Effect of crop management intensity on energy and carbon dioxide balance of two bioenergy *Sorghum bicolor* hybrids

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Abstract

Although bioenergy sorghum has many traits that make it ideal for biofuel production, management conditions that can affect the productivity and sustainability of these systems are still poorly understood. This paper estimated the energy and CO_2 balance of two bioenergy sorghum (*Sorghum bicolor* L. Moench.) hybrids (H128 and H133) cultivated during two growing seasons and under two different levels of crop management, high and low input. At the end of both growing season, sorghum was harvested for biomass yield determination. Calorific value and net energy production were also estimated. Crop management had important effects on sorghum CO_2 and energy balance. The energy produced varied between 126 and 365 GJ ha^{-1} depending on crop management, hybrid and growing season. Regarding of the CO_2 balance, the high level of crop management had a superior CO_2 emission. However, the energy produced per kg of CO_2 emitted was higher (>300%) than the energy produced with the use of fossil fuels. The use of bioenergy sorghum can contribute to better energy sustainability and reduced CO_2 emission in Mediterranean ecosystems.

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Introduction

Renewable sources are contributing in meeting energy requirements with the added advantage of greater environmental protection, especially in terms of carbon dioxide (CO_2) emissions (Monti and Ventura, 2003). In this context, biomass is a promising renewable energy source. An important challenge related to the use of alternative crops for energy production is quantifying the environmental sustainability of these crops in the long term (Bonari *et al*., 1992). For this purpose, energy and CO_2 balances represent appropriate tools for the evaluation of such sustainability. It is accepted that the energy obtained from biomass has not carbon emissions associated because the carbon emitted in its combustion is the same that plants absorbed while growing (Royal Society, 2008). Thus, the energy produced by energy crops must be higher than the energy required to produce them, to have a positive energy balance (Scholz and Ellerbrock, 2002). The energy balance shows the energy produced per unit of energy used in the process of production and transformation of biomass into electrical energy (Sartori *et al*., 2005). This balance has been widely used in different studies (Bonari *et al*., 1992; Dubuisson and Sintzoff, 1998; West and Marland, 2002; Heller *et al*., 2003; Sartori *et al*., 2005; Mead and Pimentel, 2006; Boehemel *et al*., 2008; Gasol *et al*., 2009; Nassi o di Nasso *et al*., 2010). On the other hand, CO_2 balance has also been used (Lewandowski *et al*., 1995; Cannell, 2002; Kaur *et al*., 2002; Hoosbeek *et al*., 2006) for evaluating sustainability. It estimates the emissions generated in the whole crop production cycle and compared them to the CO_2 fixed by the plant during its growth. CO_2 balance takes into account all the issues arising from field operations and considers not only the emissions produced during the combustion of the biomass, but also the emissions generated by the production inputs (fertilisers, herbicides, *etc*.).

There is a wide range of woody and herbaceous species used to produce energy from biomass. Bioenergy sorghum (*Sorghum bicolor* L. Moench) is among the most promising herbaceous species as it is considered a multifunctional crop (Lynd *et al.,* 1991; Ding, *et al*., 2017) due that it can provide a wide range of products, like sugars, alcohol, syrups, biofuels, paper, and food. This crop has low input requirements, is drought tolerant, has a great yield stability under a wide range of environmental conditions (Miller and Mcbee, 1993; Buxton *et al*., 1999; Wight *et al*., 2012; Amatya *et al*., 2014; Ameen *et al*., 2017), and does not directly compete with food crops because thanks to its short growing cycle it can be cultivated in rotation with winter food crops (Garofaldo *et al*., 2016). Besides, the crop is used to obtain biofuel due to its high quantity of carbohydrates. Given the remarkable work of selection done with this species (El Bassam, 1998), sorghum has a large spectrum of varieties. Among them we can find sweet sorghums, forage sorghums, grain sorghums, scope sorghums and fibre sorghums. The latter, considered hybrids between grain and scope sorghums (El Bassam, 1998). These hybrids are characterised by internodes rich in fibre and are used for the production of biomass for energy purposes. Bioenergy sorghum is an herbaceous annual crop of high yield easy to incorporate in ordinary crop rotations (Berenguer and Faci, 2001). The species is a C4 metabolism plant, returning 4-5 units of energy for every unit of energy used. C4 plants are one of the most efficient in converting solar energy into biomass (Lewandowski *et al*., 1995). Previous studies have already shown the potential of sorghum as a source of biomass, obtaining positive results in the energy balance and showing a significant reduction in CO_2 emissions with respect to the use of fossil fuels. For example, Ding *et al*. (2017) has concluded that sweet sorghum straw-based ethanol has advantages in terms of energy consumption, with a well to wheel decrease of 85% fossil energy and 44% global warming potential, as compared with gasoline. Cai *et al*. (2013) concluded that grain sorghum-based ethanol could reduce well-to-wheels greenhouse gas (GHG) emissions when wet or dried distillers grains with solubles is the co-product and fossil natural gas is consumed as the process fuel. Although bioenergy sorghum has many traits that make it ideal for biofuel production, management conditions that can affect the productivity and sustainability of these systems are still poorly understood. The objective of this paper is to analyse the effect of crop management intensity (high and low input) on CO_2 and energy balance of two bioenergy sorghum hybrids (H128 and H133) cultivated during two consecutive growing seasons.

Materials and methods

Study area

The study was conducted at *Centro di Ricerche Agro-ambientale* (CIRRA) *Enrico Avanzi* at Pisa University (Italy). The experimental field is situated in San Piero a Grado, 43°40' N and 10°21' E at 5 m above sea level and 2 km far from the sea. The soil was a Xerofluvent (clay 20.1%, silt 40.5%, sand 39.4%), typical of the lower River Arno, which is an alluvial plain characterised by a superficial water table (1.8 m deep in the driest conditions) and good nutrient availability (organic matter 1.8%, total nitrogen content 1.3 g kg^{-1}, available phosphorus 8.8 mg kg^{-1} and exchangeable potassium 128.3 mg kg^{-1}). The previous crop was wheat. Figure 1 shows average climatic conditions site during the trial.

Experimental design

Sorghum experiments were carried out through two different levels crop management, high input (HI) and low input (LI). In both treatments, we utilised two sorghum hybrids: H128, early maturing hybrid; and H133, an early-medium hybrid, both of them are fibre sorghums. The trial was set up on plots of 2000 m^2 with a total area of 12.000 m^2. The experiment was set up as a 2×2 Latin square where the treatments where the hybrid (H128 *vs* H133) and the crop management level (HI *vs* LI). In the first season, both hybrids were planted on April 10, 2006. The harvest was made on September 15, 2006. In the second season (2007), the planting took place on April 8 and the harvest on September 14.

High input: The study was conducted from April 2006 to mid-September 2007 during two consecutive growing seasons. Weed control was carried out using the herbicide Pendimentalin® with a dose of 0.5 l ha^{-1} followed by a subsoiling. A plowing was also provided. The seeding was performed using precision pneumatic seeders (Damax® PNL Mt. 4) placing the seed at a depth of 20 mm, in a density of 20 plants per square meter (0.25 m row spacing, 0.2 m within the row, 13 kg seed ha^{-1}). As regards the fertilisation, the doses used were 70 kg ha^{-1} of urea [32.2 kg of nitrogen (N)] and 80 kg ha^{-1} of triple superphosphate [36.8 kg of phosphorous (P)] in pre-sowing, and 90 kg ha^{-1} of urea after sowing (panicle initiation stage, approximately 32 days after emergence). The final harvest was done with a mowing-propelled forage harvester (Claas Jaguar 870) in mid-September, 10-20 days before flowering stage, at maximum dry matter accumulation and cellulose content in the plant (Peyre, 1979). Once the crop was harvested, a soil restoration with a subsoiling was done.

Low input: The differences regarding HI management were as follows: i) plowing was not carried out after subsoiling; ii) fertilis-

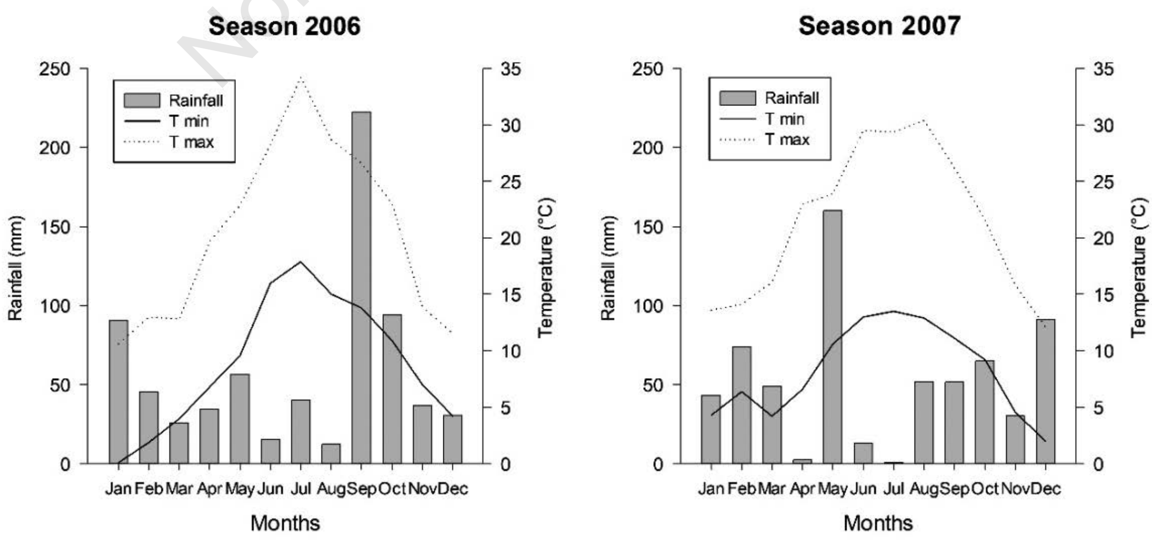

Figure 1. Average climatic conditions at the field experimental station in growing season 2006 and 2007. T min, minimum temperature; T max, maximum temperature.

er doses used were 40 kg ha^{-1} of urea and 50 kg ha^{-1} of triple superphosphate in pre-sowing and 60 kg ha^{-1} of urea after sowing. All the others operations were exactly the same.

Above-ground biomass production was estimated by manual cutting and sampling of four replicates of 10 m^2 randomly taken from each experimental field. Approximately 6 kg from each biomass sample was weighed, dried at 105°C until reaching a constant mass, and re-weighed to calculate dry matter content. Samples have been taken with a monthly frequency since June in order to observe the development in plant biomass. To avoid border effects, were chosen the plants growth under regular cultivation shade excluding external lines of the parcel. Student's *t*-test at P=1% was used to compare biomass yield of different treatments. The data related to each sorghum sampling were subjected to statistical analysis using the CoStat program version 6.205, submitting all the data to a completely randomised two-way block ANOVA analysis, where the factors analysed were the level of crop management and the hybrid employee. The statistical significance of the differences between the averages was analysed with the Student's *t*-test for $P \leq 0.01$, performed only on those parameters that were significant for the analysis of variance.

Energy balance

This study considered the flows of energy associated to the operations necessary for the sorghum cultivation, excluding the energy required to transport the biomass from field to the electric power plant, and then for the conversion of biomass into electricity.

The energy input required for sorghum cultivation was estimated considering the energy costs for manufacturing and maintaining agricultural machinery (tractor and tools), fertilisers and herbicides production and fuel and oil consumption in the various crop operations.

It was assumed that the tractors and equipments have been used in 200 ha and have a useful life of 10 years. Energy costs for building, maintenance and depreciation of tractors were estimated taking into account the useful life. These were then converted into amounts of energy through appropriate coefficients found in international scientific literature produced on this topic (Table 1). The energy production of the system (output) was determined by multiplying the dry matter biomass yield by the calorific value of the biomass calculated using the Mahler bomb calorimeter (ASTM D2015). Subsequently, we calculated the net energy production (output – input) and the energy efficiency (output/input).

The net energy production was calculated as follows (Eqs. 1-3):

$$\text{Net energy production [GJ ha}^{-1}\text{]} = \text{Energy produced [GJ ha}^{-1}\text{]} - \text{Energy consumed [GJ ha}^{-1}\text{]} \quad (1)$$

where:

$$\text{Energy produced [GJ ha}^{-1}\text{]} = \text{Calorific value [GJ Mg}^{-1}\text{]} \times \text{biomass yield [Mg DB ha}^{-1}\text{]} \quad (2)$$

$$\text{Energy consumed [GJ ha}^{-1}\text{]} = \text{Energy of operations [GJ ha}^{-1}\text{]} + \text{Energy of production factors [GJ ha}^{-1}\text{]} \quad (3)$$

where, DB means dry biomass.

We created a database to determine the energy used in performing each of the farming operations (Table 2). We itemised direct and indirect energy costs of different operations, being direct cost those related to the cost of the specific operations, while indirect costs are related to the energy cost for the construction of machinery, equipment and implements. Most of the data presented in Table 2 are part of Sisco software, developed for calculating energy balances at Enrico Avanzi Centre (Bonari *et al*., 1999). Other coefficients were calculated by measuring fuel consumption of tractors in different farming operations at field trials.

CO_2 balance

Data on fuel and oil consumption was taken from International Panel on Climate Change (ICPP, 2006). According to this source, the emissions generated by one kilogram of fuel and one kilogram of oil are 3.19 kg of CO_2 and 2.95 kg of CO_2, respectively. CO_2 emissions generated by other agricultural inputs (fertilisers, herbicides, *etc*.) were calculated with data from West and Marland (2002) (Table 3). Specific consumption for farming operations was obtained from Bonari (1999), for similar operations (Table 4) at the same areas. Data regarding to the harvest was determined directly during the experiment.

Results

Climatic behaviour

During the experimentation period, the hottest month was July with an average temperature of over 21°C and with maximum values even above 30°C. The 2006 season was characterised by a rather harsh winter in which the minimum temperatures from

Table 1. Energy equivalent used in this study and the respective source.

	Unit of measure	Energy equivalent	Reference
Machine	MJ kg^{-1}	108	Kalk and Hulsbergen, 1996
Fuel	MJ l^{-1}	42.7	Bohemel *et al.*, 2008
Oil	MJ l^{-1}	80	Bonari *et al.*, 1992
N	MJ kg^{-1}	47.1	Acaraglu and Semi, 2005
P_2O_5	MJ kg^{-1}	15.8	Kaltschmitt *et al.*, 1997
Herbicides	MJ kg^{-1}	276	West and Marland, 2002

N, nitrogen; P_2O_5, triple superphosphate.

Table 2. Direct and indirect energy used in farming operations and inputs.

Operation	Tractor (Kw)	Consumed energy (MJ ha^{-1}) Direct	Indirect	Total
Plow	132	1500	479	1979
Subsoiling	73	332	308	640
Fertilisation	48	334.6	161	495.6
Weeding	48	303	164	467
Sowing sorghum	48	661.6	210	871.6
Sorghum harvest	132	884	624	1508
Sorghum seed (MJ kg^{-1})		59.5		59.5
N (MJ kg^{-1})		47.1		47.1
P_2O_5 (MJ kg^{-1})		7.03		7.03
Herbicide (MJ L^{-1})		138		138

N, nitrogen; P_2O_5, triple superphosphate. N, nitrogen; P_2O_5, triple superphosphate.

January to March were more than a degree lower than the long-term values, while the summer temperatures of July exceeded 34°C and those of September and October respectively 26°C and 23°C. In 2007, the winter months of January and February were mild, while in the summer the hottest month, unlike the other years was that of August with temperatures above 30°C.

Rainfall distribution was similar in both years, which were characterised by heavy rains in the autumn months and droughts in the months of July and August. However, the annual rainfall was characterised by lower values than the long-term one (940 mm), recording 705 mm in 2006 and 632 mm in 2007.

Biomass production

As expected, HI treatment yielded higher dry biomass than LI treatment for both hybrids and growing seasons under study (Figure 2). However, hybrid H128 was more responsive to the HI management in season 2006, while hybrid H133 had a superior yield in HI management in 2007. A significant difference between the two levels of cultivation intensity was identified in 2006, with HI treatment being the most productive. In 2007, the situation was comparable to 2006, with significant differences between the two levels of crop intensification at harvest time (averaging 20.7 Mg ha^{-1} for HI *vs* 14.4 Mg ha^{-1} for LI, respectively). On the other hand, no significant differences were observed regarding to the different hybrids in either of the two experimental years. In addition, there was not a significant hybrid × management interaction. It is important to note that the great difference in biomass yield between 2006 and 2007 it was mainly due to the low percentage of plant survival in the first year of experimentation.

Energy balance

Table 5 shows calorific value for hybrid sorghums, growing seasons and level of crop management under study. In general, no statistical differences were observed.

The total energy cost for growing sorghum was 45% higher in the HI treatment (16.04 GJ ha^{-1}) with respect to the LI treatment

Table 3. Conversion factors for CO_2 emissions of different inputs according to West and Marland (2002).

Inputs	Conversion factor (kg CO_2 kg^{-1})
N	3.15
P_2O_5	6.04
Herbicide	15.92
Sorghum seed	3.15

CO_2, carbon dioxide; N, nitrogen; P_2O_5, triple superphosphate.

Table 4. Fuel and oil consumption of different agricultural operations and its related CO_2 emissions.

Operation	Diesel (kg ha^{-1})	Oil consumption (kg ha^{-1})	CO_2 emissions (kg CO_2 ha^{-1})
Plow	50	0.20	180.4
Subsoiling	14.6	0.04	46.5
Fertilisation	7.8	0.02	24.9
Weeding	10.9	0.06	34.7
Sowing sorghum	11.9	0.05	37.9
Sorghum harvest	20.6	0.10	65.7

CO_2, carbon dioxide.

Table 5. Calorific value of H128 and H133 sorghum hybrids in 2006 and 2007 at two levels of crop intensification (high and low inputs).

Sorghum hybrid	Calorific value (MJ kg^{-1}) 2006	2007
H128 HI	16.9[a]	16.7[A]
H128 LI	18.4[a]	18.4[A]
H133 HI	17.7[a]	17.0[A]
H133 LI	17.2[a]	17.0[A]

Values having a common letter are not significantly different at P-level=1%; lowercase is for season 2006, uppercase is for season 2007. HI, high input; LI, low input.

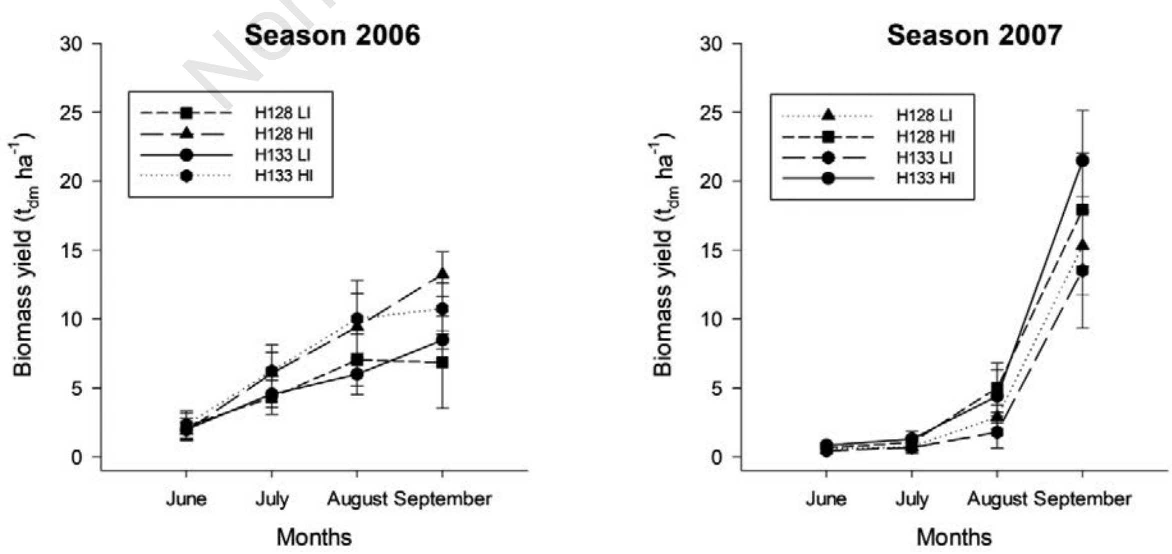

Figure 2. Dry biomass of H128 and H133 sorghum hybrids under two different levels of intensification in 2006 and 2007. HI, high input; LI, low input.

(11.02 GJ ha^{-1}). The overall energy cost was related to fertilisation, which represents 56.7% of the total cost in HI and 54.9% in LI treatments. There were no significant differences between the hybrids so in Table 6 it is shown the energy balance for the mean of the two sorghum hybrids at two different levels of crop management (HI) and (LI), during the growing seasons 2006 and 2007. In addition, there was no statistical interaction between the hybrid and the level of crop management.

The output showed significant differences between the two levels of crop management analysed with a mean increment of 68.7% and 88.1% in HI and LI respectively from 2006 to 2007, mainly due to the low percentage of plant survival in the first year of experimentation and the consequent lower energy output. Comparing the output value for the two levels of crop intensification adopted, our results showed that the average for both hybrids at HI yielded a higher amount of energy than at LI in both years, with 207.1 GJ ha^{-1} *vs* 136.04 GJ ha^{-1} in 2006 and 349.33 GJ ha^{-1} *vs* 255.94 GJ ha^{-1} in 2007. However, the behaviour showed was always the same for both years, with values slightly higher for H128 than H133 but with no statistical differences between them. As regards the net energy produced by the system (output-input), there were no statistical differences between the two hybrids, nevertheless an average difference of 34.56% and 22.73% between HI and LI during the two growing seasons respectively. Consequently, analysing the energy efficiency of the system, results showed a better performance in 2007 due to the higher production of biomass.

CO_2 balance

Table 7 shows the emissions associated with crop operations for the production of bioenergy sorghum in HI and LI treatments. As expected, HI crop management system has 60.73% higher CO_2 emissions than LI crop management. Obviously, the advantage in term of GHG saving in the LI treatment was a consequence of reduced diesel consumption for the field operations and the N fertilisation. At this point it is important to note that most of the carbon emissions are due to fertilisation, representing 62.41% and 63.24% respectively for HI and LI.

Discussion

Biomass production

Regarding the number of plants per unit area, it is important to notice that it had been severely compromised in the 2006 season due to seed predation by the entomofauna. Probably, on the emergency rate it also affected the water stagnation that occurred in some study areas. In fact, with a sowing dose of 20 seeds m^{-2}, at a distance of about one month from sowing, the average percentage of emergency was as follows:

- LI: 46% (about 9 plants m^{-2}) emergency in H128 hybrid, and 43% emergency (about 8 plants m^{-2}) in H133.
- HI: hybrid H128 emergency of 34% against 33% of the hybrid H133 (for both about 6 plants m^{-2}).

In contrast, in 2007 the number of plants emerged was, on average, 13 plants m^{-2} for both hybrids. This is 65% emergency.

The study of the trend of biomass accumulation in the 2006 and 2007 growth seasons (Figure 2) shows that in the first year of experimentation the growth of fibre sorghum was constant until August for both level of crop management. From August to September the biomass accumulation remains constant in the HI and increase in the LI. season. In contrast, in the 2007 growth season, the accumulation of biomass was very low until August, while a strong increase in the development of plants was recorded between August and September. Statistically significant differences were identified in relation to the level of crop intensification only in the month of August and in correspondence with the harvest (September) for both years of experimentation. This, given the same trend observed for the two compared hybrids, could depend on a different strategy of response of the crop to the climatic conditions. In fact, in 2006 the summer season from June to July was characterised by rains for 55.4 mm, while in the same time frame in 2007 were recorded only 13.8 mm of rainfall which results in a

Table 6. Energy balance for the mean of two hybrids of sorghum (H128 and H133) made at two different levels of crop management (high and low inputs), during the growing seasons 2006 and 2007.

Year	Output (GJ ha^{-1})		Net energy production (GJ ha^{-1})		Energy efficiency	
	HI	LI	HI	LI	HI	LI
2006	207.10[a]	136.04[b]	191.06[a]	125.02[b]	12.91[a]	12.34[b]
2007	349.33[A]	255.94[B]	316.96[A]	244.92[B]	21.78[A]	23.22[B]

Values having a common letter are not significantly different at P-level=1%; lowercase is for season 2006, uppercase is for season 2007. HI, high input; LI, low input.

Table 7. CO_2 emissions of cropping sorghum with high and low input.

Operations	CO_2 emissions (kg CO_2 ha^{-1}) HI	LI
Plow	180.4	-
Subsoiling	93	93
Fertilisation	49.8	49.8
Weeding	34.7	34.7
Sowing sorghum	37.9	37.9
Sorghum harvest	65.7	65.7
Sorghum seed	40.95	40.95
N	231.84	130.41
P_2O_5	483.2	302
Herbicide	7.96	7.96
Total	1225.45	762.42

CO_2, carbon dioxide; N, nitrogen; P_2O5, triple superphosphate; HI, high input; LI, low input.

Table 8. Energy produced per kg of CO_2 emitted with H128 and H133 sorghum hybrids at high and low level of intensification versus fossil fuels.

Energy source		MJ Produced per kg of CO_2 emitted 2006	2007
H128	HI	169.6	258.6
	LI	151.1	355.0
H133	HI	142.2	285.3
	LI	176.9	287.5
Coal*		73.3	
Fuel Motor*		54.5	
Natural Gas*		72.9	
Kerosene*		53.5	

*www.eia.gov Official Energy Statistics from the U.S. Government; CO_2, carbon dioxide; N, nitrogen; P_2O_5, triple superphosphate; HI, high input; LI, low input.

lower biomass accumulation. As we have already anticipated previously at the time of collection, a statistically significant difference was found between the two different levels of crop management, being the HI the most productive against 7.67 t ha^{-1} of the LI. In 2007, the situation was completely similar, with statistically significant differences between the two different levels of crop management at the time of harvest (20.7 t ha^{-1} for HI *vs* 14.4 ha^{-1} for LI). This may be due to the higher amount of potassium, since nitrogen, according to other authors (Garofalo *et al.,* 2015, 2016), is not a key element in terms of biomass production. For example, Ceotto *et al*. (2014) who indicated that the productivity of sorghum under nitrogen 0 treatment was comparable to that for partial and fully fertilised sorghum even after 5 years. Moreover, there were not statistically significant differences with respect to the two different hybrids during the two years of experimentation.

Our results corroborated that the level of crop management and the year of cultivation exerted important effects on sorghum biomass production. In other studies, sorghum yield values were similar to those obtained in our study, the variation is mainly due to the irrigation doses. For example, Curt *et al*. (1998) in a trial conducted in Spain, obtained yields from 18 to 48 t ha^{-1} depending on 4 different doses of irrigation. Hallam *et al*. (2001), in a study conducted in Iowa (USA), proposed different doses of fertilisation for yields ranging from 15.3 to 20.7 t ha^{-1}. Habyarimana *et al*. (2004) carried out an experiment in Italy on sorghum, applying different irrigation water amount on several hybrids with crop yield ranging from 20 to 51 t ha^{-1}. In a study carried out in northern Italy, Barbanti *et al*. (2006) proposed different doses of fertiliser in fibre and sweet sorghum with yield ranging from 17.7 to 24.2 t ha^{-1}. Giovanardi *et al.* (2008), in the Friulian plain (Italy) using hybrids of irrigated sorghum obtained yields varying between 19 and 40 t ha^{-1}. Zhao *et al.* (2009) conducted a trial in Beijing (China) with 5 different sorghum hybrids and testing different irrigation doses obtained yields from 13.2 to 35.2 t ha^{-1}.

Energy balance

The results indicate a better performance in the HI energy balance. The difference between treatments is basically due to the higher biomass production, since in the other variables there have not been significant differences. Results obtained in the second year of the trial confirm those reported in previous publications (Lewandowski *et al*., 1995; Monti *et al*., 2003). Monti *et al*. (2003), obtained input values of 15.9 MJ ha^{-1} with an energy efficiency of 23. In other studies conducted on annual crops for energy use, the ratio output/input ranges from 13 to 39 (Venturi and Venturi, 2003). In herbaceous perennial crops such as miscanthus or common reed, output/input ratio were 30 and 40, respectively (Ercoli *et al*., 1999; Angelini *et al*., 2005), while the biomass produced from conventional forestry had energy efficiency values between 10-25 (Mead and Pimentel, 2006).

The hybrid choice in this study was not relevant. What was relevant was the level of intensification utilised, obtaining higher yields with a higher level of crop intensification. Most of the energy consumption was mainly due to the fuel and N production and use. Thus, reducing the contribution of these inputs led to a significant decline in the energy consumption. Other authors observed a significant energy saving was achieved by reducing soil tillage and N application, with improvement in energy balance and efficiency of energy crops (Liebam *et al.*, 2008). In any case, an economic analysis should be done to evaluate if the investment required in the high level of intensification is justified with the sale of biomass.

CO_2 balance

CO_2 emissions of the production of HI sorghum were higher than those of LI (–37.2%), and considering the emissions the low input would be the most convenient alternative. The most impacting factors on the GHG emissions (N and fuel consumption for the crop management) are also the easiest to modulate, so if we want to reduce emissions, we must act on these two factors, mainly. In a review of different energy crops Cosentino *et al*. (2008) obtained emission values that ranged between 18.9 and 33 tons of CO_2 ha^{-1}. Their values were higher than those obtained in the present study because they analysed the complete cycle of energy production, including the biomass conversion process. The values for the CO_2 emissions of this study could be compared to those obtained in studies of corn, barley and soybean. Borin *et al*. (1997) in a study that include experimental tests carried out with different levels of crop intensification obtained values that vary between 2.336 and 3.05 Mg ha^{-1} yr^{-1} of CO_2. Further testing, such as that achieved by Dornburg *et al*. (2005), reported emission values of hemp and wheat ranging from 1.56 to 3.1 Mg ha^{-1} yr^{-1} of CO_2, respectively.

Table 8 shows a comparison of carbon emissions for the energy production with fossil fuels and sweet sorghum under the reported cropping systems. Even though, emissions will arise if consider the sugar-bioethanol conversion process, it is clear that the latter alternative is much more affordable than using fossil fuels.

Conclusions

Based on results of this study it can be concluded that energy cropping systems based on sorghum can contribute in reducing greenhouse gas emissions, specifically through the adoption of low intensification cropping systems. We can conclude that the cultivation of the H128 and H133 hybrids of sorghum has a positive energy balance. In terms of biomass, there are no significant differences by the clone chosen, but there are significant differences by the type of crop management used, being the intensive management the most productive. In terms of energy balance, the intensive crop management yields more energy than LI management, but there are no significant differences between the performances observed in the two hybrids. In terms of CO_2 emissions, LI management produced fewer emissions than the high input management. Today, an issue to consider is that these types of crops can compete with food crops, in that case, the goal is to achieve the greatest energy return from a cropped unit to fulfil energy demands. However, when there are no limits in the land available, the level of crop management with the higher energy efficiency should be preferred, to achieve improved energy output with reduced fossil energy use during the crop cycle. Thus, the use of renewable energy sources such as sorghum biomass can effectively contribute to a better energy sustainability through reducing greenhouse gases emissions. Nevertheless, further studies on energy and CO_2 balances of biomass sources as fuel are needed.

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