, etc.. More specifically, biodiversity will be affected by the trend for monoculture of a unique specific crop in a given area due to, for example, the gradual elimination of some species and the disturbance of soil nutrients balance. At this light, there are approaches modelling crop-to-field spatial distribution targeting on the effect of various changes on a farm at a financial level (Rounsevell, Annetts, Audsley, Mayr, Reginster, 2003), while others assess the best possible energy crop allocation for the establishment of a sustainable bioethanol production system (Hattori & Morita, 2010). Additionally, there are approaches that focus not only on spatial but also on temporal crop allocation problems, considering certain agronomic constraints (Sorel, Viaud, Durand, Walter, 2010). As a further step to this, using specific models the crop-to-field allocation may provide with feedback about land use in order to determine its dynamics as well as the system's development (Verburg, 2006).

The present study is an expansion of the one presented by Sopegno et al. (2016). In that work, Sopegno et al. developed a computational tool in order to estimate the energy requirements of a single crop (*Miscanthus giganteus*) on individual fields. They included a detailed analysis and took account of the involved in-field and transport operations by using partly real data and other more generic norms for the energy requirements estimation.

In the present study, a more in-depth analysis is presented regarding the pre-processing energy input estimation based mostly on real data, but also an expansion is attempted given that this tool takes into account multiple crops energy requirements. More specifically, the current study proposes a tool for the allocation of multiple energy crops to multiple dispersed fields under the objective of the maximization of the energy gains of the system. The developed tool takes into account the energy consumption requirements for all in-field operations and also the farm-field and field-storage transportation, as well. Two different programming methods, binary programming (BP) and linear programming (LP), are used to solve the allocation problem. BP refers to the restriction that only one crop should be allocated to a specific field and LP allows the combination of more than one crop to a field. For the demonstration of the tool, a case study was selected including a real farm composed by a number of fields and a biomass processing plant in a region of Northern Italy.

2. MATERIALS AND METHODS

2.1 SYSTEM BOUNDARIES

The system boundaries selected for the energy requirements consideration of the developed tool include all the in-field operations and the relative transportations from the field to the farm and from the field to the storage location (or bio-refinery plant) (Fig.1). The transportations between the field and the farm are related to input materials (e.g. fertilizers and agrochemicals) and field machinery, while the transportations between the field and the storage facilities regard the produced biomass. The limits of the system extend to biomass storage only in terms of the transportation of the produced biomass and no other process is included in the aims of the current assessment, e.g. the transformation of biomass into other by-products.

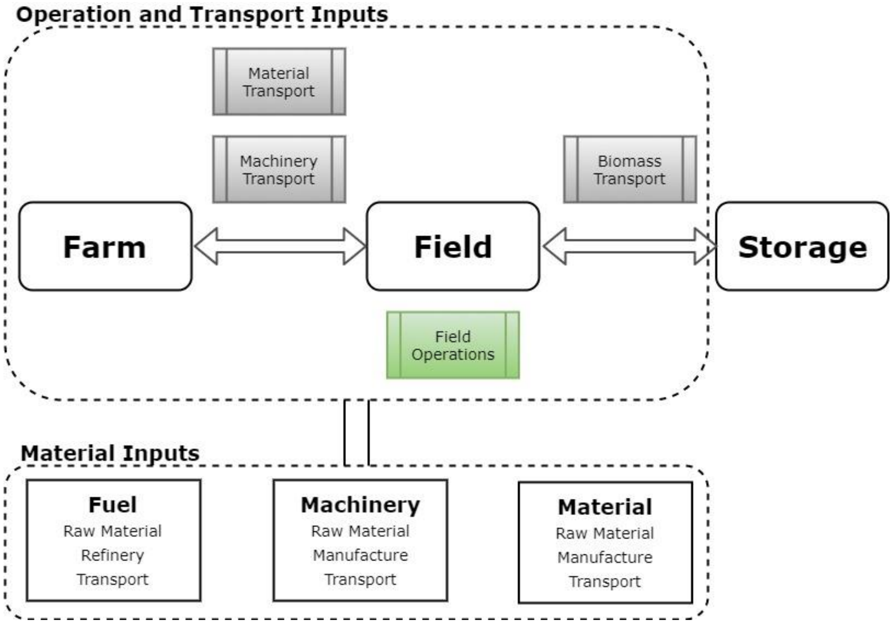

Fig. 1: System Boundaries

2.2 ALLOCATION PROBLEM

The ultimate purpose of the proposed tool is to allocate a number of different crops to a number of dispersed fields, with the aim of maximizing the energy balance of the system, considering a number of specific constraints. Optimizing crop allocation is very important in the operation management of complex agricultural systems, which include a large number of dispersed fields and different types of crops, as it minimizes the energy spent and the overall cost of transportation. For the approach of the allocation problem, let $C = \{1,2, \dots \dots, l\}$ denote the set of the indices corresponding to the different energy crops, where l is the number of the different crops, and let $F = \{1,2, \dots \dots, k\}$ denote the indices of the fields, where k is the total number of the fields available. Two different approaches are attempted to solve the allocation problem, depending on the number of crops that are cultivated in each field. These two approaches, the BP and the LP methods, were modelled by using the mathematical software MatLab© and they are presented below.

2.2.1 Binary programming

Using the binary programming solution of the allocation problem, the user ensures that only one crop is cultivated in each field, thus not allowing crop combinations. The decision variables are given by:

$$b_{ij} = \begin{cases} 1, if\ crop\ i\ is\ allocated\ to\ field\ j \\ 0, otherwise \end{cases}, i \in C, j \in F$$

Considering that $eb_{ij}, i \in C, j \in F$ corresponds to the energy balance of the cultivation of crop i in the field j, the BP problem is formulated as:

Maximise
$$\sum_{i=1}^{l}\sum_{j=1}^{k} b_{ij} \cdot eb_{ij}$$

Subject to
$$\sum_{i \in C} b_{ij} = 1 \quad \forall \ j \in \mathrm{F} \qquad [i]$$

$$\sum_{j \in F} b_{ij} \cdot a_j \geq t \cdot \sum_{j \in F} a_j \quad \forall \ \mathrm{i} \in \mathrm{C} \qquad [ii]$$

$$b_{ij} \in \{0,1\} \forall \, i \in C, j \in F \qquad [iii]$$

Constraint [i] ensures that exactly one crop is assigned in each field and [ii] ensures that the total area (a) allocated to a crop is larger than the minimum threshold area (t) that has to be assigned to each of the crops. Constraint [iii] is the binary constraint.

2.2.2 Linear programming

In the case of the linear programming, the decision variable is the sub-area sa_{ij} of field j that is allocated to crop i. In this case, the optimal solution allows for more than one crops to be assigned to each field considering specific limitations. Let

aeb_{ij} denote the unit area energy balance of the cultivation of a unit area of field j with crop i. The programming problem is formulated as follows:

Maximise
$$\sum_{i=1}^{l}\sum_{j=1}^{k} sa_{ij} \cdot aeb_{ij}$$

Subject to
$$\sum_{i \in C} sa_{ij} = a_{ij} \quad \forall \ \mathrm{j} \ \in \mathrm{F} \tag{iv}$$

$$\sum_{j \in F} sa_{ij} \cdot a_j \geq t \cdot \sum_{j \epsilon F} a_j \qquad \forall \ \mathrm{i} \ \in \mathrm{C} \tag{v}$$

$$0 \ \leq \ sa_{ij} \ \leq max\{a_j\} \ \ \forall \, i \ \in C, j \ \in F \tag{vi}$$

Constraint [iv] ensures that, for each field, the sum of areas assigned to each crop must be equal to the area of the specific field. Constraint [v], as previously mentioned, ensures that the total area allocated to a crop is larger than the minimum threshold area (t) that has to be assigned to each of the crops. The last constraint [vi] ensures that the area of each crop is greater than 0 and less than the area of the larger of the fields.

2.3 ALLOCATION TOOL

Fig. 2 shows the algorithmic representation of the proposed allocation tool, which is used to optimize field assignment and maximize energy balance. Two main processes are depicted, the one that is related to the energy estimation process and the other regards to the field allocation process.

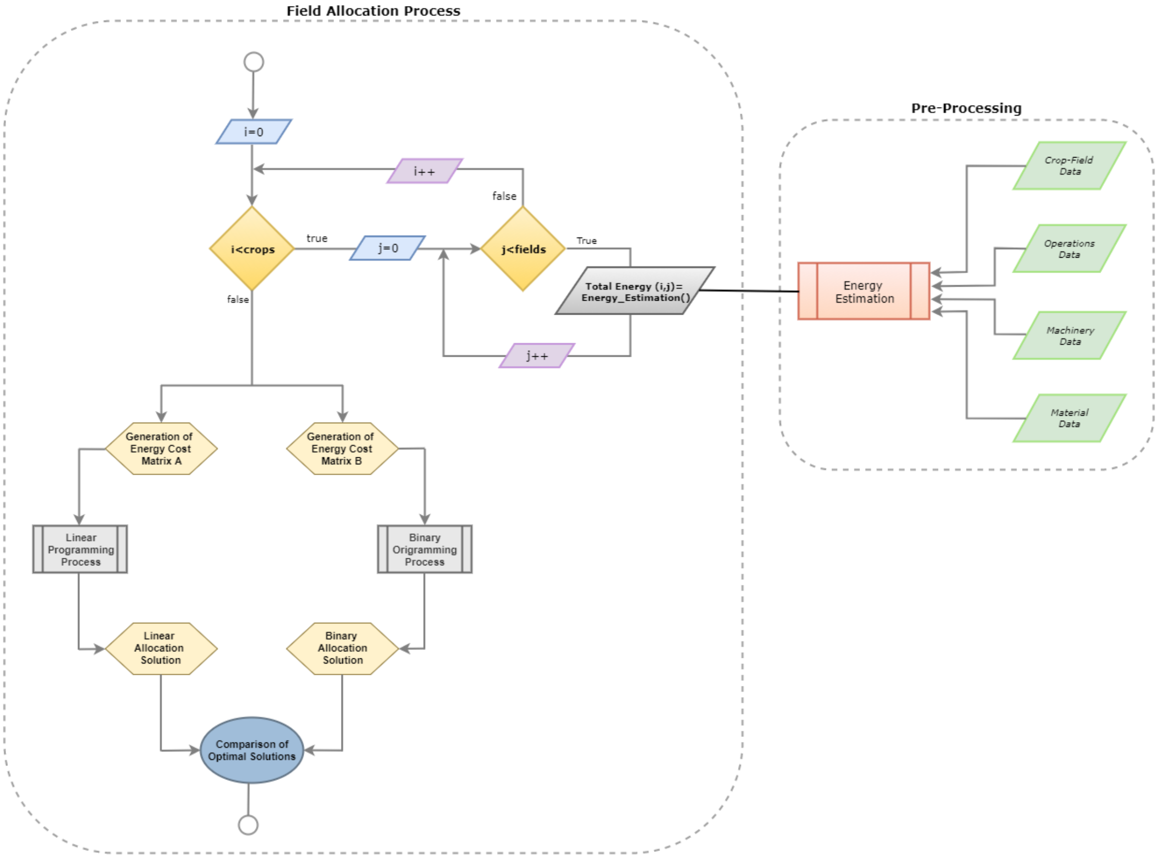

Fig. 2: An overview of the allocation tool

The input parameters can be divided to: fields and crops features parameters (e.g. field areas, distances, yield, etc.), field machinery parameters (e.g. tractor power, mass, etc.), operational parameters (e.g. operations to be executed annually, operating width and speed, efficiency, etc.), and material parameters that regards to any applied fertilizer or agrochemical, such as dosages, energy coefficients, etc. (Fig.3).

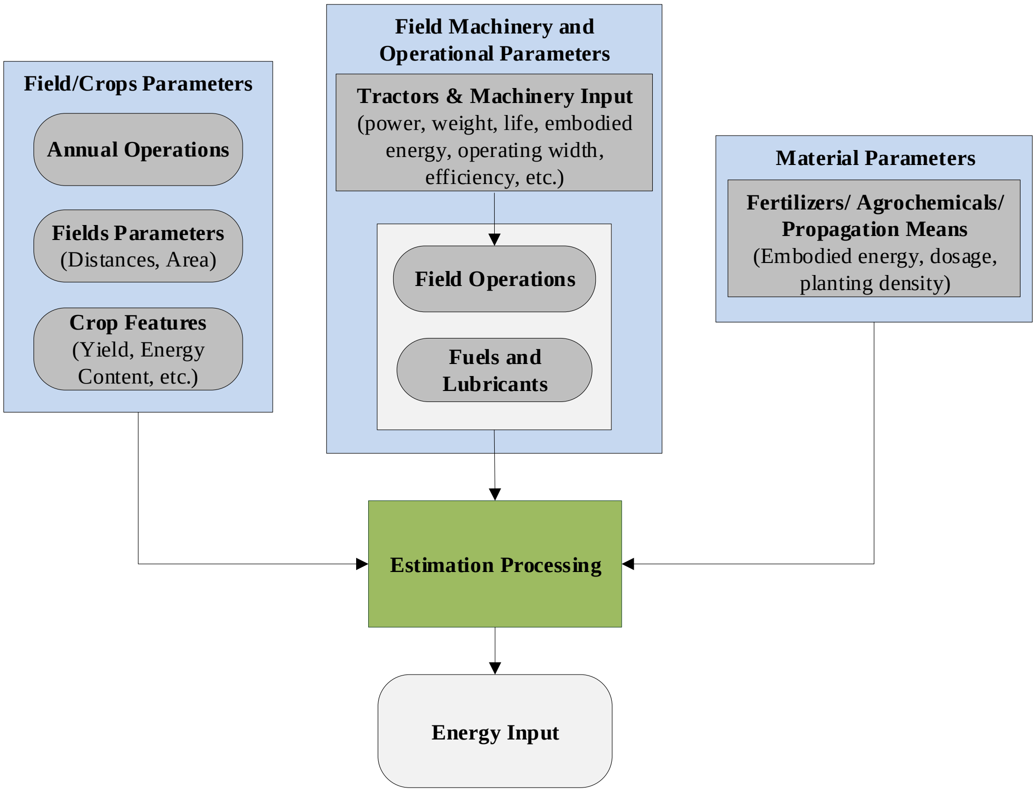

Fig. 3: An overview of the pre-processing energy input estimation

Field operations can be divided into three types as follows. The neutral material flow (NMF) operations (operations with no material flow, e.g., ploughing), the input material flow (IMF) operations (operations that include material flow e.g., fertilization), and the output material flow (OMF) operations (i.e., harvesting) (Bochtis & Sørensen, 2009, 2010). Accommodating these, the field operations are allocated to in-field operations (included in all the above-mentioned types), field-farm transport (included in all the above-mentioned types) and field-biogas plant transport (included in only OMF type).

Regarding the in-field part of every operation the energy input regards the fuel energy, the machinery embodied energy and the material input energy when IMF operation is held. As it is shown briefly in Fig. 4, at the beginning the in-field capacity is calculated based on the operating features, i.e. the operating width, the operating speed, and the field efficiency. Given this capacity and the field area, the operating time can be estimated. As a further step, for fuel energy estimation apart from operating time, fuel consumption, tractor power, and tractor coefficients are taken into account. It should be noted that specific input and estimation calculations are included regarding lubricants use in agricultural machinery. In parallel, for machinery embodied energy, the parameters that involved are these presented in Fig.4. The embodied energy is defined as the energy required during the product's life cycle from its early production stages up to its introduction in the agricultural production system (Kitani, 1999). Finally, the input material energy (IMF operations) should be included given the parameters presented in green colour in Fig. 4. This corresponds to any agrochemical, fertilizer or propagation means.

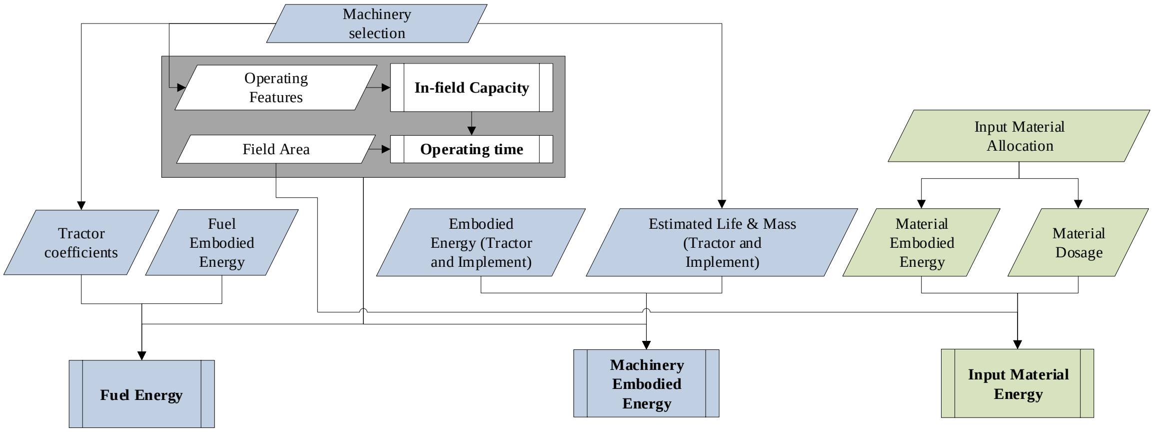

Fig. 4: In-field main energy elements estimation (including IMF operations in green color)

In every field operation the machinery transport from farm-to-field and vice versa is included (Fig. 5 - blue colour regards only on IMF operations and green colour for both NMF and IMF operations). For IMF operations this transport cycle is connected with the material application. In this case, for the estimation of energy consumption, the number of trips might be required. In the rest of the field (NMF) operations, the energy required in this round trip is considered only once. Apart from the number of trips in IMF operations, the fuel consumption per trip, the fuel energy coefficient and the maximum volume/weight of wagon/tanker (for planting and fertilization/agrochemicals spreading, respectively) are included for the fuel energy calculation. The embodied energy content of tractor and implement/wagon/tanker combined with their features (i.e. lifetime, weight), the number of trips (in IMF operations), the distance from farm to field and the road speed are taken into consideration for the embodied energy estimation.

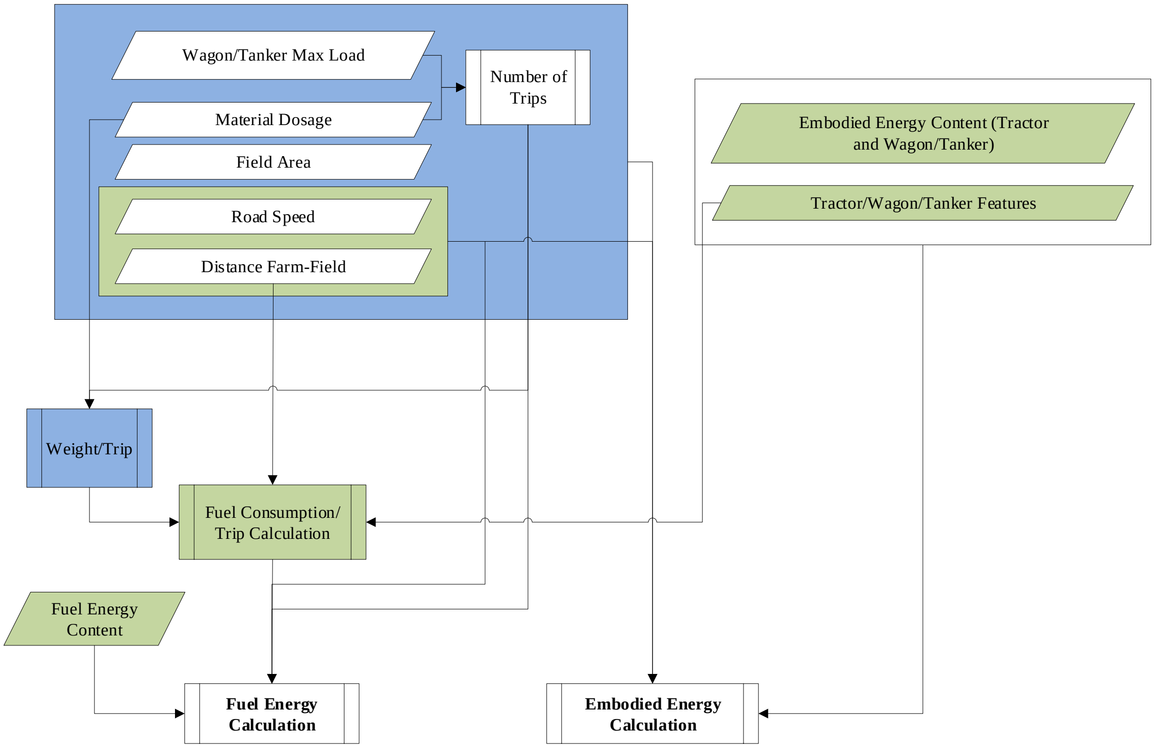

Fig. 5: Farm-field NMF and IMF transport operations energy input (blue colour regards only IMF operations and green colour on both NMF and IMF operations)

The transportation of harvested product from each field to biomass processing plant is considered as the last field operation in each production year (OMF operations). Similar to the abovementioned farm-field transportation, fuels, and embodied energy are considered as the main energy consuming categories. The energy calculation of this transportation process is depicted in Fig. 6 and is as follows. As a first step, the number of required trips are calculated. A cycle traveling time from field to plant is considered for the estimation of the number of transport carts for the execution of biomass transportation. In this cycle, unloading and driving back to the field is included according to wagon transporting capacity and the in-field harvesting capacity. At a second level, the fuel energy input is estimated, including the fuel consumption/trip and the fuel energy content. In parallel, the embodied energy of machinery is considered given the number of trips, the embodied energy coefficients and the machinery set features (tractor and machinery lifetime and weight).

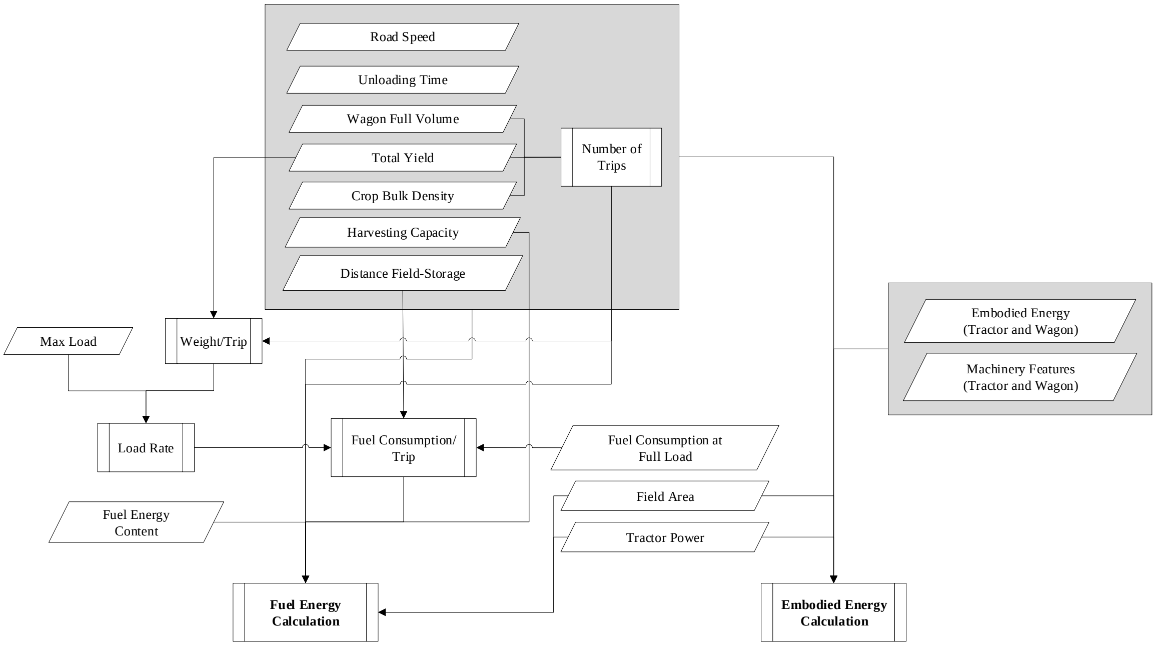

Fig. 6: Field-to-Plant transportation energy input estimation

From the above-mentioned processes, the energy cost matrices and, in further, the energy balances are generated and inserted as input in both BP and LP processing (Fig. 2) in order to determine the optimal solutions (field-to-crop allocation) for both methods under the objective of maximization of the energy balance. Finally, the two programming methods are compared in order to select the one that generates the optimal solution. For the evaluation of the allocation tool, a specific case study was selected and is presented below.

3. CASE STUDY DESCRIPTION

3.1 AREA AND PRODUCTION SYSTEM FEATURES

The case study chosen for the implementation of the allocation tool includes a number of dispersed fields located within the greater area of a biogas plant in Italy, where the hypothetical agricultural production system is set up. The area chosen is Rodallo-Caluso located in the broader region of Piedmont in Northern Italy. It is a lowland area with no particular altitude differences. The application of the computational tool seeks to optimally assign the selected crops to the available fields in order to maximize the energy balance, taking into account a number of constraining factors.

The total field area to be cultivated in this case study equals 356.77 ha and ranges from 1.63 ha to 18.8 ha. The shape of the fields is assumed that have no effect on the allocation tool results. In addition, the average farm-field distance was calculated at 8.07 km - ranging from 1.3 km up to 26.6 km. The average field-plant distance was estimated at 8.42 km and ranged from 0.99 km up to 18.3 km. In both cases, the farm-field and field-plant distances were calculated by using Google Maps© application. It should be noted that not all the fields examined are adjacent to roads registered in the Google Maps database. In these cases, the corresponding distances from the field to the closest registered road were considered including the relevant distances.

3.2 CROP FEATURES

The selected crops for the evaluation of the allocation tool are the energy crops *Miscanthus giganteus*, *Arundo donax*, and *Panicum virgatum*, all of them cultivated for biomass production. These energy crops are highly promising within the production system designed, as they are largely resource-efficient, requiring low inputs compared to their dry matter yields (Knoll, Anderson, Strickland, Hubbard, Malik, 2012).

Miscanthus giganteus is a perennial grass crop with a lifetime of more than 10 years, which belongs to the C_4 photosynthetic pathway plants (Rodias, Berruto, Bochtis, Busato, Sopegno, 2017). Due to its high lignocellulosic content, *Miscanthus giganteus* is considered a promising crop for the production of biofuels and other bio-based products (Fernando, Costa, Barbosa, Monti, Rettenmaier, 2016). Reaching up to 4 m of height, this energy crop is characterized by high dry matter yield while simultaneously it is resource efficient regarding the materials (water, herbicides, and fertilizers) used during its cultivation (Price, Bullard, Lyons, Anthony, Nixon, 2004). *Miscanthus giganteus* is a crop that easily adapts to diversified climatic conditions and soils (Angelini, Ceccarini, Nassi o Di Nasso, Bonari, 2009).

Arundo donax, along with *Miscanthus giganteus* is also a very promising perennial crop from the Poaceae family (Angelini et al., 2009). *Arundo donax*, also known as “giant cane” or “giant reed”, is a sterile plant which is also adaptable to various climatic conditions. However, the plant, which can ideally reach a height of 10 m, produces its maximum yield if it is planted in soils with rich water potential (Corno, Pilu, Adani, 2014). In specific cases, dry matter yields up to app. 37 t ha^{-1} annually there have been reported (Angelini et al., 2009).

Panicum virgatum, which is also known as switchgrass, is a perennial crop known for its promising features as an energy crop (Ameen, Tang, Han, Xie, 2018). *Panicum virgatum*, which is adaptable to different climatic conditions and as perennial crop requires less input, especially compared to biomass resulting from annual crops and is considered as the most promising among the perennial energy crops (Lewandowski, Scurlock, Lindvall, Christou, 2003). It has a height of 50-250 cm and it can provide a yield of up to 25t ha^{-1} in optimal conditions (Cristian et al., 2001; Lewandowski et al., 2003).

3.3 AGRONOMIC PROTOCOL

Initially, prior to the analysis of the agronomic protocol and the related field operations of this case study, it should be noted that the following assumptions were taken into account:

- The field machinery can enter the field from any point on its boundaries.
- The energy content is assumed to remain constant for each year and crop.
- The crop yield is assumed to remain constant for each year.

Table 1 presents all the necessary field operations (presented as full tiny squares) that take place over a period of ten years, in-line with the production scenario. These field operations are defined by the agronomic protocol adopted, which is based on common agricultural practices following the production of each crop (Table 1).

Table 1: In-field operations for a ten-year energy crop cultivation

Year	Crops	Operations								
		Plough	**Disk-harrow**	**Agrochemical Spreading**	**Planting/ Seeding**	**Fertilization**	**Mowing**	**Harvesting**	**Irrigation**	**Transport**
1	**C_1**	■	■	■	■	■	□	□	■	□
	C_2	■	■	□	■	■	□	□	■	□
	C_3	■	■	■	■	■	□	□	■	□
2	**C_1**	□	□	□	□	■	□	■	■	■
	C_2	□	□	□	□	■	□	■	■	■
	C_3	□	□	■	□	□	■	■	■	■
3	**C_1**	□	□	□	□	■	□	■	■	■
	C_2	□	□	□	□	■	□	■	■	■
	C_3	□	□	■	□	■	■	■	■	■
4	**C_1**	□	□	□	□	■	□	■	■	■
	C_2	□	□	□	□	■	□	■	■	■
	C_3	□	□	□	□	■	■	■	■	■
5	**C_1**	□	□	□	□	■	□	■	■	■
	C_2	□	□	□	□	■	□	■	■	■
	C_3	□	□	□	□	■	■	■	■	■
6	**C_1**	□	□	□	□	■	□	■	■	■
	C_2	□	□	□	□	■	□	■	■	■
	C_3	□	□	□	□	■	■	■	■	■
7	**C_1**	□	□	□	□	■	□	■	■	■
	C_2	□	□	□	□	■	□	■	■	■
	C_3	□	□	□	□	■	■	■	■	■
8	**C_1**	□	□	□	□	■	□	■	■	■
	C_2	□	□	□	□	■	□	■	■	■
	C_3	□	□	□	□	■	■	■	■	■
9	**C_1**	□	□	□	□	■	□	■	■	■
	C_2	□	□	□	□	■	□	■	■	■
	C_3	□	□	□	□	■	■	■	■	■
10	**C_1**	□	□	□	□	■	□	■	■	■
	C_2	□	□	□	□	■	□	■	■	■
	C_3	□	□	□	□	■	■	■	■	■

C_1: *Miscanthus giganteus*, C_2: *Arundo donax*, C_3: *Panicum virgatum* (▪ when an operation is applied and ▫ when is not applied)

Common operations for all crops include a light soil preparation, without the need for any further soil treatment, which is essential before establishing the crops (Angelini et al., 2009). This involves light plowing, and disk-harrowing at a depth of 20 cm, prior to planting. Regarding weed control, *Miscanthus giganteus* and *Arundo donax* are characterised as weed resistant plants, thus not requiring any special weed control during their growth phase. For this reason, only for *Miscanthus giganteus* a single herbicide application was considered to be applied just after the soil preparation and before planting, in order to minimize weed competitiveness against the newly-emerged plants. On the contrary, the fact that *Panicum virgatum* is established by seeds makes it very sensitive against weeds and requires more thorough weed control, especially during the first years following its establishment (Piscioneri, Pignatelli, Palazzo, Sharma, 2001). The herbicide quantities used for the protection of the crops during these first years are presented in Table 2.

Table 2: Agronomic Protocol for the production of three energy crops

Operations	*Miscanthus giganteus*	*Arundo donax*	*Panicum virgatum*
Soil Preparation	Plow and Disk-harrow (20 cm depth)		
Weed control	One glyphosate application of 20 kg ha^{-1} in the 1st year	No herbicide application	Atrazine application of 1.12 kg ha^{-1} before the establishment and 2,4-D application of 4.26kg ha^{-1} in the 2nd and 3rd year (1),(2)
Planting	16,000 rhizomes ha^{-1} planted using a row crop planter (2)-(4)	20,000 rhizomes ha^{-1} planted using a row crop planter (5)	150,000 plants ha^{-1} using a seeder (6),(7)
Irrigation	450 mm every year parallel with rainfall (8)	450 mm every year parallel with rainfall (8)	240 mm every year parallel with rainfall (9)
Fertilization	50 kg N, 21 kg P_2O_5 and 45 kg K_2O ha^{-1} and year (10)	80 kg N, 200 kg P_2O_5 and 100 kg K_2O ha^{-1} (1st year) 80 kg N, 50kg P_2O_5 ha^{-1} (every even year) 80 kg N, 50kg P_2O_5 and 100 kg K_2O ha^{-1} (every odd year) (11),(12)	100 kg P_2O_5 and 100 kg K_2O ha^{-1} (1st year) Second year no fertilization is required 75 kg N, 100kg P_2O_5, 100kg K_2O ha^{-1} (every even year on) 75 kg N, (every odd year on) (11),(12)
Harvesting	Harvesting with conventional forage harvester every year starting from the 2nd year (13)	Harvesting with conventional forage harvester every year starting from the 2nd year (5)	Mowing and then Harvesting with conventional mower and forage harvester every year starting from the 2nd year (6)
Yield	24 t ha^{-1} (14)	26.8 t ha^{-1} (5)	16 t ha^{-1} (15)
Energy Content	18.2 MJ kg^{-1} (14)	17.1 MJ kg^{-1} (8),(14)	18.3 MJ kg^{-1} (14)

(1)(Caslin, Finnan, Easson, 2010),(2)(Pyter, Heaton, Dohleman, Voigt, Long, 2009),(3)(Garten et al., 2010),(4)(Schmer, Vogel, Mitchell, Perrin, 2008),(5)(Angelini, Ceccarini, Bonari, 2005),(6)(Piscioneri, Pignatelli, Palazzo, Sharma, 2001), (7)(Sokhansanj et al., 2009),(8)(Mantineo, D'Agosta, Copani, Patanè, Cosentino, 2009),(9)(Cristian et al., 2001), (10)(Lee, 2011), (11)(Atkinson, 2009), (12)(Vermerris, 2008), (13)(Heaton et al., 2010), (14)(Bassam, 2010), (15)(Hood, Nelson, Powell, 2011)

Miscanthus giganteus and *Arundo donax* are propagated by rhizomes with the use of row-crop planters, whilst *Panicum virgatum* is established with the use of seeds. The usual planting density for *Miscanthus giganteus* is 15,000-17,000 rhizomes per hectare, considering an average loss rate of 30-40% (Garten et al., 2010; Schmer, Vogel, Mitchell, Perrin, 2008). For *Arundo donax*, the planting density ranges between 20,000-40,000 plants ha^{-1} (Angelini, Ceccarini, and Bonari, 2005). Regarding *Panicum virgatum*, a planting density of 10-20 plants per m^2 is considered beneficial for the plant's health (Piscioneri, Pignatelli, Palazzo, Sharma, 2001; Sokhansanj et al., 2009). The number of plants per hectare that were selected for the present study is demonstrated in Table 2.

Regarding the irrigation of all the fields included in the production system under examination, a low flow-irrigation system has been considered. In the present case study, *Miscanthus giganteus* and *Arundo donax* require 450 mm of water in addition to rainfall water that may be accumulated in the soil (Mantineo, D'Agosta, Copani, Patanè, Cosentino, 2009). The irrigation needs for *Panicum virgatum* are slightly lower and along with rainfall 240 mm of water are considered to be applied. The fertilization needs for each crop are presented in Table 2. *Miscanthus giganteus* has low nutrient needs, while *Arundo donax* and *Panicum virgatum* have higher nutrient requirements. *Miscanthus giganteus* is usually harvested annually after the second year on while *Arundo donax* can be harvested annually or biannually. In both crops, forage-harvester machinery is usually used, in conjunction with a tractor-wagon system that moves along with the harvesting machine for the direct collection of the harvested biomass. For the harvesting of *Panicum virgatum*, as a first stage mowing is performed, in order to let the mowed biomass, dry in the field, which is then collected by a harvester at a second stage. This process is usually performed 1-2 times per year for optimal crop production (Atkinson, 2009). Table 2 also presents the average yield and the energy content of the three crops.

3.4 MACHINERY AND MATERIAL INPUT

The field machinery inputs, as they are incorporated in the allocation tool for both in-field operations and transportation, are presented in Table 3. Regarding tractor embodied energy it was assumed a single coefficient for both type of tractors (Kitani, 1999) even though there are studies that compare energy demand for different sizes of tractors (Mantoam, Romanelli, Gimenez, 2016). In addition to this, it should be clarified that the field machinery are assumed to be used exclusively in these crops. For the micro-irrigation system, it was assumed that the water is pumped from a 10 m deep well. The irrigation system lifetime is considered to be 20 years while the energy coefficient of electricity and the PVC pipe embodied energy is 8.1 MJ kWh^{-1} and 110.66 MJ kg^{-1}, respectively (Barber, 2004; Diotto, Folegatti, Duarte, Romanelli, 2014; Wells, 2001).

Regarding material input, propagation means, fertilizers and agrochemicals are included. For *Miscanthus giganteus* and *Arundo donax* propagation means, a value of 0.00431 MJ per rhizome and 0.00345 MJ per rhizome were considered (Price, Bullard, Lyons, Anthony, Nixon, 2004), while the energy content of *Panicum virgatum* seeds is 2.86 MJ kg^{-1} (Caslin, Finnan, Easson, 2010; Kitani, 1999). Regarding fertilization, only the main fertilizer ingredients were considered for all crops, as presented in the aforementioned agronomic protocols. Their corresponding energy coefficients are 78.1 MJ kg^{-1} for N, 17.4 MJ kg^{-1} for P_2O_5 and 13.7 MJ kg^{-1} for K_2O (Schmer et al., 2008). Finally, for the agrochemicals application the herbicides glyphosate (for *Miscanthus giganteus* production), atrazine and 2,4-D (in *Panicum virgatum*) were used. Their corresponding energy content is 454 MJ kg^{-1} for glyphosate, 190 MJ kg^{-1} for atrazine and 85 MJ kg^{-1} for 2,4-D (Caslin, Finnan, Easson, 2010; Garten et al., 2010; Schmer, Vogel, Mitchell, Perrin, 2008).

Table 3: Machinery and Transportation Inputs

		Operations							
		Plough	**Disk-harrow**	**Agrochemical Spreading**	**Fertilization**	**Planting/ Seeding**	**Mowing**	**Harvesting**	**Transport**
Field Machinery Inputs	**Operation Width (m) ***	3	4.5	24.4	24.4	3.22	3.1	3.3	-
	Operating Speed (km h^{-1})(1)	7	10	11	11	9	11	5	-
	Field Efficiency(1)	0.85	0.8	0.7	0.7	0.65	0.8	0.7	-
	Tractor Embodied Energy (MJ kg^{-1})(2)	138	138	138	138	138	138	138	-
	Implement Embodied Energy (MJ kg^{-1}) (2)	180	149	129	129	133	110	116	-
	Tractor Weight (10^3 kg) *	7.55	7.55	3.48	3.48	3.48	7.55	7.55	7.55
	Implement Weight (10^3 kg) *	2.3	1.83	3.35	3.35	1.05	0.65	2.04	-
	Tractor Estimated Life (10^3 h)(1)	16	16	12	12	12	12	16	12
	Implement Estimated Life (10^3 h) (1)	2	2	1.2	1.2	1.5	2	2.5	-
	Fuel Energy Content (MJ L^{-1}) (3), (4)	41.2	41.2	41.2	41.2	41.2	41.2	41.2	41.2
	Tractor Power (kW) *	123	123	80	80	80	123	123	123
	Lubricant Energy Content (MJ L^{-1}) (5)	46	46	46	46	46	46	46	46
Transportation Inputs	**Average Road Speed (km h^{-1})**	20	20	20	20	20	20	20	20
	Tanker/Wagon Weight (10^3 kg) *	-	-	1.5	6.8	2.5	-	-	14.5
	Tanker/Wagon Embodied Energy (MJ kg^{-1})	-	-	140	140	108	-	-	108
	Tanker/Wagon Estimated Life (10^3 h) (1)	-	-	3	3	3	-	-	3
	Fuel Road Consumption (L km^{-1}) *	0.935	0.935	0.954	0.954	0.954	0.935	0.935	0.935
	Wagon Full Volume (m^3) *	-	-	-	-	3	-	-	40

*Commercial values, (1)(American Society of Agricultural and Biological Engineers, 2011), (2)(Kitani, 1999), (3)(Barber, 2004), (4)(Wells, 2001), (5)(Saunders, Barber, Taylor, 2006)

4. RESULTS - DISCUSSION

4.1 BASIC SCENARIO

The proposed allocation tool was evaluated under the objective of maximization of the energy balance (EO-EI) of the case study production system (basic scenario). In Fig. 7, the farm chosen as the field machinery depot is presented, as well as the 40 fields selected for demonstrating the allocation tool and the biogas plant for the biomass storage and processing regarding the LP solution for t=0.3.

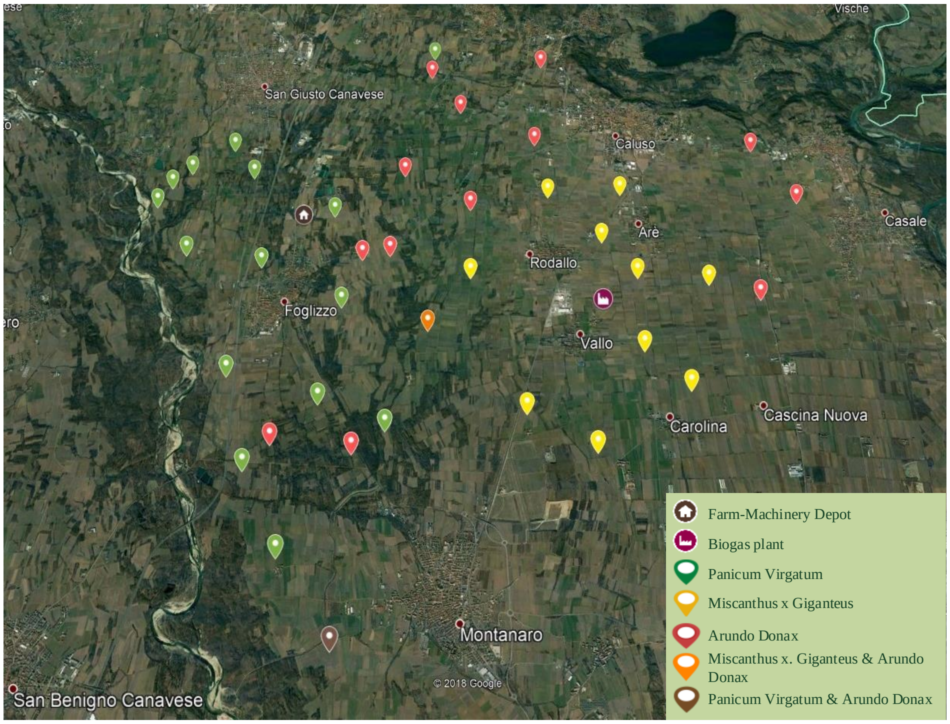

Fig. 7: Geographical representation of fields allocation for t=0.3 (LP solution)

Fig. 8 presents the two optimal allocation solutions (BP and LP, respectively) extracted by the tool for a threshold area of t=0.3. By the BP solution, only one crop is assigned to each field, while by the LP solution more than one crop may be assigned to each field.

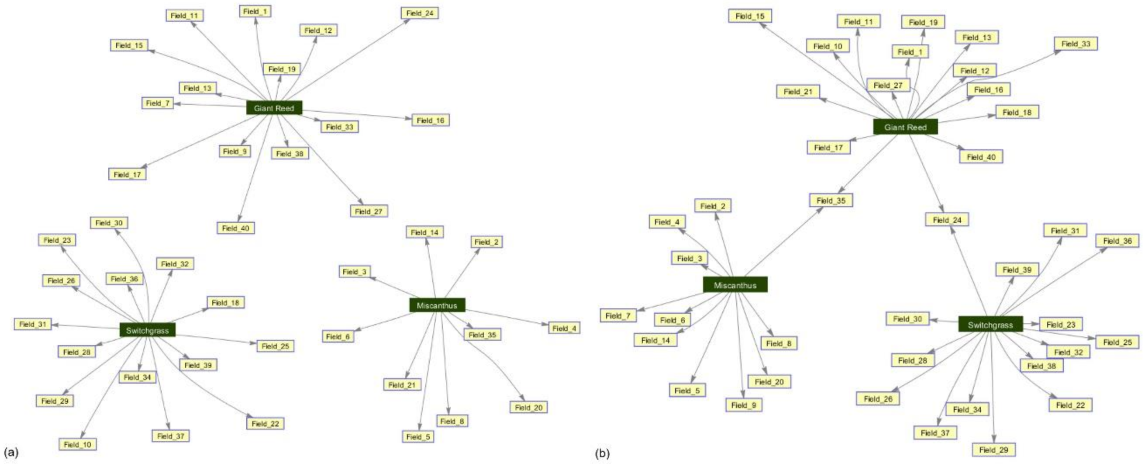

Fig. 8: (a) BP and (b) LP allocation solution for the maximization of energy balance (t=0.3)

In the BP solution, 10 fields are allocated to *Miscanthus giganteus*, 15 to *Panicum virgatum* (switchgrass) and the rest (15 fields) to *Arundo donax*. In the LP solution, *Miscanthus giganteus* is assigned to 11 fields, *Panicum virgatum* to 15 fields and *Arundo donax* to 16 fields. The maximum energy balance for the BP and the LP solution is $1,208.1 \cdot 10^3$ GJ and $1,208.2 \cdot 10^3$ GJ, respectively.

To evaluate further the implementation of the allocation tool, a threshold area of t=0.15 was assessed. Fig. 9 depicts the geographical allocation of fields in the presented area according to LP solution for t=0.15. Furthermore, Fig. 10 represents both the BP and LP allocation solutions of the basic scenario for t=0.15. Here, 5 fields are allocated to *Miscanthus giganteus*, 7 fields to *Panicum virgatum* and 28 fields to *Arundo donax* regarding the BP solution (Fig. 10 (a)). On the other side, for the LP solution 6 fields are assigned to *Miscanthus giganteus*, 7 fields to *Panicum virgatum* and 28 fields to *Arundo donax* (Fig. 10 (b)). The EB in the BP solution was $1,294.6 \cdot 10^3$ GJ compared to $1,294.7 \cdot 10^3$ GJ in the LP solution for t=0.15 in the basic scenario.

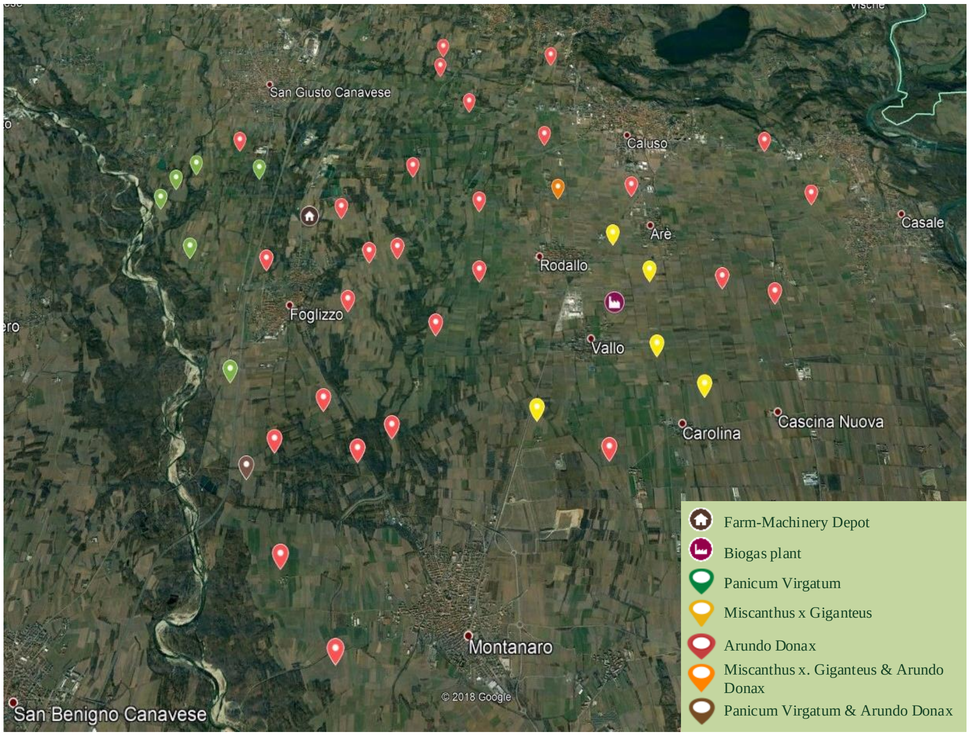

Fig. 9: Geographical representation of fields for t=0.15 (LP solution)

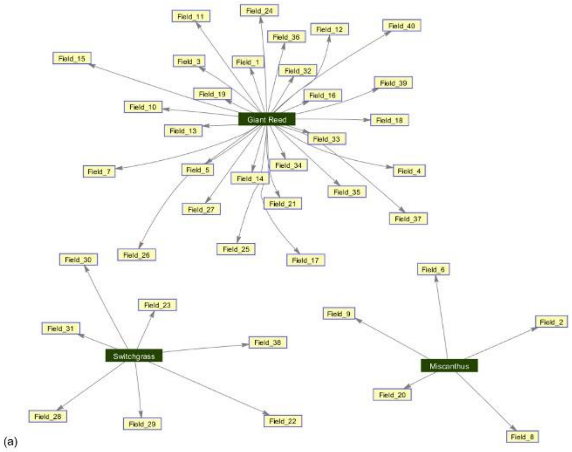

Fig. 10: (a) BP and (b) LP allocation solution for the maximization of energy balance (t=0.15)

As it has been mentioned above, in the current study the relevant distances between the field and the closest registered road were assumed. Given that these relevant distances were generally small, a range of +/-5% in the relevant distances was applied in order to the extract the. At this light, the energy balance for the binary solution would vary from 1,207.8 10^3 GJ up to 1,208.4 10^3 GJ and for the linear solution would vary from 1,207.9 10^3 GJ up to 1,208.5 10^3 GJ.

The distribution of the energy input (EI) included in (i) in-field operations, (ii) farm-field transportation, (iii) field-storage transportation, and (iv) the embodied energy of agricultural material (fertilizers, herbicides, and propagation means) is shown in Figure 11, indicatively for t=0.3 in LP solution. The EI distribution for different *t* and by using both programming methods (binary or linear) has similar results with minor variation. In the basic scenario, the highest EI regarding the in-field operations comes from irrigation, fertilization and harvesting while for the material application, the energy consumption regards mainly on fertilizers embodied energy and less on the embodied energy of herbicides and propagation means. The main energy consuming operations regards on fertilization, irrigation and harvesting. This occurs because all of them are connected to annual operations with high energy components.

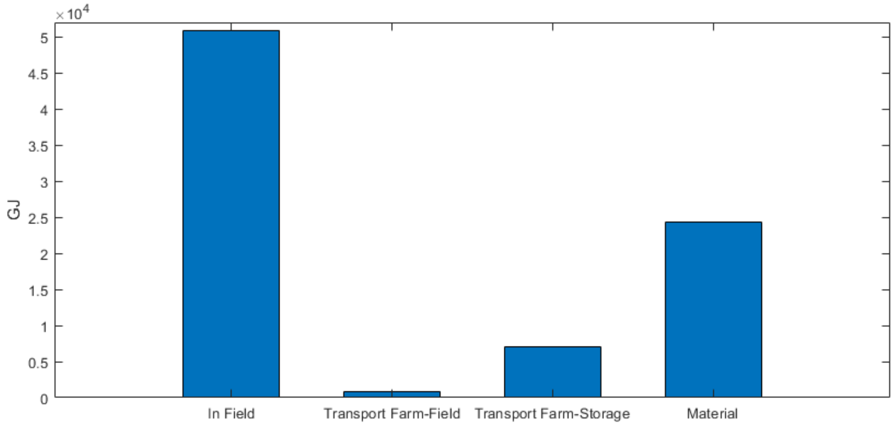

Fig. 11: Distribution of the total energy consumption (in GJ) (LP solution)

The main objective of the basic scenario is the maximization of the total energy balance. This is achieved by the optimal allocation of the given crops to the number of fields. For this optimal allocation, the individual energy balances in compliance with the allocated field area per crop are presented in Fig. 12 for t=0.3. Fig. 12 represents the LP solution, though the BP solution will be represented similarly. It is noticeable that the total field area allocated to both *Miscanthus giganteus* and *Panicum virgatum* (switchgrass) are similar given that the tool targets to the fulfillment of the prerequisite regarding the minimum allocated area per crop (here t=0.3).

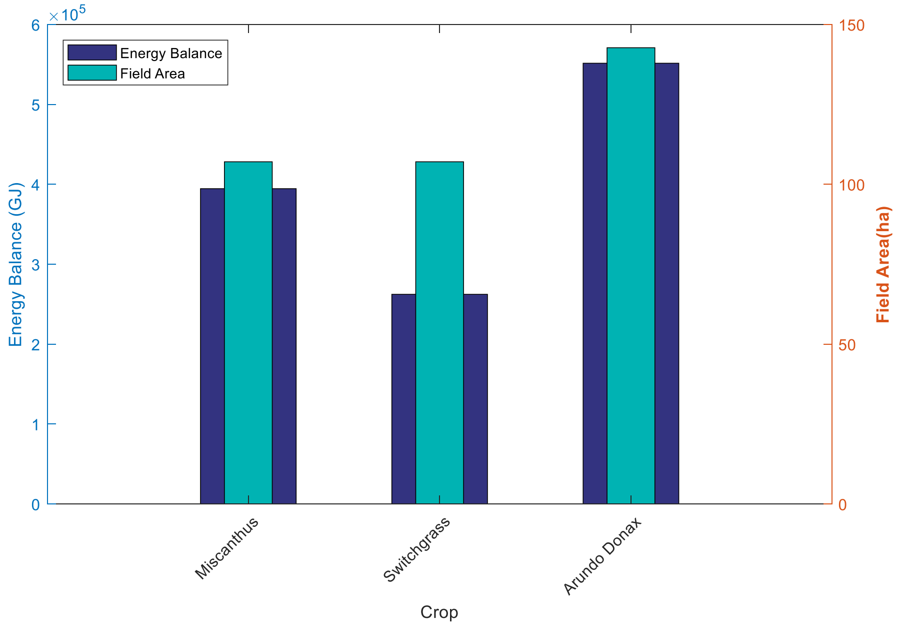

Fig. 12: Energy balance (in GJ) and field area (in ha) per crop for t=0.3 (LP solution)

In order to include in the current study a short evaluation of the embodied energy connected to the tractors, a compromised energy coefficient was adopted from Mantoam, Romanelli & Gimenez (2016).In this case, the total energy balance for ten years in the basic scenario with t=0.3 was 1,208,510 GJ for binary solution and 1,208,630 GJ for linear solution. These solutions of course are better than the ones presented above due to the lowest embodied energy of the tractors.

4.2 ALTERNATIVE SCENARIOS

To expand further the potential of the proposed allocation tool, further hypothetical scenarios were evaluated and are the following: Alt. Scenario 1: Big fields located far from the farm, Alt. Scenario 2: Big fields located far from the biogas plant, Alt. Scenario 3: Small fields located far from farm, and Alt. Scenario 4: Small fields located far from the biogas plant. In all the above-mentioned scenarios, it is assumed that all the corresponding distances remain as in the original case study and only the field areas are relocated to the hypothetical locations. To make it clearer, for example, in the Alt. Scenario 1 all the big fields are assigned to the positions that other smaller fields were previously located in the basic scenario. The extracted EB by the allocation tool for all scenarios, regarding both programming (binary and linear) methods and both *t* alternatives are presented in Table 4.

Table 4: Energy Balance (in GJ) for all scenarios in ten years period

Scenario	t=0.3		t=0.15	
	Bin	Lin	Bin	Lin
Original	1,208,114	1,208,235	1,294,571	1,294,675
Alt. Scenario 1	1,208,209	1,208,263	1,294,541	1,294,637
Alt. Scenario 2	1,205,129	1,205,221	1,291,883	1,292,042
Alt. Scenario 3	1,206,888	1,207,015	1,293,720	1,293,826
Alt. Scenario 4	1,209,445	1,209,606	1,296,035	1,296,187

The EB per field area is depicted in Fig. 13 (in GJ ha^{-1}) for t=0.3 in the original scenario and the four alternative scenarios regarding BP solution for ten year period. Alt. Scenario 2 is the worst among all the scenarios, while Alt. Scenario 4 is the optimal one. This is logical given that bigger fields that are far from the plant have higher energy cost given that harvesting and transport field-to-plant operations are held every year during the decade. Small fields that are located far from the farm have also low EB per hectare given that the operational cost is higher for smaller fields, compared to bigger. In the case of t=0.15, the trend is similar as the one presented in Fig. 13 because the EB per hectare is affected more by general agronomical and transportation reasons as they described above and not by the crop-to-field allocation.

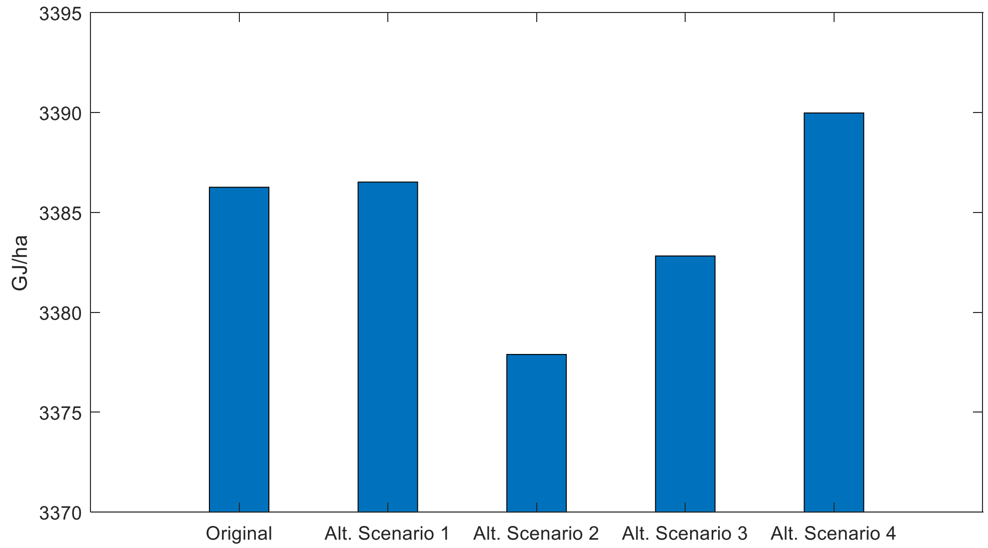

Fig. 13: Energy Balance per field area (in GJ ha^{-1}) for ten year period (t=0.3)

In order to evaluate better the functionality of the allocation tool, the average size (area) of the of fields that are allocated to each crop for all scenarios is calculated and presented in Fig. 14 for both t=0.3 and t=0.15 regarding LP solution. According to the results, *Miscanthus giganteus* has high variability on the size of the fields that is allocated to through the different scenarios, while switchgrass tends to be established in medium-size fields in all scenarios, apart from the alternative scenario 1 that the big fields are located far from plant where switchgrass tends to be assigned mostly to big fields. Finally, *Arundo donax* follows medium size fields in all scenarios.

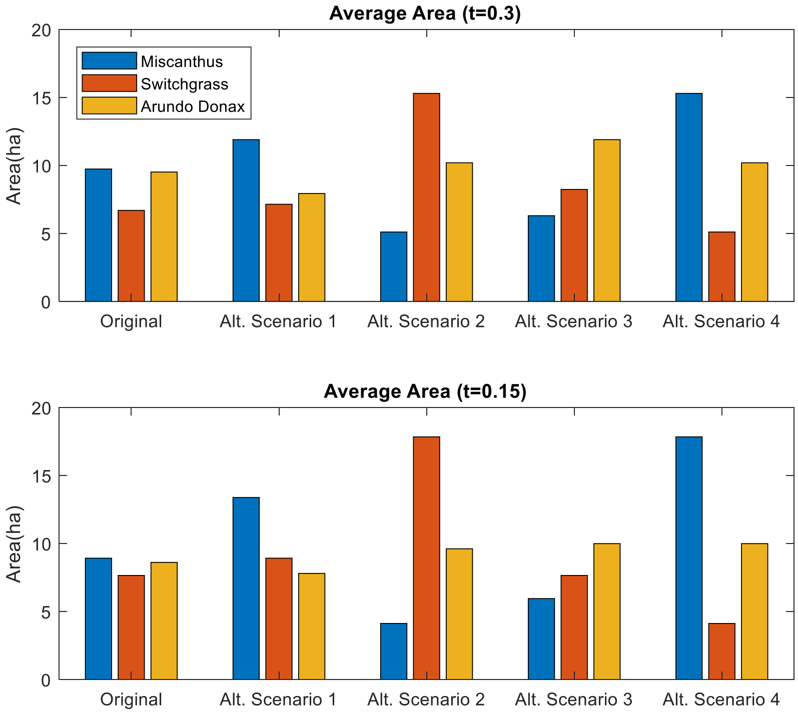

Fig. 14: Average size (area) of the group of fields allocated to each crop for the 5 scenarios in both t=0.3 and t=0.15 (LP)

5. CONCLUSION

Examining the different allocation configurations that resulted from testing different scenarios, it is concluded that the optimal crop allocation is strongly related to the user preferences. The threshold area t is an important factor that allows different constraints to be considered in the optimization process. For example, the interest from a biomass processing plant point-of-view is to maximize its overall energy gain. However, there are limiting factors such as the total cost of the cultivation or the composition of the biomass for the production of biofuels that have to be considered. On the other hand, the interest from a producer's point-of-view could focus on the minimization of the total input of the system either to reduce the economic cost or to address the adverse environmental impacts of the cultivation process.

The proposed tool is adaptable to user preferences and can be expanded further in order to provide with optimal allocation schemes considering multiple farms, multiple fields, and multiple biomass plants. Also, the tool could be enhanced in order to provide with optimal crop allocation for all kinds of crops based on user-defined constraints and preferences. This feature could be of significant importance under the objective of minimizing the production costs, the energy consumption or the greenhouse gas emissions and it could also assist in crop rotation. As a further step, the use of such tools can provide with valuable feedback regarding the land use dynamics and the overall evaluation of the production system. This might be a quite significant step in the decision-making process regarding the sustainability of a production system in a wider region given its high complexity and multiple-parameterization.

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