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The Effect of Distance and Field Area on Energy Balance of Switchgrass

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Energy crops, nowadays, constitute a significant share of energy production through biomass sources. Switchgrass is among the energy crops with high potential in biomass energy production, given some of its specific features. In order to evaluate the efficiency and sustainability of each energy crop, it is crucial to estimate specific energy parameters, such as the energy consumption, the energy output, the Energy Return on Investment (EROI) or energy balance, etc. A computational tool is used in order to estimate the energy balance of a Switchgrass crop under a basic scenario of individual field including an in-depth analysis of the involved in-field and transportation operations. By this way, all the in-field and transport operations that contribute in the estimation of the energy consumption, firstly, and, furthermore, the energy balance are taken into account. Every energy input that is inserted into this crop's system, directly or indirectly, is assessed. One of the most important energy inputs, according to this analysis, corresponds to the energy consumption during operation of any kind of transportation. In this paper, given that biomass energy crops are directly connected to transportation issues, the effect of the two main distances that contribute to this system's energy balance (i.e. the distance from farm to field and the one from field to biomass storage facilities) is estimated given various distances. Finally, regarding various field areas under this cultivation scenario, the variation of energy balance is presented.

1. Introduction

Switchgrass has been studied in many researches as an energy crop regarding the energy requirements (Bassam, 2010) and the probability of optimization in specific characteristics of the crop (i.e. farm practices and other agronomic parameters) ((Miesel et al., 2011; Piscioneri et al., 2001; Christian et al., 2001)). In other cases, switchgrass has been studied in comparison to other energy crops ((Lewandowski et al., 2003; Thériault et al., 2003)). Given the fact that switchgrass has many beneficial characteristics as a potential energy crop, the majority of the approaches correspond to the optimization of the crop production process under different criteria, such as fertilization or agrochemicals application. Though, it is necessary for an energy crop to be assessed for the whole supply chain, i.e. from the establishment of the crop to the harvest and the transportation of the harvested product to the storage-processing facilities. Overall, in this way, the evaluation of the energy consumption will be more accurate for the whole supply chain. At this level a model for energy analysis of miscanthus production that includes both in-field and transport operations has been presented by Sopegno et al. (2016). In a similar way, in the present study, a calculation code has been created by using MatLab programming software in order to execute all the estimation process.

2. Crop requirements

Switchgrass has many positive characteristics as a potential biomass crop, namely the high net energy production per hectare, the low production costs, the low nutrient requirements, the high water and nitrogen efficiency, the large range of geographical adaptation, the low ash content, its cold tolerance after winter

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hardening, its tolerance in acid conditions, its adaption in wide range of soils and the potential for carbon storage in soil (Piscioneri et al., 2001; Christian et al., 2001; Bassam, 2010; Garten et al., 2010). Specifically, switchgrass is a warm season, perennial (over 15 years under proper management) herbaceous grass, normally established by seed. It develops rhizomes and its root system is quite deep. It grows up to 50-250 cm tall depending on the variety and climatic conditions. Productivity may vary between 6 t of dry matter (DM)/ha in areas with low fertility up to 25 t of DM/ha in fertile areas (Christian et al., 2001).

Regarding the crop operations needed, seedbeds are normally prepared using traditional ploughing and secondary cultivation to produce a firm seedbed with a fine-textured surface. During the first growth, it is significant for the seedbed to have been weed controlled thoroughly because switchgrass is not competitive during the first establishment period (Bassam, 2010). This occurs because it is established by seed. The number of plants established can be up to 400 plants per m^2 ((Bassam, 2010; Christian et al., 2001). As for fertilization, switchgrass can produce high yield even under limited fertility (75 $kg \cdot ha^{-1}$ of nitrogen (Vermerris, 2008). In the first year there is no need for nitrogen fertilizers because it is not necessary for the development of the crop and may promote weed growth leading to competition against the new plants. Phosphorus and potassium should be applied if soil availability is low and after a soil analysis. In the following years application of nutrients should be at such a level that anticipates rising productivity and also takes into account losses of minerals in harvested biomass (Christian et al., 2001). Diseases and serious pest problems have not been reported in switchgrass in Europe (Bassam, 2010; Christian et al., 2001). Regarding harvesting, there is no technical reason so as the crop not to be cut and harvested by traditional grass-harvesting machinery (Bassam, 2010). Given that switchgrass does not perform well when is harvested too frequently, one or two cut harvests per year are usually employed (Vermerris, 2008). Switchgrass yield is estimated to vary considerably, from less than 1 t of DM/ha to almost 40 t of DM /ha. The most frequently observed yield class across all ecotypes, cultivars, soils, and management practices is between 10 and 12 t of DM /ha (Hood et al., 2011).

3. Materials and methods

3.1 Description of the system

In the presented study the system boundary includes three basic categories of operations, i.e. the in-field operations, the corresponding field-to-farm transports of the machinery and wherever needed the transportation of materials that should be applied in the field, and the biomass field-to-storage facilities transportation. The storage of biomass or any other processing of the biomass is not taken into account. .

3.2 Analysis of the energy inputs

The energy consumption is connected with the direct and indirect energy inputs. As for indirect inputs, here, they regard the embodied energy of the operating machinery, the materials applied in the field, and the fuels and lubricants. In Table 1, the main energy inputs required by the crop of switchgrass are presented.

Table 1: The main energy coefficients

Inputs	Energy coefficients	Units	References
Moldboard plough	180	MJ/kg	(Kitani, 1999)
Disk-harrow	149	MJ/kg	(Kitani, 1999)
Planter	133	MJ/kg	(Kitani, 1999)
Mower	110	MJ/kg	(Kitani, 1999)
Harvester	116	MJ/kg	(Kitani, 1999)
Fertilizer Spreader	129	MJ/kg	(Kitani, 1999)
Tractors	138	MJ/kg	(Kitani, 1999)
Wagon-trailer	50	MJ/kg	(Kitani, 1999)
Diesel fuel	41.2	MJ/l	(Wells, 2001; Barber, 2004)
Lubricants	46	MJ/l	(Saunders et al., 2006)
Seeds	2.9	MJ/kg	(Boydston, 2010)
Nitrogen (N)	78.1	MJ/kg	(Kitani, 1999)
Phosphorus (P_2O_5)	17.4	MJ/kg	(Kitani, 1999)
Potassium (K_2O)	13.7	MJ/kg	(Kitani, 1999)
Herbicide	85/190	MJ/kg	(Boydston, 2010; Renz et al., 2009)
Human Power	1.96	MJ/h	(Hamedani et al., 2011)
Irrigation Pipe	110.6	MJ/kg	(Diotto et al., 2014)
Electricity	8.1	MJ/kWh	(Wells, 2001; Barber, 2004)

The basic scenario regards a “unit” field of 1 ha area that is located 1000 m from the base farm and 1000 m from the biomass storage facilities. The farm operations that take place for the ten-year period (Y1-Y10) are shown in Table 2 in a binary expression, i.e. 0 means that the operation is not held and 1 when the operation is executed. This system was evaluated for an exploitation period of 10 years in its basic scenario in order to evaluate it further regarding the effect of the distance and the field area on the energy consumption

Table 2: Field operations per year

Operations	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10
Ploughing	1	0	0	0	0	0	0	0	0	0
Disk-harrowing	1	0	0	0	0	0	0	0	0	0
Planting	1	0	0	0	0	0	0	0	0	0
Mowing	0	1	1	1	1	1	1	1	1	1
Harvester	0	1	1	1	1	1	1	1	1	1
Fertilizer Spreading	1	0	1	1	1	1	1	1	1	1
Agrochemicals Spreading	1	1	1	0	0	0	0	0	0	0
Transport	0	1	1	1	1	1	1	1	1	1
Irrigation	1	1	1	1	1	1	1	1	1	1

Farm machinery contributes as energy consumption, not only through the fuel and lubricant energy input that are included in each operation, but also through the embodied energy of each machinery, implement or tractor. In the embodied energy, parameters such as the construction energy of raw materials, the energy of construction of farm machinery, the transport energy to the final consumer and the repair-and-maintenance energy of machinery for their estimated lifetime are included. By using the energy inputs of machinery, and given their corresponding weights, their estimated lifetime and the operational capacity for each farm operation (Wells, 2001; Alluvione et al., 2011)**,** the machinery energy consumption can be extracted in MJ/ha.

Concerning fertilization, based on the literature, the following fertilization planning was adopted: for the first year 100 kg·ha^{-1} P_2O_5 and 100 kg·ha^{-1} K_2O were applied, in the second year there was no fertilization, the following odd years (3rd, 5th, 7th and 9th) were applied 75 kg ·ha^{-1} of nitrogen fertilizers, 100 kg·ha^{-1} P_2O_5 and 100 kg·ha^{-1} K_2O per year, and the following even years (4th, 6th, 8th and 10th) was considered an application of only nitrogen fertilizers in an amount of 75 kg·ha^{-1} per year. In order to keep up with these nutrients demands, urea, single superphosphate and potassium chloride were selected, respectively.

Switchgrass requires weed control for the first years of establishment in order to compete against weeds. In the present study, agrochemicals spreading were operated the first three years, according to the following plan: the first year it was applied a pre-planting herbicide application in quantity of 1.12 kg·ha^{-1} by using Atrazine and for the second and third year application of 4.26 kg·ha^{-1} by using 2,4-D (2,4-Dichlorophenoxyacetic acid) herbicide. Switchgrass does not have any requirements in other agrochemicals application (herbicide, pesticide, fungicide, etc.) from the fourth year on.

The typical plant density of switchgrass presents huge variation. In the present study, plant density of 15 plants per m^2 was selected.

Regarding harvesting, it was considered one cut per year starting from the second year. Firstly, mowing is operated in order to give some time to the mowed plants to get dry during winter (Piscioneri et al., 2001) and then, forage harvester operates, too. Switchgrass yield, in this study, was considered to be 11 t·ha^{-1} with corresponding energy content of 19.2 MJ·kg^{-1} of dry matter (Sokhansanj et al., 2009).

As for irrigation, given the many choices that are suggested, it was selected micro-irrigation to be established in the crop in order to achieve sustainability goals. The emitters that included in the estimation were two per m^2. The water was pumped from 10 m depth well and the total water lift for the whole system was considered 34 m. The annual water demand for this crop is 240 mm (Christian et al., 2001). In order to evaluate the total pipe mass the Eq. 1 adopted from Diotto et al. (2014):

$$w = e^{\{-8.714+[1.911\times\ln(D)]+4.53\times10^{-7}\times PC^2} \qquad (1)$$

where w is the pipe mass for PVC pipes in kg·m^{-1}, D is the commercial diameter in mm and PC is the pipe pressure class in kPa. For the operation of irrigation, an electric pump has been considered.

4. Results

4.1 Basic scenario

The energy contribution per field operation can be divided mainly in three categories, i.e. fuels energy, embodied energy and materials energy. Regarding embodied energy, it corresponds to the energy that is embodied in field machinery, but for irrigation it refers to the embodied energy of pipes, pump and each other component. As for material, it includes the agrochemicals, fertilizers and propagation means embodied energy. The energy consumption for these categories is presented in Table 3.

Table 3: Main categories of energy consumption per field operation for a ten-years' crop life (MJ ha^{-1})

Operation	Fuels Energy	Embodied Energy	Material Energy	Total Energy
Ploughing	720	74	-	796
Disk-harrowing	551	52	-	605
Planting	287	50	20	359
Mowing	8,192	453	-	8,670
Harvester	20,772	728	-	21,557
Fertilizer Spreading	647	307	48,415	49,374
Agrochemicals Spreading	204	37	4,189	4,432
Transport	2,212	6,796	-	9,131
Irrigation	26,244	9,322	-	35,566

Given all the energy inputs and other parameters, the total consumed energy per operation for the ten-year period was calculated and presented in Figure 1. The main categories of energy consumption that contribute to the total energy input are directly connected mainly to in-field operations and material embodied energy and less in transportation operations, as it is presented in Figure 2.

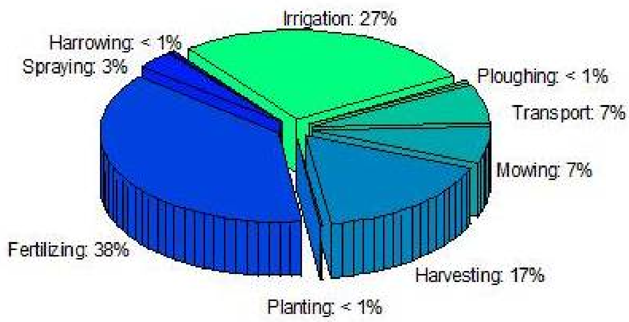

Figure 1: Energy consumption allocation (%) per field operation over 10 years' crop life

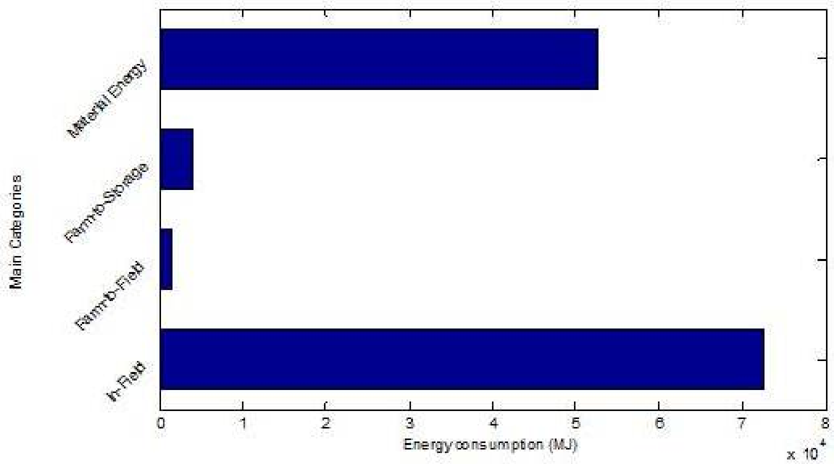

Figure 2: Main categories' allocation of energy consumption over 10 years' crop life

According to the previous analysis the Energy return on investment (EROI) of the basic scenario ratio for the tested period is 14.56.

4.2 Field area and distance variability

In order to evaluate better the crop, the basic scenario was tested in a set of field areas and distances, varying from 1 to 50 ha and 1 to 50 km distances from farm to field and from field to biomass facilities, respectively and compare the variance of the EROI. The production practice that has been considered is the same as described in the basic scenario. The result of this evaluation is presented in Figure 3. A significant increase is presented from smaller to bigger field areas and a more mild decrease is shown from closer to longer distances. This depicts the higher significance of the in-field operations and every energy input that is included in the field more than the logistics operations of farm machinery during the production period and biomass product after harvesting.

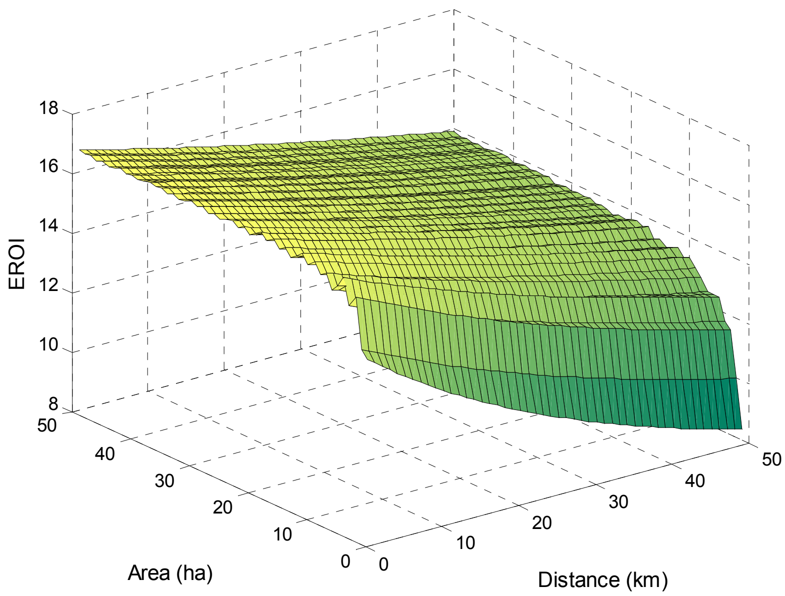

Figure 3: Variability of EROI according to field area and distance

5. Conclusions

The Energy return on investment (EROI) is significant in order to evaluate a crop, especially when it is an energy crop that will be used in the biomass production. For this reason, in the current study, switchgrass was selected in order to evaluate it firstly under a basic scenario case study and, in further, to predict, in a way, the results of the same scenario under variable scenarios with different parameters such as the field area and the distance from field to storage facilities. The results of this study show that over certain levels of field areas and distances the EROI is changing. This is presented clearly enough in surface-type Figure 3. The EROI is increasing significantly for field areas up to 10 ha compared to larger field areas that the EROI is shown to be more and more steady as the field area increases. On the other hand, regarding the distance effect, from Figure 3, it is presented that there is a smooth decrease in EROI as the distance increases. The current study can be used as a basis for future research on the estimation of the ideal range of distances from field to biomass storage facilities in order to predict the perfect position of a biomass plant. Furthermore, it can be used in order to design a specific production system or to find the best solutions to optimise a system.

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