Sweet sorghum in a bioethanol supply chain: effects of different soil and nitrogen management on energy performances and greenhouse gas emissions

Pasquale Garofalo[1], Laura D'Andrea[1], Alessandro Vittorio Vonella[1], Michele Rinaldi[2], Angelo Domenico Palumbo[1]*

Abstract: *The high biomass production level of sweet sorghum jointly with a good sugar content make this crop suitable as an efficient renewable energy resource. However, to fully explore the potential of sweet sorghum for the bioethanol supply chain, it is necessary to maximize the energy performance and efficiency rather than the productivity of the crop. In this field experiment, the sweet sorghum was cultivated under three different energy input levels (HIGH, MID and LOW), modulating the nitrogen doses and varying the soil management. Although the biomass production was slightly reduced under middle and low energy input (24.87 t ha^{-1} of dry biomass, as mean) if compared with the highest energy treatment (26.15 t ha^{-1} of dry biomass), the energy performance and efficiency resulted greatly improved (+ 35% for the net energy gain and + 76% for the energy ratio in favour of LOW compared to HIGH treatment). Finally, the simulated greenhouse gas (GHG) emissions to produce 1 MJ of energy from the whole bioethanol supply chain resulted more than halved when comparing the extreme treatments (20.9 vs 8.1 g MJ^{-1}, in HIGH and LOW, respectively).*
Keywords: *Greenhouse gases; energy balance; energy efficiency; energy crops.*

Riassunto: *L'elevata produzione di biomassa del sorgo zuccherino unito ad una discreta quantità di zucchero, rende questa coltura utilizzabile come risorsa energetica rinnovabile. Comunque, per sfruttare il potenziale del sorgo zuccherino per la filiera del bioetanolo, è necessario massimizzare la prestazione ed efficienza energetica piuttosto che la produttività della coltura. In questo esperimento di campo il sorgo zuccherino è stato coltivato con tre differenti input energetici (HIGH, MID e LOW), modulando le dosi di azoto e le pratiche del suolo. Sebbene la produzione di biomassa sia stata leggermente ridotta nell'input energetico medio e basso (24.87 t ha^{-1} per la biomassa secca come media) se confrontato con il trattamento ad elevato input energetico (26.15 t ha^{-1} di biomassa fresca) la prestazione ed efficienza energetica sono risultate fortemente migliorate + 35% per il guadagno energetico netto e + 76% per il rapporto energetico in favore del trattamento LOW confrontato con HIGH). Infine, le emissioni di gas serra (GHG) stimate per la produzione di 1 MJ di energia dall'intera filiera del bioetanolo sono risultate più che dimezzate, confrontando i due trattamenti estremi (20.9 vs 8.1 g MJ^{-1}, rispettivamente per HIGH e LOW).*
Parole chiave: *Gas serra; bilancio energetico, efficienza energetica, colture energetiche.*

INTRODUCTION

The primary energy needed worldwide is provided by the fossil fuels for a percentage equal to 80% and the combustion of fossil fuels account for 73% of carbon dioxide emissions in the world (Nigam and Singh, 2011). Despite there is uncertainty about the climate change over the next 50 years, there is agreement that the increasing greenhouse gas (GHG) emissions at 450 ppm will increase temperatures by 0.8 to 1.0 °C, will determine high variability of rainfall with prolonged drought coupled with extreme events as reported by the IPCC AR4 analysis (IPCC, 2007).

Thus EU commission, throughout the Directive "20-20-20 targets" established that GHG emissions and the amount of primary energy use should be reduced of 20% and 20% of energy consumption should come from renewable resources (EU Renewable Energy Directive, RED, 2009). The purposes of RED is to reduce the amount of GHG by introducing new processes and technology or a better efficiency of the current knowledge for an effective contribution to global warming mitigation. The renewable resources and the corresponding supply chain should achieve the highest energy efficiency and reduce significantly the GHG emissions with respect to the fossil fuel replacement. The transport industry is responsible for most of GHG emissions and its CO_2 emission into the air has risen by 90% over the last two decades (EU, Biofuels Advisory Council, 2006). Existing knowledge and investigations underline that liquid fuels derived from biomass are the main alternatives for

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transportation fuels (Biofuels Technology Platform, 2008). To cope with further increases in GHG emissions, the EU Renewable Energy Directive (RED, 2009) defined a framework for the promotion of energy from renewable sources. The biofuels can reduce significantly the GHG emissions with a percentage up to 67% (Liska *et al.*, 2009)

Currently, the production of biofuels requires fossil energy for their production, generating GHG emissions. This implies that to achieve the best benefit from biofuels, the energy output from biuofuels must outperform the energy input from fossil fuels with a negative balance in term of GHG emissions. To assess if a crop is suitable for producing biofuels, several indicators can be used, i.e. the energy gain and efficiency, expressed as the difference between the energy output and input and their ratio, respectively (Pervanchon *et al.*, 2002; Farrell *et al.*, 2006) The higher is the energy gain and efficiency, the greater is the environmental benefit from the energy crops . This means that the crop management should target to minimize the energy input guarantying sufficient energy yield or vice versa maximizing the energy output with moderate energy expenditure.

Although some authors indicated as the reduced energy input cropping systems did not affect greatly the crop performance (de Vries *et al.*, 2010; Nassi o Di Nasso *et al.*, 2011) with benefit in term of climate change mitigation (Liska *et al.*, 2009), others pointed out as the productivity of the crop (and the potential energy achievable form the conversion process biomass-biofuel) was affected negatively with reduced input management (Boehmela *et al.*, 2008; Patil *et al.*, 2013).

The sweet sorghum showed a great potential as energy crop (Audilakshmi *et al.*, 2010), thanks to its fast growth rate and early harvesting season, great adaptability to poor soils, high radiation, water and nutrient use efficiency (Garofalo *et al.*, 2011; Garofalo and Rinaldi, 2013; Palumbo *et al.*, 2014), allowing this crop suitable for the bioethanol supply chain in Mediterranean environment. Moreover, thanks to its short growing cycle it can be placed in rotation with winter crops and the sowing and harvesting practices does not require dedicated machineries. Again, the high sugar content accumulated in the stem before being allocated to the grain, make the sweet sorghum suitable for production of first-generation biofuel, as indicated by Garofalo *et al.*, (2015).

In Europe there is a high percentage of biomethane but in general gas-fuelled cars still have a limited market share (IEA Bioenergy ExCo67 Workshop, 2011). In light of this, the investigation was carried out for the potential bioethanol production from sorghum as first-generation biofuel.

In this research the sweet sorghum cropped in Southern Italy was managed under different energy inputs, modulating the nitrogen doses and varying the soil management, in order to assess: i) the productivity and energy performance of the crop and ii) the GHG emissions reductions as consequence of reduced input at field.

MATERIALS AND METHODS

The field experiment was carried out over the 3-year period 2010-2012 in Foggia (latitude, 41°88'7"N; longitude, 15°83'05"E; altitude, 90 m a.s.l., Apulia region), Southern Italy. The soil was a vertisol of alluvial origin, Typic Calcixeret (USDA, 2010) classified as silty-clay with the following characteristics: organic matter: 2.1%; total N: 0.122%; $NaHCO_3$-extractable P: 41 ppm; NH_4OAc extractable K_2O: 1598 ppm; pH (water): 8.3; field capacity water content: 0.396 $m^3 m^{-3}$; permanent wilting point water content: 0.195 $m^3 m^{-3}$; available soil water: 202 mm m^{-1}. The climate is "accentuated thermo-Mediterranean" (Emberger, 1962), with temperatures below 0 °C in winter and above 40 °C in summer. The annual rainfall (mean: 550 mm) is mostly concentrated in the winter months. The class "A pan" evaporation is 1033 mm over the year, and 657 mm from May to August. The daily meteorological data of temperature, humidity, rainfall, wind velocity and solar radiation were recorded in the meteorological station located at the same experimental farm.

Field experiment

Sweet sorghum (*Sorghum bicolor* L. Moench; *cv* Sucro 506) was sown at the beginning of May, in rows 0.5m apart and a distance of 0.08m between seeds in each row (250,000 seeds per hectare). The crop was harvested immediately after flowering (stage 6, BBCH-scale; half of August) to maximize the sugar content in the stem (Dalla Marta *et al.*, 2014). We assumed the production of first-generation biofuel through fermentation of simple sugars accumulated in the biomass which requires less energy cost and pre-treatment of hemicelluloses and lignin accumulated in plants at maturity (typical of the second-generation biofuel). Moreover, as reported by Economou *et al.* (2010), the semi-solid fermentation or even the liquid culture is suitable for the biofuel production in sorghum rather than the solid-state fermentation.

Irrigation of crop was managed according to the water consumed by plants determined with the

gravimetric method (0-0.8 m depth). Each time the water used reached 60 mm respectively, irrigation was triggered. To ensure uniform water distribution, a drip irrigation system was disposed, with one line for each plant row and drippers with a 4 L h^{-1} flow. Total amount of water applied with irrigation on sorghum was 120, 176 and 300 mm for the first, second and third experimental year, respectively, with the rainfall equal to 79, 73 and 68 mm during the growing season in 2010, 2011 and 2012.
The high input management (*HIGH*) was carried out according to the conventional tillage or a shallow ploughing (25 cm) performed with a five-furrow plow, followed by disc harrowing, power harrowing, and seeding with a precision driller. In *HIGH* treatment 150 kg of N per hectare were applied. In the middle energy input treatment (*MID*) the soil tillage followed the same practice of *HIGH*, but halving the N dose to 75 kg ha^{-1}. Finally, in the low energy input (*LOW*) no tillage and N application were performed. N application was split in two doses, as basal dressing before sowing and top dressing at the end of June. Phosphate fertilizer was applied before sowing (100 kg ha^{-1} of P_2O_5) in all the treatments. In *LOW*, before seeding, 5 L ha^{-1} of glyphosate [isopropylamine salt of N-(phosphonomethyl) glycine] were applied for the weed control. Direct seeding (GASPARDO NOTILL) was performed in *LOW* treatment. The main treatment was related to the soil tillage, whilst the secondary one accounted for the different N supplies. The experimental design was arranged in a split plot design with three replications. Each subplot was extended 84 m^2. The fuel consumption was measured on the field, taking into account the amount of diesel necessary to refill the tank of the tractor between two following operations, as well as the time needed to complete each crop operation. Lubricant and oil consumption was considered negligible. At harvest the fresh and dry biomass (after drying the fresh biomass in an oven at 70 °C until constant weight) were weighted. Total soluble solids (*TSS*) content of sorghum stem juice in °Brix was measured. The estimation of energy input and output fluxes followed as reported by Garofalo *et al.,* (2015).
The potential sugar yield from biomass was estimated as reported by Wortmann *et al.*, (2010):

$$CSY = (FMY - DMY) * °Brix * 0.75;$$
$$JY\_80\%\,extracted = [FMY - (DMY - CSY)] * 0.8; \qquad \text{Eq. (1)}$$
$$SY = JY * °Brix * 0.75$$

where *CSY* is conservative sugar yield (t ha^{-1}), *FMY* is the fresh matter yield (t ha^{-1}), *DMY* is dry matter yield (t ha^{-1}), *JY* is juice yield (t ha^{-1}), and *SY* is sugar yield (t ha^{-1}). Sugar concentration of juice is 75% of °Brix expressed in g kg^{-1} sugar juice and 95% of the extracted sugar is converted to ethanol.
°Brix multiplied by the fresh biomass furnished *TSS*.
The water use efficiency (*WUE*; Curt *et al.*, 1995; Mastrorilli *et al.*, 1999; Garofalo *et al.*, 2011. Garofalo and Rinaldi, 2013) and nitrogen use efficiency (*NUE*; Ra *et al.*, 2012; Tamang *et al.*, 2011; Palumbo *et al.*, 2014;), were obtained as ratio between the sum of rainfall and irrigation water and productivity parameters for the former and ratio between the nitrogen dose and the observed parameters, for the latter.

Energy balance and efficiency

The energy cost for the crop management was calculated separately for tractor, implements, fuel, seed and chemicals, accounting for the direct and indirect input. The latter concerned the materials and energy engaged to build tractors, machineries, implements and their maintenance.
The energy coefficient (E_{ct}) for the machineries and implements was calculated as follow:

$$E_{ct} = \frac{E_e * M_w}{L} \qquad \text{Eq. (2)}$$

where:
E_e (MJ kg^{-1}) is the energy cost for building, maintenance and transport (Nagy, 1999), M_w (kg) is the mass, and L (h) is the lifespan (local survey).
The energy cost for the human power consumption (1.08 MJ h^{-1}; Kitani, 1999) multiplied by the labour time on the field provided the energy input for labour (E_l).
The energy coefficient of seed (E_s; MJ ha^{-1}) was estimated with:

$$E_s = E_{ps} * S_r \qquad \text{Eq. (3)}$$

where E_{ps} (MJ kg^{-1}) is the energy value for the seed production (54 MJ kg^{-1}, Monti and Venturi, 2003) and S_r is the seed rate (14 kg ha^{-1}).
The energy cost for the fertilizers and chemical was calculated as:

$$E_{N,P,G} = EC_{N,P,G} * R_{N,P,G} \qquad \text{Eq. (4)}$$

where *N*, *P* and *G* are the indexes referred to the amount of nitrogen, phosphorus and glyphosate applied, *EC* is the corresponding energy coefficient (48.89 MJ kg^{-1} for nitrogen, 15.23 MJ kg^{-1} for phosphorus and 268.4 MJ kg^{-1} for glyphosate; RED, 2009) and *R* the application rate.

The energy input for irrigation (I_c; MJ ha^{-1}) was attributed to the electricity absorbed by the electrical pump with a power of 3.5 kWh as follow:

$$I_c = \frac{\delta * g * H * Q}{n_1 * n_o} * 10^{-6} \quad \text{Eq. (5)}$$

where:
δ is the water density = 1000 kg m^{-3};
g is the acceleration of gravity = 9.8 m s^{-2};
H is the total dynamic head or the differences between the level of water suction in the well (10 m) and the level of the water surface in the collecting basin (5 m);
Q is the total water applied with irrigation (m^3 ha^{-1});
n_1 is the pump efficiency = 0.65 (Stout, 1999);
n_0 is the electric engine efficiency = 0.22 (Stout, 1999).
The energy cost for material transportation (seed and chemicals) from the factory to the farm ($E_{t(I)}$,) and transportation of fresh biomass from farm to the conversion plant ($E_{t(II)}$,) was estimated taking into account the diesel consumption (D_t) of the truck with a payload (*Pl*) of 27 tons, (0.34 l km^{-1} or 0.27 kg km^{-1}; Delivand *et al.*, 2015). Thus:

$$E_{t(I,II)} = \left(D_t * D_{(I,II)} * \frac{W_m}{Pl} \right) * D_{ef} \quad \text{Eq. (6)}$$

where $D_{(I,II)}$ is the distance from the factory to farm ($_I$, 100 km) and from farm to conversion plant ($_{II}$, 70 km as maximum distance in the short supply chain for the Apulia region; Reg. N°42/2012) respectively; W_m (t) is the mass transported and D_{ef} the energy density of diesel (43.1 MJ kg^{-1}; RED, 2009).
The gross energy output of bioethanol (*BE*) was assumed as 26.8 MJ kg^{-1} (Venturi and Venturi, 2003), whereas the energy required for processing feedstock into anhydrous ethanol (*CE*) was 18.33 MJ kg^{-1} (Monti and Venturi, 2003).
The net energy gain (*NEG*; GJ ha^{-1} was obtained as:

$$NEG = (BE * SY) - (CE * SY) - (EFI + ET_I + ET_{II}) \quad \text{Eq. (7)}$$

where *EFI* is the total energy input from field to conversion plant and calculated as follow:

$$EFI = (Et_{(I,II)} + D_c * D_{ef} + E_{ct} + E_l + E_s + E_{N,P,G} + I_c) \quad \text{Eq. (8)}$$

with D_c referred to the diesel consumption for the crop management. Ratio between *NEG* and the sum of *EFI* plus $ET_{(I,II)}$ provided the energy ratio (*ER*).

Criteria to account the Greenhouse Gas emissions
After the proper quantification of the material and energy flows, the transformation into GHG emissions followed the approach proposed by the EU *BioGrace* project (2009) with respect to the available conversion factors. In this approach, at each material and energy flow is associated the specific conversion factor for CO_2, N_2O and CH_4 emission. Again, to standardize the emissions of these elements in term of CO_{2_eq} the multiplying factor of 1, 296 and 23 for CO_2, N_2O and CH_4 respectively, were applied.
So the GHG emissions (E_{GHG}; kg ha^{-1}) were calculated as:

$$E_{GHG} = EDc + EEs + E_{N,P,G} + EI_c + ECE \quad \text{Eq. (9)}$$

where:
EDc = GHG emissions (kg ha^{-1}) for the transport;
EEs = GHG emissions (kg ha^{-1}) for seeding;
$E_{N,P,G}$ = GHG emissions (kg ha^{-1}) for the nitrogen, phosphorus fertilizer and glyphosate manufacturing and application; for the nitrogen fertilizer was calculated also N_2O emitted from field and equal to 1% of N mineral applied (IPCC Tier 1 guidelines, 2006).
ECE = GHG emissions for the sugar- bioethanol conversion.

Statistical analysis
The analysis was performed by using the statistical analysis software SAS/STAT® (SAS Institute Inc., Cary, NC, USA). Data were submitted to analysis of variance (ANOVA), considering the Year as the random effect and the appropriate error test for soil management (in main plot), nitrogen (in sub-plot) and their interactions. Differences among treatments were assessed by using the Tukey-Kramer test and significance was accepted at $P \leq 0.05$.

RESULTS

Climatic behaviour
In Fig. 1 is shown the path of climatic variables (temperature and cumulated rainfall) observed from 2010 to 2012 compared with the long term averages (1952-2010). Focussing on the crop growing period (beginning of May-half of August), emerged as in the first two years the maximum and the minimum temperature were in line with the long term values. On the other side, 2012 was characterized by higher temperature (about 3 °C on average) compared to the long term data for most of the growing period. Excepting the copious rains observed in May 2011, the rainfall recorded during the growing cycle in all experimental years was lower with respect to the long term data, and this gap was equal to about 70 mm.

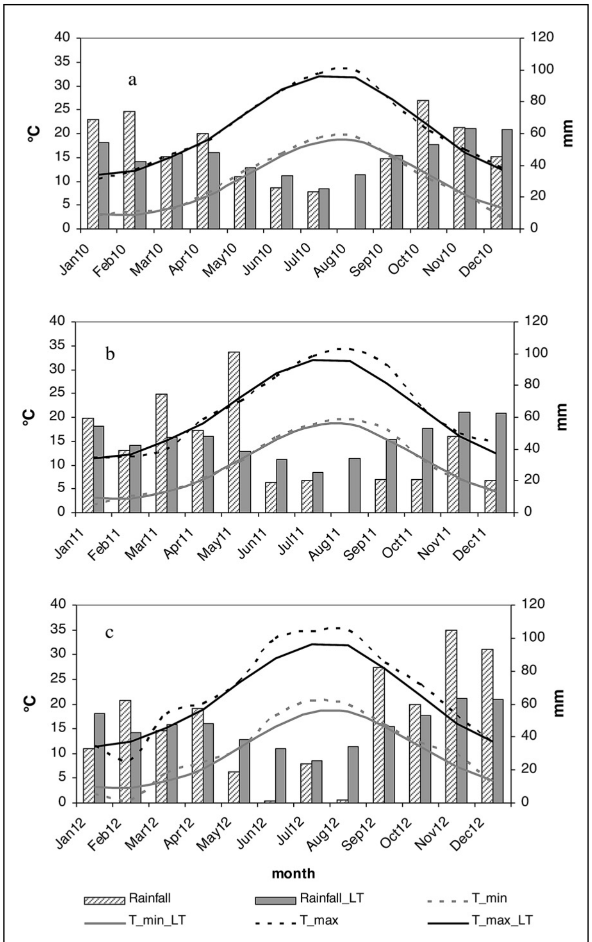

Fig. 1 - Climatic behaviour of the three experimental years (2010 a, 2011 b, 2012 c).
Fig. 1 - Andamento climatico dei tre anni di esperimento (2010 a, 2011 b, 2012 c).

Crop productivity

The productivity parameters averaged for the experimental years are reported in Tab. 1. *HIGH* treatment provided the best response in term of fresh and dry biomass, as well as for the corresponding *WUE*. However, the loss in performances with reduced input treatments resulted not significant, being equal to 10% (*MID*) and 15% (*LOW*) for the dry matter, and 6% *(MID)* and 10% (*LOW*) for the fresh biomass, compared to *HIGH* treatment. These results were in line with Habyarimana *et al.*, (2004) which reported values of dry biomass ranging between 20 to 29 t ha^{-1} under similar pedo-climatic condition. However, lower values for fresh (39-67 t ha^{-1}) and dry biomass (12-21 t ha^{-1}) were found by Dalla Marta *et al.*, (2014) in Northern Italy.

TSS in *MID* and *LOW* treatments was reduced by 10% if compared to *HIGH* treatment. Same results were found out for the *WUE* parameters (i.e. fresh, dry biomass and *TSS*), where the gap between *HIGH* and the others treatments ranged between 15 and 10% in favour of the highest energy management.

Since as the productivity level of the three managements resulted comparable, *NUE* in the halved N treatment was greatly improved, with an increment of 140 and 49 kg ha^{-1} for dry biomass and *TSS*, respectively, per kg of N applied in comparison with the full N treatment.

Finally, the response in term of potential bioethanol production (Eq. 1) followed the productivity performances, and equal to 4.15, 3.80 and 3.73 t ha^{-1} for the *HIGH*, *MID* and *LOW* input management.

Treat.	*DB* t ha^{-1}	*Brix* Degrees	*TSS* t ha^{-1}	*WUEdm* kg m^{-3}	*WUEtss* kg m^{-3}	*NUEdb* kg kg^{-1}	*NUEtss* kg kg^{-1}
HIGH	26.2 (± 4.3)	9.0 (± 3.9)	9.1 (± 2.6)	10.4 (± 3.2)	3.8 (± 1.6)	174.3 (± 56.8) b	60.7 (± 34.8) b
MID	23.6 (± 7.0)	8.9 (± 3.8)	8.3 (± 3.4)	9.3 (± 3.9)	3.4 (± 2.1)	314.6 (± 46.8) a	110.1 (± 22.9) a
LOW	22.2 (± 4.0)	9.3 (± 3.7)	8.0 (± 2.7)	8.7 (± 3.4)	3.3 (± 1.7)	-	-
Mean	*24.0* (± 5.6)	*9.1* (± 4.0)	*8.5* (± 3.3)	*9.5* (± 3.4)	*3.5* (± 1.9)	*244.5* (± 88.1)	*85.4* (± 38.2)

DB = Dry biomass; *TSS* = total soluble solid; *WUE* = water use efficiency for dry biomass (*db*) and total soluble solid (tss); *NUE* = nitrogen use efficiency for dry biomass (*db*) and total soluble solid (*tss*).

Tab. 1 - Biomass performance, water and nitrogen use efficiency of sweet sorghum as affected by soil tillage and nitrogen fertilization during the experimental trial (2010-2012). Different letters indicate different means at P ≤ 0.05 (Tukey-Kramer test).
Tab. 1 - Prestazioni produttive, efficienza d'uso dell'acqua e dell'azoto del sorgo zuccherino in risposta alle lavorazioni del suolo e fertilizzazione azotata durante la prova sperimentale (2010-2012). Lettere differenti indicano medie differenti a P ≤ 0.05 (test di Tukey-Kramer).

Energy input

The total energy consumption for the crop management was 18.47 in *HIGH*, 14.39 in *MID* and 9.45 GJ ha^{-1} in *LOW* treatment. Fig. 2, underlines as the N fertilization had a great energy requirement, but mainly due to its manufacturing rather than the field application. Indeed, at full N application its impact was 7.35 GJ ha^{-1} with a contribution on the total energy input equal to 40% followed by the energy for fuel usage, the latter impacting for 24%. The energy requirement for the biomass transportation from field to the bioethanol conversion plant was 2.91 GJ ha^{-1}, with a contribute to the total energy counting equal to 16%. The remaining share of the input (3.69 GJ ha^{-1}) was split among the other parameters, with the highest impact for the P fertilizer, followed by the seed production and finally the electricity for the water pumping. In *MID* treatment, excepting the energy saving for the N fertilizer (-3.67 GJ ha^{-1}), all the other energy costs resulted in line with *HIGH* treatment. In this case the energy demand for the diesel consumption for the crop management resulted equal to 30% whereas that for transportation of biomass was 19%. The indirect energy cost, due to the machineries manufacturing and maintenance was equal to 0.73 GJ ha^{-1} for *HIGH* and *MID* treatments. In *LOW* management, the highest energy saving came out by the avoided N application (-7.35 GJ ha^{-1}) followed by the reduced diesel consumption for the soil tillage (-50%) with respect to *HIGH* treatment. The chemical for the weed control had an incidence equal to 14 %, same value for the fertilizer application of P. Electricity and seed energy cost did not differ from the other treatments, whereas the indirect energy input of the machineries was lowered by 63% compared to *HIGH* treatment. Although there is a scarce literature on energy consumption in sweet sorghum cultivation, for other crops the energy input showed a great variability depending also by the cropping site. Generally, in the Northern European Countries the energy input at field was about 27 GJ ha^{-1} for sugar beet (Tzilivakis *et al.*, 2005; Hülsbergen *et al.*, 2001), lower in the Southern ones and oscillating from 4 to 18 GJ ha^{-1} for the giant reed cultivation (Angelini *et al.*, 2005), 10.5 GJ ha^{-1} for sunflower (Kallivroussis *et al.*, 2002), or from 12.7 to 18.5 GJ ha^{-1} in Italy for durum wheat (Alhajj *et al.*, 2013; Alluvione *et al.*, 2011).

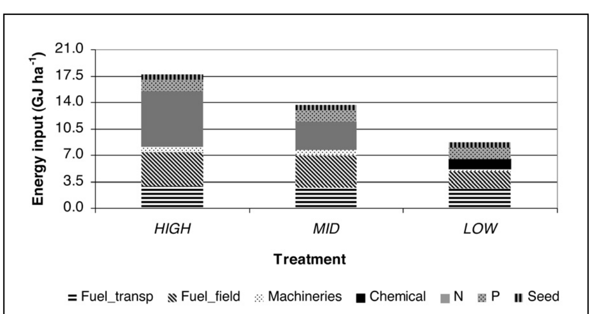

Fig. 2 - Energy input applied at field level for fuel, machineries and materials in sweet sorghum and for the three different energy managements.
Fig. 2 - Input energetico applicato al campo per carburante, macchinari e materiale nel sorgo zuccherino e per i tre differenti management.

Energy balance ad efficiency

The energy yield achievable from the potential bioethanol production, taking into account the cost for the sugar extraction-bioethanol conversion, was slightly affected by the energy input at field (Fig. 3a). Indeed, the estimated values for the energy yield were 35.2, 32.1 and 31.6 GJ ha^{-1} passing from the highest to the lowest energy treatment, even if with no statistical significance.

When subtracting the energy cost for cropping management and transport of biomass to the energy yield, the results proved to be inverted. Indeed, in *LOW* treatment *NEG* was 22.1 GJ ha^{-1}, so 4.4 and 5.4 GJ ha^{-1} greater than *MID* and *HIGH*, respectively (Fig. 3b). Same pattern was recorded for *ER* (Fig. 3c). The energy return per energy invested was strongly improved when lowering the energy input, so resulting higher in *LOW* treatment compared to *MID* (+ 49%) and even more to *HIGH* treatment (+ 75%). Definitely, the higher was the energy engaged to produce bioethanol, the lower resulted the energy efficiency expressed by *ER* (Fig. 4).

GHG counting

GHG emissions for each sorghum cropping system is reported in Fig. 5. The higher is the energy intensity, the higher is the GHG emissions. The emissions saving was remarkable when comparing the two energy input extremes, with a gap of 68% in favour of *LOW* treatment compared to *HIGH*, 63% with respect to *MID* treatment. The highest impact of CO_{2_eq} emission per unit of cropped surface, derived from the N fertilization. Indeed, the GHG emissions resulting from the N fertilizer manufacturing and N_2O from field, accounted for 60 and 55% in *HIGH* and *MID* respectively, on the whole CO_{2_eq} counting. The sum of the GHG emissions from the diesel for the crop management and for the biomass transportation ranged between 615 and 650 kg CO_{2_eq} ha^{-1} with a share on the total GHG emissions equal to 33 and 29% referring to *HIGH*

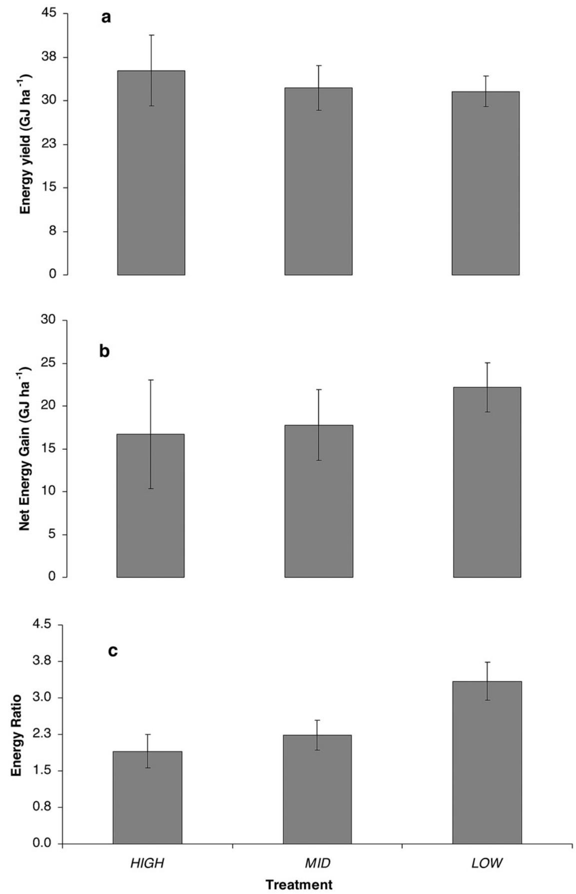

Fig. 3 - Energy yield (a), Net Energy Gain (b) and Energy Ratio (c), calculated for the sweet sorghum-bioethanol supply chain. Bars indicate the standard error.
Fig. 3 - Rendimento energetico (a), guadagno energetico netto (b) e rapporto energetico (c) calcolato per la filiera del sorgo-bioetanolo. Le barre indicano l'errore standard.

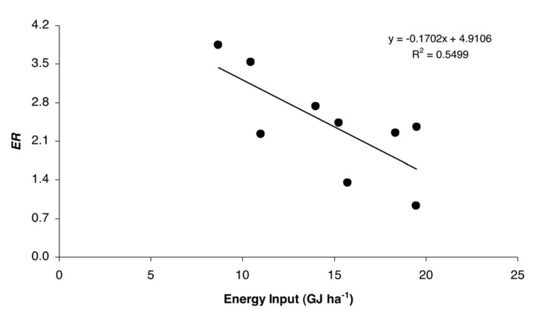

Fig. 4 - Linear regression analysis between energy input and energy ratio (*ER*).
Fig. 4 - Regressione lineare tra l'input energetico ed il rapporto energetico (ER).

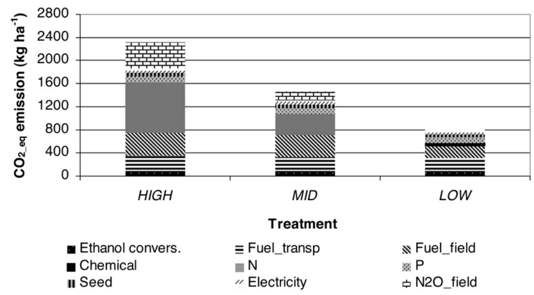

Fig. 5 - GHG emissions expressed as CO_2 equivalent along the whole sweet sorghum-bioethanol supply chain.
Fig. 5 - Emissioni di GHG espresse come equivalenti di CO_2 lungo tutta la filiera produttiva del sorgo-bioetanolo.

and *MID* treatment. Obviously, the advantage in term of GHG saving in the lowest energy treatment was a consequence of reduced diesel consumption for the field operations and the N fertilization. Interestingly, the impact of the sugar extraction and conversion into bioethanol, covered a small amount of the GHG emissions (88 kg CO_{2_eq} ha^{-1}), indicating the "downstream" process as the most impacting step of the analyzed supply chain.
To produce 1 MJ of energy at the end of the supply chain, the GHG emissions were 20.85, 19.45 and 8.08 g of CO_{2_eq}, passing form the highest to the lowest energy input management. The values are in line with the averaged GHG emissions calculated for several herbaceous energy crops as reported by Fazio and Monti (2011); however, the authors estimated GHG emissions of 34 g CO_{2_eq} MJ^{-1} for producing first-generation biofuel from wheat and maize. The lower value compared with our findings is due to the higher amount of biomass and potential bioethanol production achievable from sorghum with respect to the examined crops.

DISCUSSION

Sweet sorghum showed a good adaptability to low-input managements with reduced N doses and no tillage practice.
This is confirmed also by other research studies, such as those of Ceotto *et al.*, (2014) who reported that the productivity performance of sweet sorghum was comparable under different N doses (also excluding totally N fertilization) even if prolonged for 5 years.
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, which in case of

LOW reached the 50% compared to *HIGH* treatment. Other authors observed as 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). Despite the energy yield resulted slightly improved when maximizing the energy input, the balance between output and input and even more the energy return per energy invested was dramatically enhanced as the energy supply reduced. This pattern was in contrast with Ceccon *et al.*, (2003), who indicated as the gross energy output and energy efficiency achievable from some energy crops resulted improved by the highest energy input invested for the field management. Other authors, instead, indicated an improvement for *NEG* and *ER* in low energy management (Tabatabaeefar *et al.*, 2009; Liebam *et al.*, 2008), but focussing on the energy performances throughout the cradle-to-farm analysis and limiting the calculation to the gross energy achievable from the raw material (biomass not converted into biofuel). In light of the aforementioned investigations, the benefit of reduced energy management on the energy performance in sweet sorghum resulted even more promoted, since as in our study, the energy cost for transportation and conversion of sugar into bioethanol has been accounted for. Moreover in a study of Venturi and Venturi (2003), was indicated the value of *ER* equal to 2 as the minimum threshold to consider the crop suitable for energy purposes. Again, this was estimated on the gross energy output of biomass as raw material and in our findings this threshold was exceeded by *MID* and *LOW* management inclusive of the cost due to the transportation and conversion of sugar into bioethanol.

The trend of GHG emissions followed that of the energy cost. In addition, the effect of CO_2 mitigation, resulting from reduced N supply, was emphasized by reduction of N_2O emissions from the soil. The latter, covered more than 20% of the total GHG emissions in the *HIGH* treatment, while there was no contribution in *LOW* treatment.

Definitely, the most impacting factors on the energy use and GHG emissions (N and fuel consumption for the crop management) were also the easiest to modulate, unlike the energy use and GHG emissions resulting from the transport of biomass and conversion of sugar into bioethanol. This meant that the lowest GHG emissions were achievable by performing a wise N fertilization along with no tillage practice.

Sweet sorghum showed quite stable performances under different managements (C4 species with deep root system) especially if compared to other cereals (i.e. wheat), which plant growth resulted dependent on the N supply and soil tillage (Halvorson *et al.*, 2004). However the good response of sorghum under *MID* and *LOW* treatment should be considered effective for the mid term covered by this study (3 years).

CONCLUSIONS

From this research emerged as under reduced input management, not only the crop productivity remained stable compared to the conventional cropping system, but the energy performances was improved and GHG emissions largely cut down. Thanks to its short growing cycle (if harvest at beginning of flowering) the sweet sorghum can be cultivated in rotation with winter food crops, satisfying both the greening and diversification actions requests by the new Common Agricultural Policy (2014-2020) and representing an excellent energy crop, guaranteeing a further farmer's income. The benefit in term of energy from renewable resource and CO_2 mitigation of the analyzed biofuel supply chain, needs further investigation to assess for how long *LOW* and *MID* management keep the productivity level of sorghum comparable to *HIGH* treatment as provided by these three-experimental years.

REFERENCES

Alhajj Ali S., Tedone L., De Mastro G., 2013. A comparison of the energy consumption of rainfed durum wheat under different management scenarios in southern Italy. Energy, 61: 308-318.

Alluvione F., Moretti B., Sacco D., Grignani C., 2011. EUE (energy use efficiency) of cropping systems for a sustainable agriculture. Energy, 36: 4468-4481.

Angelini L.G., Ceccarini L., Bonari E., 2005. Biomass yield and energy balance of giant reed (*Arundo donax* L.) cropped in central Italy as related to different management practices. European Journal of Agronomy, 22 (4): 375-389.

Audilakshmi S., Mall A.K., Swarnalatha M., Seetharama N., 2010. Inheritance of sugar concentration in stalk (brix), sucrose content, stalk and juice yield in sorghum. Biomass Bioenergy, 34: 813-20.

BBCH monograph, 2001. Growth stages of mono- and dicotyledonous plants. Uwe Meier Ed. http://www.jki.bund.de/fileadmin/dam_uploads/_veroeff/bbch/BBCH-Skala_englisch.pdf.

Biofuels Technology Platform. 2008. European Biofuels Technology Platform: Strategic research

agenda & strategy deployment document. CPL Press, UK, January 2008.
Biograce, 2015. http://www.biograce.net/content/ghgcalculationtools/overview.
Boehmela C., Lewandowskib I., Claupein W., 2008. Comparing annual and perennial energy cropping systems with different management intensities. Agricultural Systems, 96 (1-3): 224-236.
Ceccon P., Coiutti C., Giovanardi R., 2003. Energy balance of four farming systems in North-Eastern. Italian Journal of Agronomy, 6 (1): 173-183.
Ceotto E., Castelli F., Moschella A., Diozzia M., Di Candilo M., 2014. It is not worthwhile to fertilize sweet sorghum (*Sorghum bicolor* L. Moench) with cattle slurry: Productivity and nitrogen-use efficiency. Industrial Crop and Products, 62: 380-386.
Curt M.D., Fernandez J., Martinez M., 1995. Productivity and water use efficiency of sweet sorghum (*Sorghum bicolor* (L.) Moench) cv. "Keller" in relation to water regime. Biomass and Bioenergy, 8: 401-409.
Dalla Marta A., Mancini M., Orlando F., Natali F., Capecchi L., Orlandini S., 2014. Sweet sorghum for bioethanol production: crop responses to different water stress levels. Biomass Bioenergy, 64: 211-219.
de Vries S.C., van de Ven G.W.J., van Ittersum M.K., Giller K.E., 2010. Resource use efficiency and environmental performance of nine major biofuel crops, processed by first-generation conversion techniques. Biomass and Bioenergy, 34: 588-601.
Delivand M.K., Cammerino A.R.B., Garofalo P., Monteleone M., 2015. Optimal locations of bioenergy facilities, biomass spatial availability, logistics costs and GHG (greenhouse gas) emissions: a case study on electricity productions in South Italy. Journal of Cleaner Production, 99: 129-139.
Economou C.N., Makri A., Aggelis G., Pavlou S., Vayenas D.V., 2010. Semi-solid state fermentation of sweet sorghum for the biotechnological production of single cell oil. Bioresource Technology, 101 (4): 1385-1388.
Emberger G.J., Gaussen H., Kassas M., de Philippis A., 1962. Bioclimatic map of the Mediterranean zone, explanatory notes. United Nations Educational, Scientific and Cultural Organization, Paris, France.
European Commission. 2006. Biofuels in the European Union: A vision for 2030 and beyond. Final Report of the biofuels advisory Counsil, DG Res. Sust. Energy Systems EU 22066.
Farrell A.E., Plevin J., Turner B.T., Jones A.D., O'Hare M., Kammen D.M., 2006. Ethanol can contribute to energy and environmental goals. Science, 311: 506-518.
Fazio S., Monti A., 2011. Life cycle assessment of different bioenergy production systems including perennial and annual crops. Biomass and Bioenergy, 35: 4868-4878.
Garofalo P., D'Andrea L., Vonella A.V., Rinaldi M., Palumbo A.D., 2015. Energy performance and efficiency of two sugar crops for the biofuel supply chain. Perspectives for sustainable field management in southern Italy. Energy, 93: 1548-1557.
Garofalo P., Rinaldi M., 2013. Water-use efficiency of irrigated biomass sorghum in a Mediterranean environment. Spanish Journal of Agricultural Research, 11(4):1153-1169.
Garofalo P., Vonella A.V., Ruggieri S., Rinaldi M., 2011. Water and radiation use efficiencies of irrigated biomass sorghum in a Mediterranean environment. Italian Journal of Agronomy, 6, e 21:133-139.
Habyarimana E., Bonardi P., Laureti D., Di Bari V., Cosentino S., Lorenzoni C., 2004. Multilocational evaluation of biomass sorghum hybrids under two stand densities and variable water supply in Italy. Industrial Crop and Products, 20: 3-9.
Halvorson A.D., David C., Nielsenb D.C., Reulec C.A., 2004. Nitrogen fertilization and rotation effects on no-till dryland wheat production. Agronomy Journal, 96: 1196-1201.
Hülsbergen K.J., Feil B., Biermann S., Rathke G.W., Kalk W.D., Diepenbrock W.A., 2001. A method of energy balancing in crop production and its application in a long term fertiliser trial. Agriculture, Ecosystems & Environment, 86 (3): 303-321.
http://ec.europa.eu/agriculture/policy-perspectives/policy-briefs/05_en.pdf (last access, December 2015)
IEA Bioenergy, 2012. Summary and Conclusions from the IEA Bioenergy ExCo67 Workshop, Helsinky (Fi). http://www.qibebt.cas.cn/xscbw/yjbg/201209/P020120913525522089994.pdf (last access, December 2015)
IPCC, 2006. Guidelines for national greenhouse gas inventories, In: Agriculture forestry and other land use, vol. 4. Japan: IPCC/OECD/IEA.
IPCC, 2007. In R.K. Pachauri and A. Reisinger (ed.) Climate change 2007: Synthesis report. Contribution of Working Groups I, II and III to the fourth assessment report of the Intertergovern-

mental Panel on Climate Change. IPCC, Geneva, Switzerland.
Kallivroussis L., Natsis A., Papadakis G., 2002. The energy balance of sunflower production for biodiesel in Greece. Biosystems Engineering, 81 (3): 347-354.
Kitani O., 1999. Energy & Biomass Engineering. In CIGR Handbook of Agricultural Engineering Vol. III. "Plant Production Engineering " CIGR - The International Commission of Agricultural Engineering. American Society of Agricultural Engineers; pp. 632.
Liebam M., Gibson L.R., Sundberg D.N., Heggenstaller A.H., Westerman P.R., Chase C.A., Hartzler R.G., Menalled F.D., Davis A.S., Dixon P.M., 2008. Agronomic and economic performance characteristics of conventional and low-external-input cropping systems in Central Corn Belt. Agronomy Journal, 100 (3): 600-609.
Liska A.J., Yang H.S., Bremer V.R., Klopfenstein T.J., Walters D.T., Erickson G.E., Cassman K.G., 2009. Improvements in life cycle energy efficiency and greenhouse gas emissions of corn-ethanol. Journal of Industrial Ecology, 13: 58-74.
Mastrorilli M., Katerji N., Rana G., 1999. Productivity and water use efficiency of sweet sorghum as affected by soil water deficit occurring at different vegetative growth stages. European Journal of Agronomy, 11: 207-215.
Monti A., Venturi G., 2003. Comparison of the energy performance of fibre sorghum, sweet sorghum and wheat monocultures in northern Italy. European Journal of Agronomy, 19 (1): 35-43.
Nagy C.N., 1999. Energy coefficient for agriculture inputs in Western Canada. Canadian Agricultural Energy End-Use Data Analysis Centre (CAEEDAC). Canada: pp. 41.
Nassi o Di Nasso N., Bosco S., Di Bene C., Coli A., Mazzoncini M., Bonari E., 2011. Energy efficiency in long-term Mediterranean cropping systems with different management intensities. Energy, 36: 1924-1930.
Nigam P.S., Singh, A. 2011. Production of liquid biofuels from renewable resources. Progress in Energy and Combustion Science, 37(1), 52-68.
Palumbo D., Vonella A.V., Garofalo P., D'Andrea L., Rinaldi M., 2014. Response of a two-year sugar beet-sweet sorghum rotation to an agronomic management approach diversified by soil tillage and nitrogen fertilisation. Italian Journal of Agronomy, 9: 109-114.
Patil S.L., 2013 Winter sorghum (*Sorghum bicolor*) productivity as influenced by tillage practices and nitrogen management in Vertisol of SAT, India. Soil and Tillage Research, 126: 183-192.
Pervanchon F., Bockstaller C., Girardin P., 2002. Assessment of energy use in arable farming systems by means of an agroecological indicator: the energy indicator. Agricoltural Systems, 72 (2): 149-172.
Ra K., Shiotsu F., Abe J., Morita S., 2012. Biomass yield and nitrogen use efficiency of cellulosic energy crops for ethanol production. Biomass and Bioenergy 37: 330-334.
RED; 2009/28/EC; http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:32009L0028.
Stout B.A., 1999. Energy & Biomass Engineering. In CIGR Handbook of Agricultural Engineering Vol. V. "Energy and Biomass Engineering"; CIGR - The International Commission of Agricultural Engineering. American Society of Agricultural Engineers; pp 351.
Tabatabaeefar A., Emamzadeh H., Ghasemi Varnamkhasti M., Rahimizadeh R., Karimi M., 2009. Comparison of energy of tillage systems in wheat production. Energy, 34: 41-45.
Tamang P.L., Bronson K.F., Malapati A., Schwartz R., Johnson J., Moore-Kucera J., 2011. Nitrogen requirements for ethanol production from sweet and photoperiod sensitive sorghums in the southern high plains. Agronomy Journal, 103: 431-440.
Tzilivakis J., Warner D.J., May M., Lewis K.A., Jaggard K., 2005. An assessment of the Energy inputs and green house gas emissions in sugar beet (*Beta vulgaris*) production in the UK. Agricoltural Systems, 85: 101-119.
USDA, 2010. Keys to Soil Taxonomy. 11th edn, pp. 346.
Venturi P., Venturi G., 2003. Analysis of energy comparison for crops in European agricultural systems. Biomass and Bioenergy, 25 (3): 235-255.
Wortmann C.S., Liska A.J., Ferguson R.B., Lyon D.J., Klein R.N., Dweikat I., 2010. Dryland Performance of Sweet Sorghum and Grain Crops for Biofuel in Nebraska. Agronomy Journal, 102 (1): 319-326.