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Optimal energy performance on allocating energy crops

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(Article begins on next page)

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		

29 **1. INTRODUCTION**

30 Energy demand is rising constantly across all sectors, driven by population growth and changing
31 lifestyles (Mekhilef, Saidur, Safari, Mustaffa, 2011). In the agricultural sector, efforts have focused
32 both on reducing the total energy consumed in agricultural practices (Tuomisto, Hodge, Riordan,
33 Macdonald, 2012) but also on rendering the agricultural sector a producer of renewable energy
34 (Demirbas, 2008). It is noteworthy that the agricultural and forestry sector was responsible for
35 2.15% of the total energy used in Europe in 2009 (FAO, 2009). However, during the same year,
36 bioenergy production accounted for the 52% of the total European renewable energy production,
37 with the respective number for the worldwide bioenergy production rising up to 74% (FAO, 2009).
38 There are several ways to produce energy from biomass, starting from direct combustion and
39 moving on to more complex and integrated processes such as biorefining, i.e. the refining of raw
40 materials that come from various biomass sources (Yaman, 2004). Manufacturing of biofuels is a
41 way of processing biomass which is of particular interest due to its economic and environmental
42 benefits (Sarkar, Ghosh, Bannerjee, Aikat, 2012). The cultivation of energy crops and the use of
43 agricultural residues are the main sources of biogas products (Hossain, Liu, Du, 2016). Compared
44 to biorefining process, biogas refers to a mixture of gases coming from the resolution of raw
45 materials that are connected to various biomass sources.

46 There are many studies regarding the conversion of this type of biomass in biogas (Rodriguez,
47 Alaswad, Benyounis, Olabi, 2017; Chiumenti, Boscaro, Da Borso, Sartori, Pezzuolo, 2018). Biogas
48 that comes from grasses has specific constraints that should be taken into consideration. Grasses

49 have high lignocellulosic content and a quite complex structure. Before this type of biomass
50 inserted in the anaerobic digester it should be conditioned in order to the degradation will be
51 accelerated given that the microorganisms will have wider surface area to act. This conditioning
52 process will play crucial role for the quality of the extracted biogas.

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

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

77 Even though there is enough research that includes multiple crop and multiple field production
78 systems, it is highly important to incorporate the appropriate crop-to-field allocation under certain
79 objectives, field features, and operating constraints. There are many reasons to cultivate multiple
80 crops in a large group of fields, such as biodiversity, various harvesting time, field operations

81 management, etc.. More specifically, biodiversity will be affected by the trend for monoculture of
82 a unique specific crop in a given area due to, for example, the gradual elimination of some species
83 and the disturbance of soil nutrients balance. At this light, there are approaches modelling crop-to-
84 field spatial distribution targeting on the effect of various changes on a farm at a financial level
85 (Rounsevell, Annetts, Audsley, Mayr, Reginster, 2003), while others assess the best possible
86 energy crop allocation for the establishment of a sustainable bioethanol production system (Hattori
87 & Morita, 2010). Additionally, there are approaches that focus not only on spatial but also on
88 temporal crop allocation problems, considering certain agronomic constraints (Sorel, Viaud,
89 Durand, Walter, 2010). As a further step to this, using specific models the crop-to-field allocation
90 may provide with feedback about land use in order to determine its dynamics as well as the system's
91 development (Verburg, 2006).

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

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

109 **2. MATERIALS AND METHODS**

110 **2.1 SYSTEM BOUNDARIES**

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

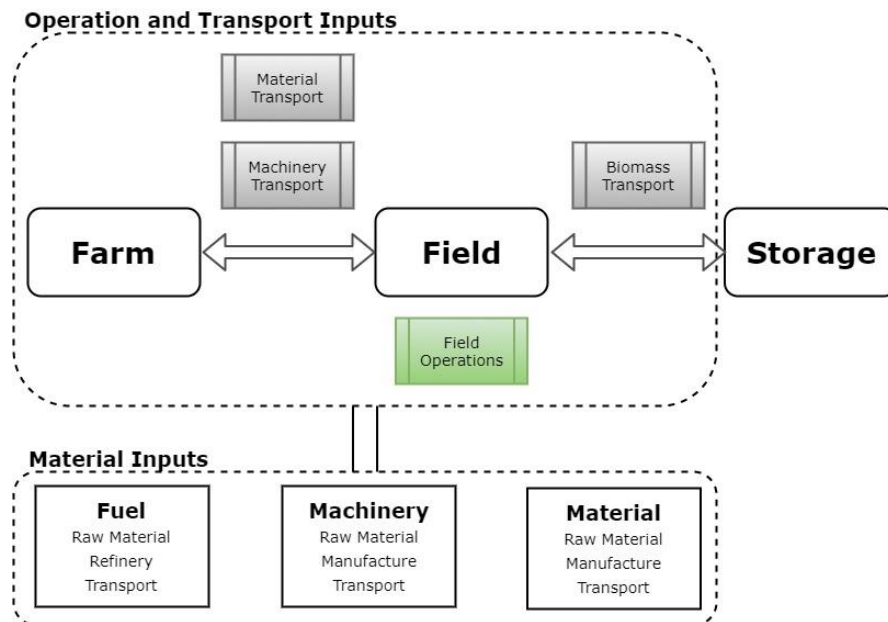


Fig. 1: System Boundaries

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122 2.2 ALLOCATION PROBLEM

123 The ultimate purpose of the proposed tool is to allocate a number of different crops to a number of
 124 dispersed fields, with the aim of maximizing the energy balance of the system, considering a
 125 number of specific constraints. Optimizing crop allocation is very important in the operation
 126 management of complex agricultural systems, which include a large number of dispersed fields and
 127 different types of crops, as it minimizes the energy spent and the overall cost of transportation. For
 128 the approach of the allocation problem, let $C = \{1, 2, \dots, l\}$ denote the set of the indices
 129 corresponding to the different energy crops, where l is the number of the different crops, and let
 130 $F = \{1, 2, \dots, k\}$ denote the indices of the fields, where k is the total number of the fields

131 available. Two different approaches are attempted to solve the allocation problem, depending on
 132 the number of crops that are cultivated in each field. These two approaches, the BP and the LP
 133 methods, were modelled by using the mathematical software MatLab[®] and they are presented
 134 below.

135 2.2.1 Binary programming

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

$$139 \quad b_{ij} = \begin{cases} 1, & \text{if crop } i \text{ is allocated to field } j, i \in C, j \in F \\ 0, & \text{otherwise} \end{cases}$$

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

$$\begin{aligned} &\text{Maximise} && \sum_{i=1}^l \sum_{j=1}^k b_{ij} \cdot eb_{ij} \\ &\text{Subject to} && \sum_{i \in C} b_{ij} = 1 \quad \forall j \in F && \text{[i]} \\ &&& \sum_{j \in F} b_{ij} \cdot a_j \geq t \cdot \sum_{j \in F} a_j \quad \forall i \in C && \text{[ii]} \\ &&& b_{ij} \in \{0,1\} \quad \forall i \in C, j \in F && \text{[iii]} \end{aligned}$$

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

145 2.2.2 Linear programming

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

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

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

$$\text{Subject to} \quad \sum_{i \in C} sa_{ij} = a_{ij} \quad \forall j \in F \quad [\text{iv}]$$

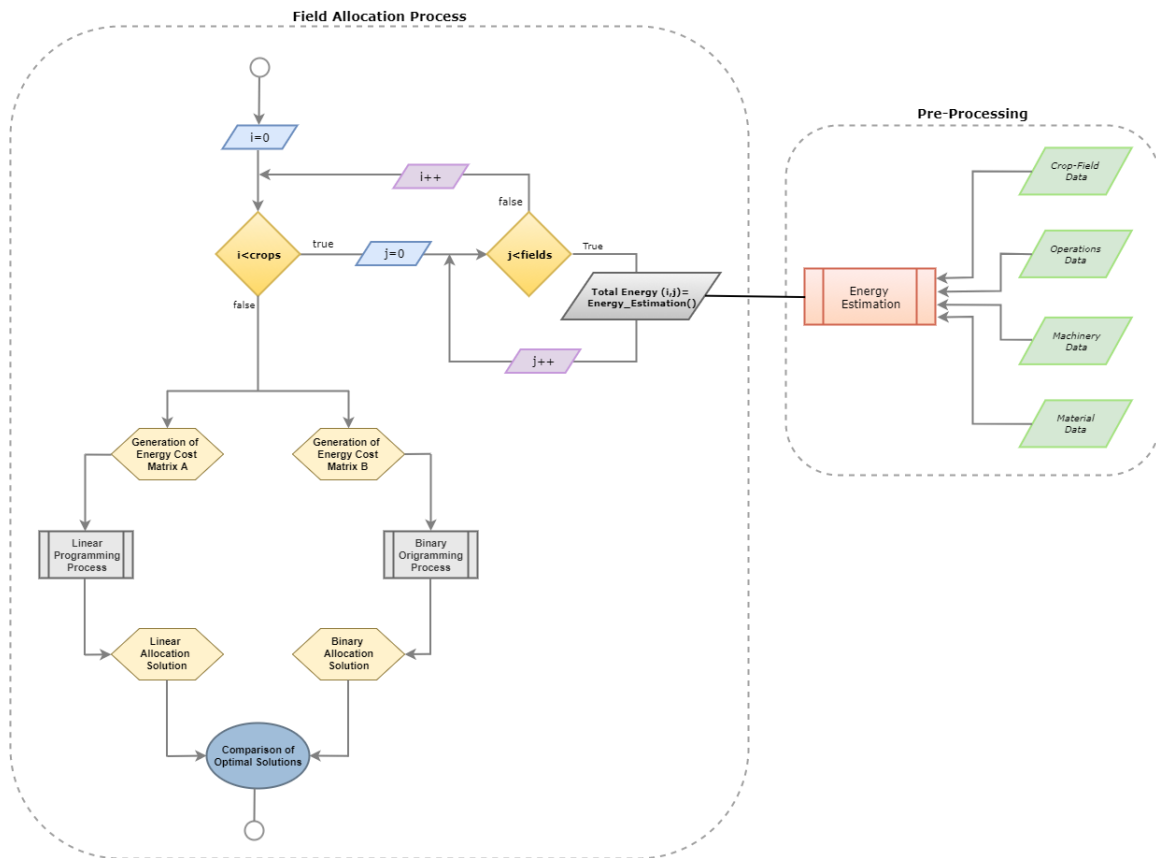
$$\sum_{j \in F} sa_{ij} \cdot a_j \geq t \cdot \sum_{j \in F} a_j \quad \forall i \in C \quad [\text{v}]$$

$$0 \leq sa_{ij} \leq \max\{a_j\} \quad \forall i \in C, j \in F \quad [\text{vi}]$$

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

156 2.3 ALLOCATION TOOL

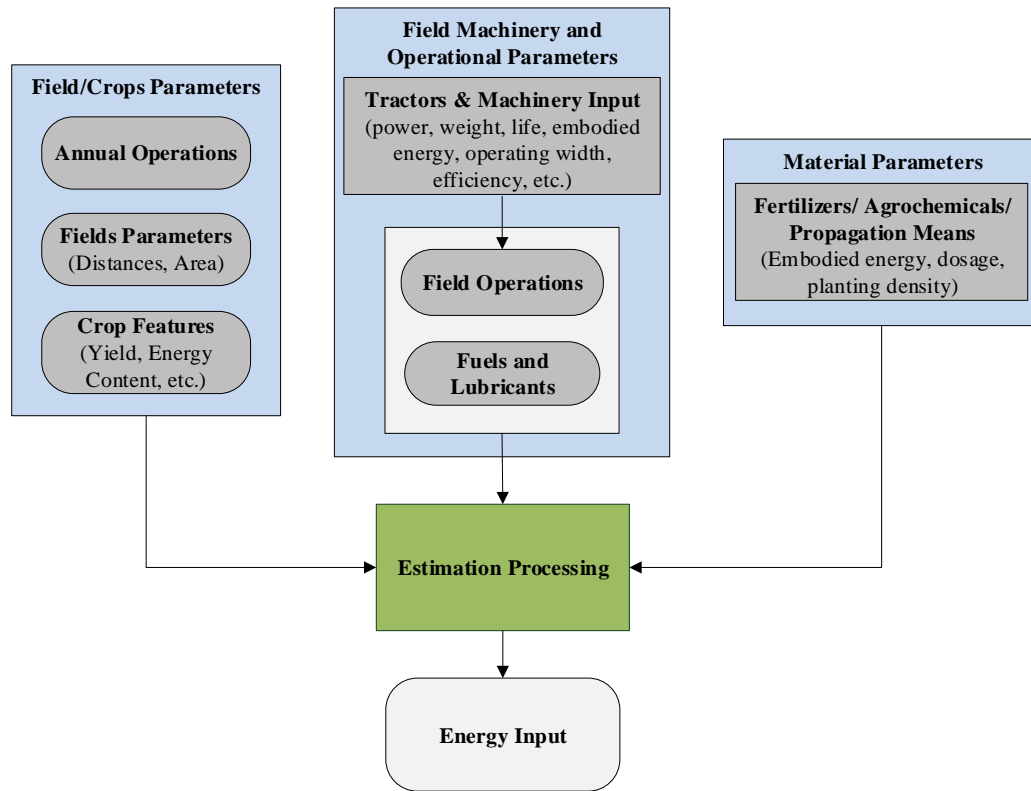
157 Fig. 2 shows the algorithmic representation of the proposed allocation tool, which is used to
 158 optimize field assignment and maximize energy balance. Two main processes are depicted, the one
 159 that is related to the energy estimation process and the other regards to the field allocation process.



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Fig. 2: An overview of the allocation tool

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



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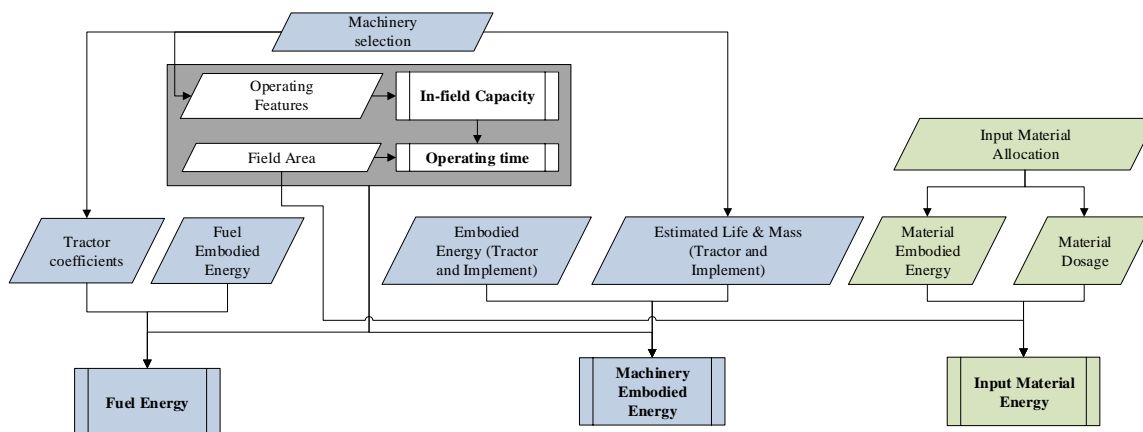
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Fig. 3: An overview of the pre-processing energy input estimation

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

177 Regarding the in-field part of every operation the energy input regards the fuel energy, the
 178 machinery embodied energy and the material input energy when IMF operation is held. As it is
 179 shown briefly in Fig. 4, at the beginning the in-field capacity is calculated based on the operating
 180 features, i.e. the operating width, the operating speed, and the field efficiency. Given this capacity
 181 and the field area, the operating time can be estimated. As a further step, for fuel energy estimation
 182 apart from operating time, fuel consumption, tractor power, and tractor coefficients are taken into
 183 account. It should be noted that specific input and estimation calculations are included regarding
 184 lubricants use in agricultural machinery. In parallel, for machinery embodied energy, the

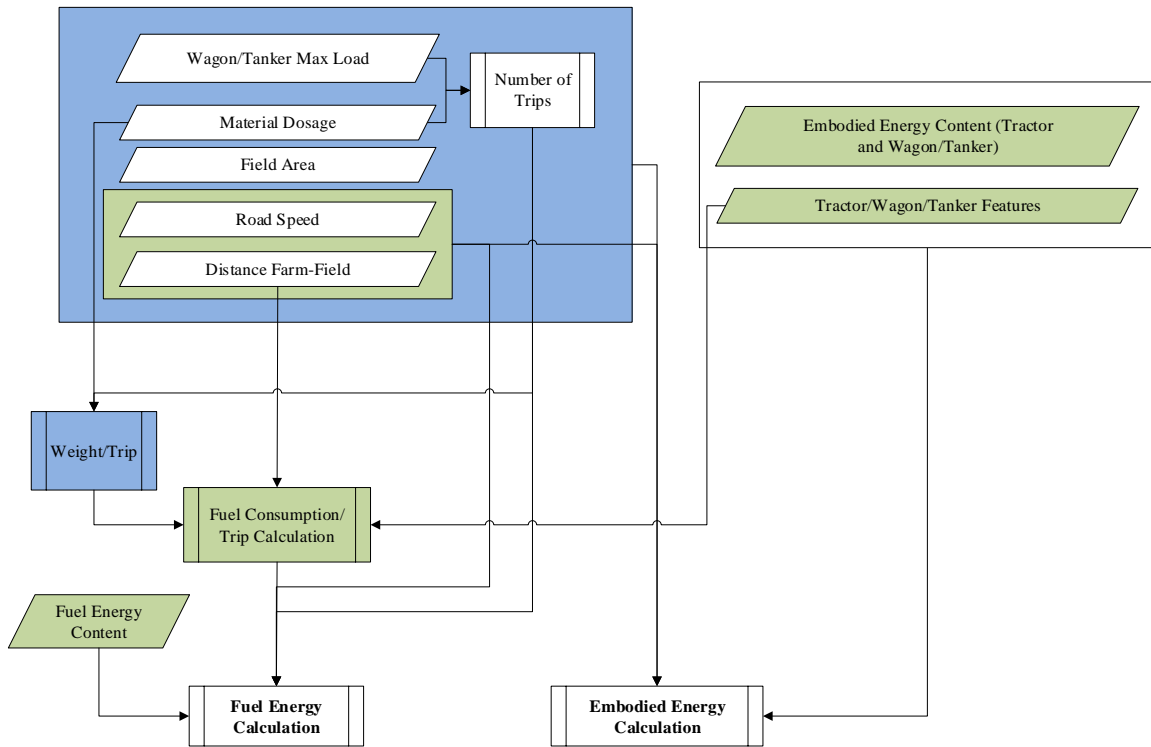
185 parameters that involved are these presented in Fig.4. The embodied energy is defined as the energy
 186 required during the product's life cycle from its early production stages up to its introduction in the
 187 agricultural production system (Kitani, 1999). Finally, the input material energy (IMF operations)
 188 should be included given the parameters presented in green colour in Fig. 4. This corresponds to
 189 any agrochemical, fertilizer or propagation means.



190

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

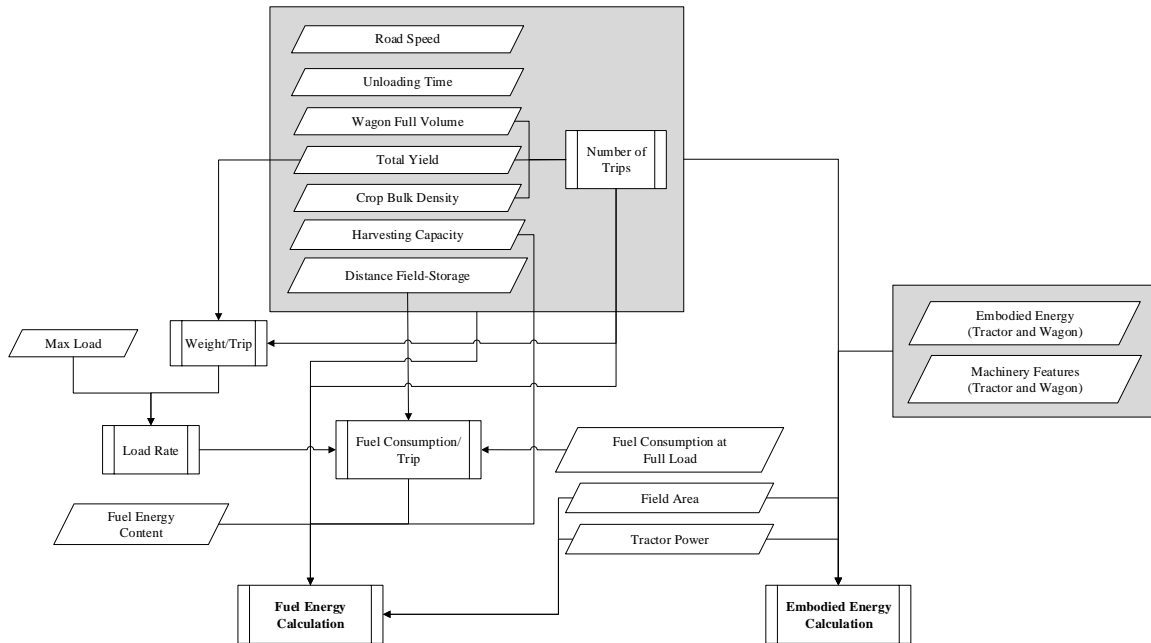
192 In every field operation the machinery transport from farm-to-field and vice versa is included (Fig.
 193 5 - blue colour regards only on IMF operations and green colour for both NMF and IMF operations).
 194 For IMF operations this transport cycle is connected with the material application. In this case, for
 195 the estimation of energy consumption, the number of trips might be required. In the rest of the field
 196 (NMF) operations, the energy required in this round trip is considered only once. Apart from the
 197 number of trips in IMF operations, the fuel consumption per trip, the fuel energy coefficient and
 198 the maximum volume/weight of wagon/tanker (for planting and fertilization/agrochemicals
 199 spreading, respectively) are included for the fuel energy calculation. The embodied energy content
 200 of tractor and implement/wagon/tanker combined with their features (i.e. lifetime, weight), the
 201 number of trips (in IMF operations), the distance from farm to field and the road speed are taken
 202 into consideration for the embodied energy estimation.



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

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



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

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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.

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225 **3. CASE STUDY DESCRIPTION**

226 **3.1 AREA AND PRODUCTION SYSTEM FEATURES**

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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.

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234 The total field area to be cultivated in this case study equals 356.77 ha and ranges from 1.63 ha to
235 18.8 ha. The shape of the fields is assumed that have no effect on the allocation tool results. In
236 addition, the average farm-field distance was calculated at 8.07 km - ranging from 1.3 km up to
237 26.6 km. The average field-plant distance was estimated at 8.42 km and ranged from 0.99 km up
238 to 18.3 km. In both cases, the farm-field and field-plant distances were calculated by using Google
239 Maps© application. It should be noted that not all the fields examined are adjacent to roads
240 registered in the Google Maps database. In these cases, the corresponding distances from the field
241 to the closest registered road were considered including the relevant distances.

242 **3.2 CROP FEATURES**

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

248 *Miscanthus giganteus* is a perennial grass crop with a lifetime of more than 10 years, which belongs
249 to the C₄ photosynthetic pathway plants (Rodias, Berruto, Bochtis, Busato, Sopegno, 2017). Due
250 to its high lignocellulosic content, *Miscanthus giganteus* is considered a promising crop for the
251 production of biofuels and other bio-based products (Fernando, Costa, Barbosa, Monti,
252 Rettenmaier, 2016). Reaching up to 4 m of height, this energy crop is characterized by high dry
253 matter yield while simultaneously it is resource efficient regarding the materials (water, herbicides,
254 and fertilizers) used during its cultivation (Price, Bullard, Lyons, Anthony, Nixon, 2004).
255 *Miscanthus giganteus* is a crop that easily adapts to diversified climatic conditions and soils
256 (Angelini, Ceccarini, Nasso o Di Nasso, Bonari, 2009).

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

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

270 **3.3 AGRONOMIC PROTOCOL**

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

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

276 Table 1 presents all the necessary field operations (presented as full tiny squares) that take place
277 over a period of ten years, in-line with the production scenario. These field operations are defined
278 by the agronomic protocol adopted, which is based on common agricultural practices following the
279 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	□	□	□	□	■	■	■	■	■

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C₁: *Miscanthus giganteus*, C₂: *Arundo donax*, C₃: *Panicum virgatum* (■ when an operation is applied and □ when is not applied)

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Common operations for all crops include a light soil preparation, without the need for any further

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soil treatment, which is essential before establishing the crops (Angelini et al., 2009). This involves

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light plowing, and disk-harrowing at a depth of 20 cm, prior to planting. Regarding weed control,

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Miscanthus giganteus and *Arundo donax* are characterised as weed resistant plants, thus not

287 requiring any special weed control during their growth phase. For this reason, only for *Miscanthus*
 288 *giganteus* a single herbicide application was considered to be applied just after the soil preparation
 289 and before planting, in order to minimize weed competitiveness against the newly-emerged plants.
 290 On the contrary, the fact that *Panicum virgatum* is established by seeds makes it very sensitive
 291 against weeds and requires more thorough weed control, especially during the first years following
 292 its establishment (Piscioneri, Pignatelli, Palazzo, Sharma, 2001). The herbicide quantities used for
 293 the protection of the crops during these first years are presented in Table 2.

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

Operations	<i>Miscanthus giganteus</i>	<i>Arundo donax</i>	<i>Panicum virgatum</i>
Soil Preparation	Plow and Disk-harrow (20 cm depth)		
Weed control	One glyphosate application of 20 kg ha ⁻¹ in the 1 st 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 2 nd and 3 rd 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 ₂ O ₅ and 45 kg K ₂ O ha ⁻¹ and year ⁽¹⁰⁾	80 kg N, 200 kg P ₂ O ₅ and 100 kg K ₂ O ha ⁻¹ (1st year) 80 kg N, 50kg P ₂ O ₅ ha ⁻¹ (every even year) 80 kg N, 50kg P ₂ O ₅ and 100 kg K ₂ O ha ⁻¹ (every odd year) ^{(11),(12)}	100 kg P ₂ O ₅ and 100 kg K ₂ O ha ⁻¹ (1st year) Second year no fertilization is required 75 kg N, 100kg P ₂ O ₅ , 100kg K ₂ O 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 2 nd year ⁽¹³⁾	Harvesting with conventional forage harvester every year starting from the 2 nd year ⁽⁵⁾	Mowing and then Harvesting with conventional mower and forage harvester every year starting from the 2 nd 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⁾

295 ⁽¹⁾(Caslin, Finnan, Easson, 2010), ⁽²⁾(Pyter, Heaton, Dohleman, Voigt, Long, 2009), ⁽³⁾(Garten et al., 2010), ⁽⁴⁾(Schmer, Vogel, Mitchell,
 296 Perrin, 2008), ⁽⁵⁾(Angelini, Ceccarini, Bonari, 2005), ⁽⁶⁾(Piscioneri, Pignatelli, Palazzo, Sharma, 2001), ⁽⁷⁾(Sokhansanj et al.,
 297 2009), ⁽⁸⁾(Mantineo, D'Agosta, Copani, Patanè, Cosentino, 2009), ⁽⁹⁾(Cristian et al., 2001), ⁽¹⁰⁾(Lee, 2011), ⁽¹¹⁾(Atkinson, 2009),
 298 ⁽¹²⁾(Vermerris, 2008), ⁽¹³⁾(Heaton et al., 2010), ⁽¹⁴⁾(Bassam, 2010), ⁽¹⁵⁾(Hood, Nelson, Powell, 2011)

299 *Miscanthus giganteus* and *Arundo donax* are propagated by rhizomes with the use of row-crop
 300 planters, whilst *Panicum virgatum* is established with the use of seeds. The usual planting density
 301 for *Miscanthus giganteus* is 15,000-17,000 rhizomes per hectare, considering an average loss rate

302 of 30-40% (Garten et al., 2010; Schmer, Vogel, Mitchell, Perrin, 2008). For *Arundo donax*, the
303 planting density ranges between 20,000-40,000 plants ha⁻¹ (Angelini, Ceccarini, and Bonari, 2005).
304 Regarding *Panicum virgatum*, a planting density of 10-20 plants per m² is considered beneficial for
305 the plant's health (Piscioneri, Pignatelli, Palazzo, Sharma, 2001; Sokhansanj et al., 2009). The
306 number of plants per hectare that were selected for the present study is demonstrated in Table 2.

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

322 **3.4 MACHINERY AND MATERIAL INPUT**

323 The field machinery inputs, as they are incorporated in the allocation tool for both in-field
324 operations and transportation, are presented in Table 3. Regarding tractor embodied energy it was
325 assumed a single coefficient for both type of tractors (Kitani, 1999) even though there are studies
326 that compare energy demand for different sizes of tractors (Mantoam, Romanelli, Gimenez, 2016).
327 In addition to this, it should be clarified that the field machinery are assumed to be used exclusively
328 in these crops. For the micro-irrigation system, it was assumed that the water is pumped from a
329 10 m deep well. The irrigation system lifetime is considered to be 20 years while the energy
330 coefficient of electricity and the PVC pipe embodied energy is 8.1 MJ kWh⁻¹ and 110.66 MJ kg⁻¹,
331 respectively (Barber, 2004; Diotto, Folegatti, Duarte, Romanelli, 2014; Wells, 2001).

332 Regarding material input, propagation means, fertilizers and agrochemicals are included. For
333 *Miscanthus giganteus* and *Arundo donax* propagation means, a value of 0.00431 MJ per rhizome
334 and 0.00345 MJ per rhizome were considered (Price, Bullard, Lyons, Anthony, Nixon, 2004), while
335 the energy content of *Panicum virgatum* seeds is 2.86 MJ kg⁻¹ (Caslin, Finnan, Easson, 2010;
336 Kitani, 1999). Regarding fertilization, only the main fertilizer ingredients were considered for all
337 crops, as presented in the aforementioned agronomic protocols. Their corresponding energy
338 coefficients are 78.1 MJ kg⁻¹ for N, 17.4 MJ kg⁻¹ for P₂O₅ and 13.7 MJ kg⁻¹ for K₂O (Schmer et al.,
339 2008). Finally, for the agrochemicals application the herbicides glyphosate (for *Miscanthus*
340 *giganteus* production), atrazine and 2,4-D (in *Panicum virgatum*) were used. Their corresponding
341 energy content is 454 MJ kg⁻¹ for glyphosate, 190 MJ kg⁻¹ for atrazine and 85 MJ kg⁻¹ for 2,4-D
342 (Caslin, Finnan, Easson, 2010; Garten et al., 2010; Schmer, Vogel, Mitchell, Perrin, 2008).

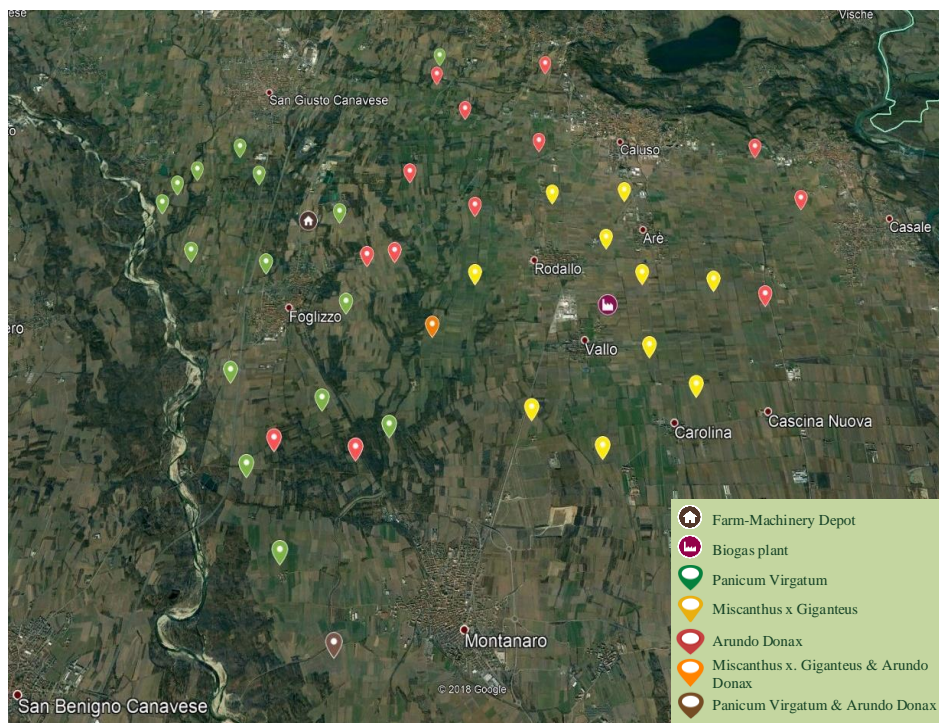
Table 3: Machinery and Transportation Inputs

		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

345 **4. RESULTS - DISCUSSION**

346 **4.1 BASIC SCENARIO**

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

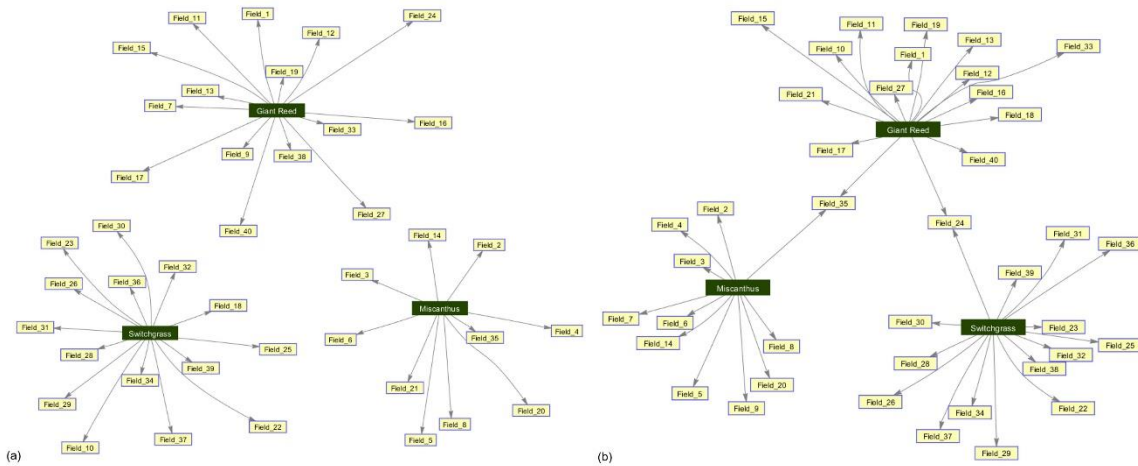


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Fig. 7: Geographical representation of fields allocation for $t=0.3$ (LP solution)

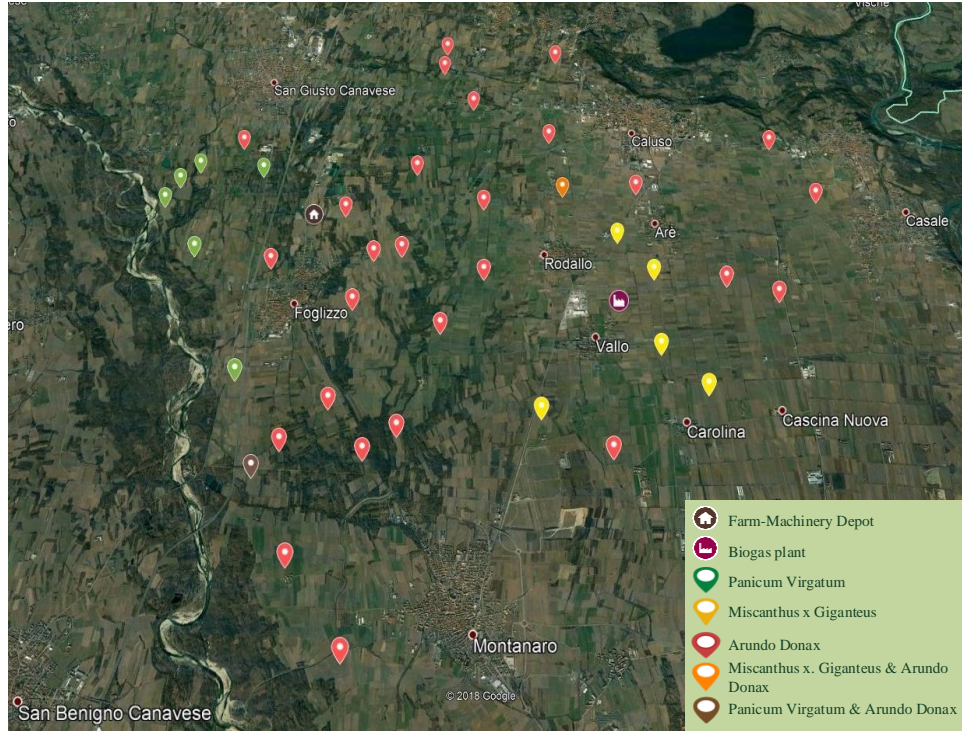
354 Fig. 8 presents the two optimal allocation solutions (BP and LP, respectively) extracted by the tool
 355 for a threshold area of $t=0.3$. By the BP solution, only one crop is assigned to each field, while by
 356 the LP solution more than one crop may be assigned to each field.



357
 358 **Fig. 8: (a) BP and (b) LP allocation solution for the maximization of energy balance ($t=0.3$)**

359 In the BP solution, 10 fields are allocated to *Miscanthus giganteus*, 15 to *Panicum virgatum*
 360 (switchgrass) and the rest (15 fields) to *Arundo donax*. In the LP solution, *Miscanthus giganteus* is
 361 assigned to 11 fields, *Panicum virgatum* to 15 fields and *Arundo donax* to 16 fields. The maximum
 362 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.

363 To evaluate further the implementation of the allocation tool, a threshold area of $t=0.15$ was
 364 assessed. Fig. 9 depicts the geographical allocation of fields in the presented area according to LP
 365 solution for $t=0.15$. Furthermore, Fig. 10 represents both the BP and LP allocation solutions of the
 366 basic scenario for $t=0.15$. Here, 5 fields are allocated to *Miscanthus giganteus*, 7 fields to *Panicum*
 367 *virgatum* and 28 fields to *Arundo donax* regarding the BP solution (Fig. 10 (a)). On the other side,
 368 for the LP solution 6 fields are assigned to *Miscanthus giganteus*, 7 fields to *Panicum virgatum* and
 369 28 fields to *Arundo donax* (Fig. 10 (b)). The EB in the BP solution was $1,294.6 \cdot 10^3$ GJ compared
 370 to $1,294.7 \cdot 10^3$ GJ in the LP solution for $t=0.15$ in the basic scenario.

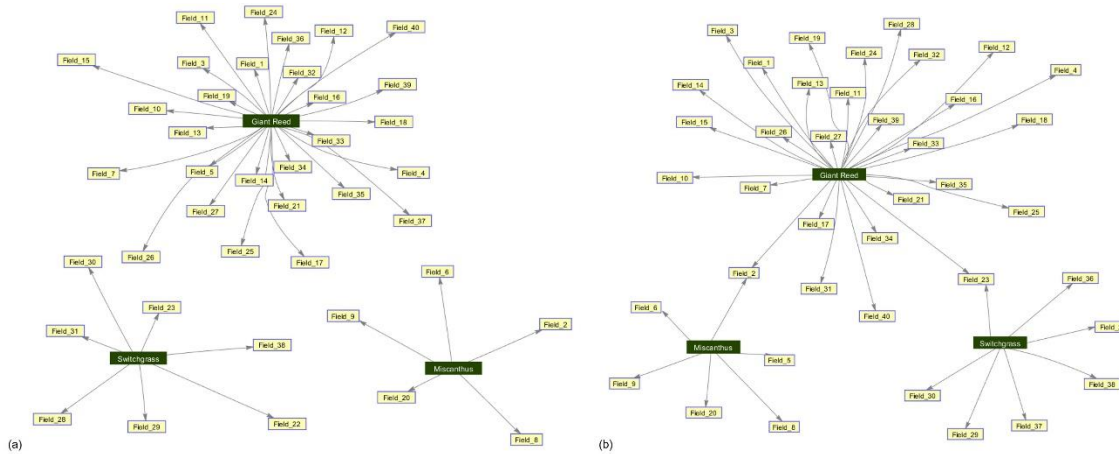


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Fig. 9: Geographical representation of fields for t=0.15 (LP solution)

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374

375

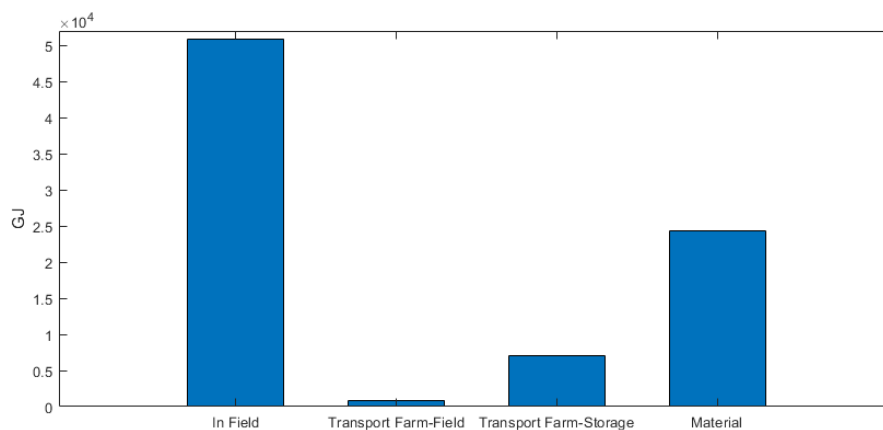
Fig. 10: (a) BP and (b) LP allocation solution for the maximization of energy balance (t=0.15)

376

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 $1,207.8 \cdot 10^3$ GJ up to $1,208.4 \cdot 10^3$ GJ and for the linear solution would vary from $1,207.9 \cdot 10^3$ GJ up to $1,208.5 \cdot 10^3$ GJ.

380

381 The distribution of the energy input (EI) included in (i) in-field operations, (ii) farm-field
 382 transportation, (iii) field-storage transportation, and (iv) the embodied energy of agricultural
 383 material (fertilizers, herbicides, and propagation means) is shown in Figure 11, indicatively for
 384 $t=0.3$ in LP solution. The EI distribution for different t and by using both programming methods
 385 (binary or linear) has similar results with minor variation. In the basic scenario, the highest EI
 386 regarding the in-field operations comes from irrigation, fertilization and harvesting while for the
 387 material application, the energy consumption regards mainly on fertilizers embodied energy and
 388 less on the embodied energy of herbicides and propagation means. The main energy consuming
 389 operations regards on fertilization, irrigation and harvesting. This occurs because all of them are
 390 connected to annual operations with high energy components.



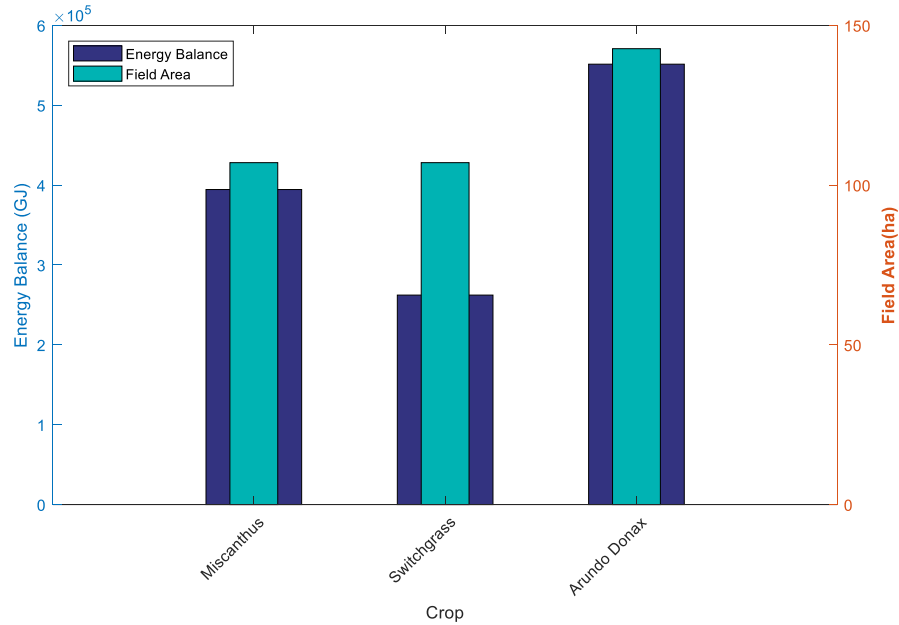
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Fig. 11: Distribution of the total energy consumption (in GJ) (LP solution)

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

400



401

402

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

403

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.

407

408 4.2 ALTERNATIVE SCENARIOS

409

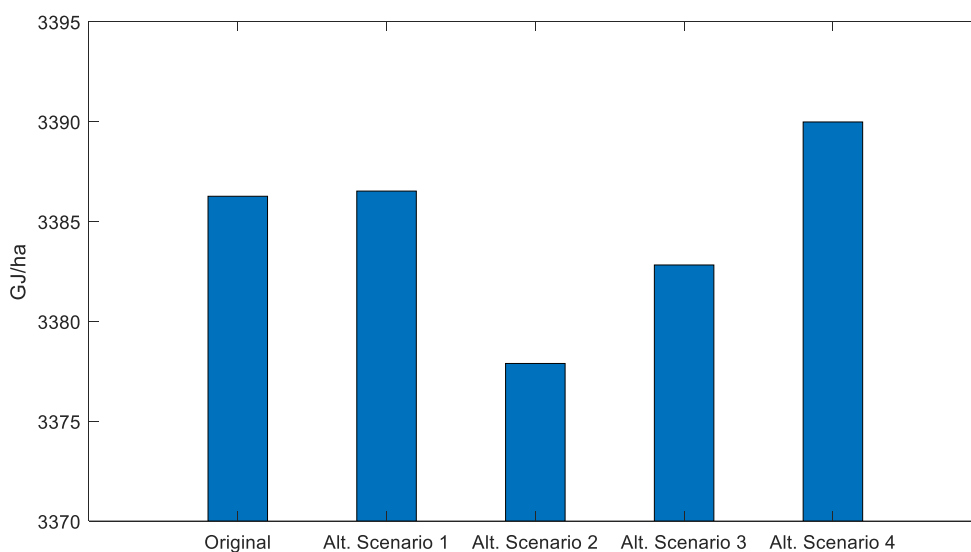
To expand further the potential of the proposed allocation tool, further hypothetical scenarios were evaluated and are the following: Alt. Scenario 1: Big fields located far from the farm, Alt. Scenario 2: Big fields located far from the biogas plant, Alt. Scenario 3: Small fields located far from farm, 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.

418

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

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



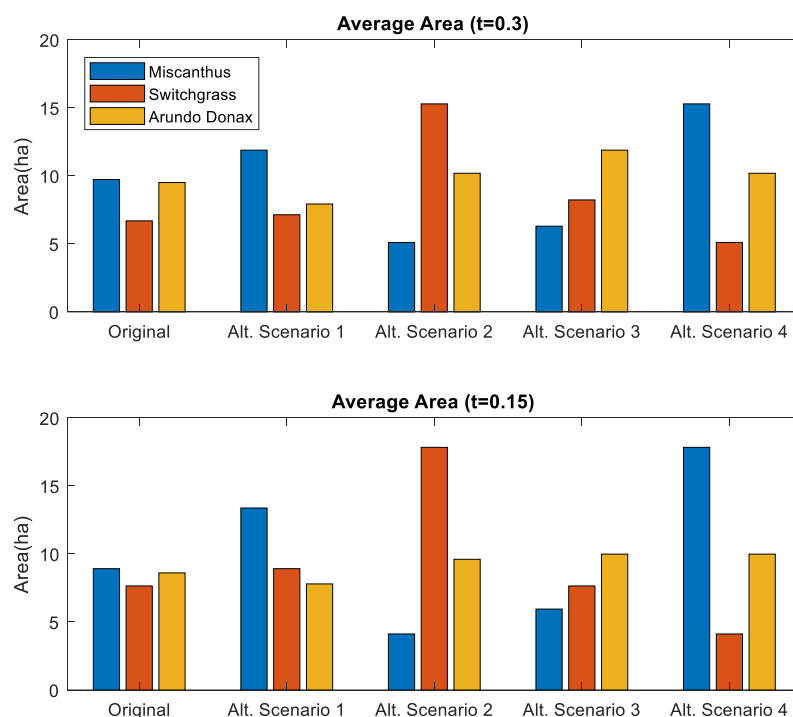
429

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

430

431 In order to evaluate better the functionality of the allocation tool, the average size (area) of the of
 432 fields that are allocated to each crop for all scenarios is calculated and presented in Fig. 14 for both

433 $t=0.3$ and $t=0.15$ regarding LP solution. According to the results, *Miscanthus giganteus* has high
 434 variability on the size of the fields that is allocated to through the different scenarios, while
 435 switchgrass tends to be established in medium-size fields in all scenarios, apart from the alternative
 436 scenario 1 that the big fields are located far from plant where switchgrass tends to be assigned
 437 mostly to big fields. Finally, *Arundo donax* follows medium size fields in all scenarios.



438

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

441 5. CONCLUSION

442 Examining the different allocation configurations that resulted from testing different scenarios, it
 443 is concluded that the optimal crop allocation is strongly related to the user preferences. The
 444 threshold area t is an important factor that allows different constraints to be considered in the
 445 optimization process. For example, the interest from a biomass processing plant point-of-view is to
 446 maximize its overall energy gain. However, there are limiting factors such as the total cost of the
 447 cultivation or the composition of the biomass for the production of biofuels that have to be

448 considered. On the other hand, the interest from a producer's point-of-view could focus on the
449 minimization of the total input of the system either to reduce the economic cost or to address the
450 adverse environmental impacts of the cultivation process.

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

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