Energy 93 (2015) 1548–1557

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Energy performance and efficiency of two sugar crops for the biofuel supply chain. Perspectives for sustainable field management in southern Italy

Pasquale Garofalo [a,*], Laura D'Andrea [b], A. Vittorio Vonella [b], Michele Rinaldi [a], A. Domenico Palumbo [b]

[a] *Consiglio per la Ricerca in Agricoltura e l'Analisi dell'Economia Agraria – Centro di Ricerca per la Cerealicoltura (CRA-CER), S.S. 673 km 25,200, Foggia, Italy*

[b] *Consiglio per la Ricerca in Agricoltura e l'Analisi dell'Economia Agraria – Unità di Ricerca per i Sistemi Colturali degli Ambienti Caldo-Aridi (CRA-SCA), via Celso Ulpiani, 5, Bari, Italy*

A R T I C L E I N F O

Article history:
Received 3 May 2015
Received in revised form
6 August 2015
Accepted 11 October 2015
Available online 19 November 2015

Keywords:
Bioethanol
Fertilization
Soil tillage
Sweet sorghum
Sugar beet

A B S T R A C T

Improvement of the energy balance and efficiency for reduced input of cropping systems is one of the main goals for the cultivation of energy crops. In this field study, two sugar crops for bioethanol production were cultivated under different soil tillage management (conventional; no tillage) and mineral nitrogen application (0, 75, 150 kg N ha^{-1}): sweet sorghum and sugar beet. The energy performance and efficiency along the bioethanol supply chain were analysed and compared. Both of these crops showed good growth adaptation to the different soil and nitrogen management, and thus the energy return, resource and energy efficiencies were significantly improved in the low-input system. Sweet sorghum provided better responses in terms of water and nitrogen use efficiency for biomass accumulation, as well as its energy yield and net gain, compared to sugar beet, whereas sugar beet showed higher energy efficiency than sorghum. According to these data, both of these crops can be cultivated in a Mediterranean environment with low energy input, which guarantees good crop and energy performances for biofuel strategy planning.

1. Introduction

European countries are largely dependent on imported fossil fuels, and the transport sector accounts for more than 30% of the imported energy [1]. Most greenhouse gas emission is due to the transport industry, and CO_2 emission into the air has risen by 90% over the last two decades (Biofuels Advisory Council, [1]). To cope with further increases in greenhouse gas emission, the EU Renewable Energy Directive [2] defined a framework for the promotion of energy from renewable sources. The target of this Directive is that by 2020 with the use of biofuels, it will be possible to achieve a 20% share of energy from renewable sources, and a reduction of 20% in greenhouse gas emissions, with 10% of this being renewable in the transport sector. Moreover the "Climate Action and Renewable Energy Package" [3] has been proposed to save energy use through an improved energy efficiency of 20% by 2020. In view of these policy targets, some investigations have focused on the role of the agricultural sector for biofuel production and the energy efficiency of different cropping systems [4–6], while others have focused on the reduction of greenhouse gas emission through the introduction of biofuels and the replacement of fossil fuel use [7].

Some studies have reported that crop productivity of several species (e.g., wheat, corn, soybean) is not compromised when the energy input is reduced at the field level (mainly through soil tillage and nitrogen management), to improve the energy balance and efficiency [8,9]. Other studies have instead indicated significant reductions in crop and energy performance with reduced energy input applied at the field level [10], as also observed for the productivity of winter sorghum [11], where a reduced tillage system lowered the water-use efficiency of the crop, and consequently the grain yield.

* Corresponding author. Consiglio per la Ricerca e la Sperimentazione in Agricoltura – Centro di Ricerca per la Cerealicoltura (CRA-CER), S.S. 673 km 25,200, Foggia, Italy. Tel.: +39 0881742972; fax: +39 0881713150.
E-mail address: pasquale.garofalo@entecra.it (P. Garofalo).

http://dx.doi.org/10.1016/j.energy.2015.10.031

Currently, the debate on second-generation biofuels remains open [12], and their energy and environmental performance are under study, although they are unlikely to have any effective impact before 2020 [13]. The conversion tecnologies are well known for the first generation of biofuels [14], whereas for second generation biofuels, these are still under development [15]. Moreover, the advantage in terms of energy performance and climate impact of second generation biofuels is achieved through low-input perennial crops [16]. Recently, the CAP reform 2014-2020 (EU Regulation 1307/2013) [17] established that two or more crops should be cultivated on farms to allow the claiming of subsidies (i.e., crop diversification as a 'greening' measure). Thus, herbaceous crops with a short growing cycle and high biomass production (e.g., sorghum) or high sugar content (e.g., sugar beet) can satisfy both the greening measure and the biofuel planning strategy.

Crops like sugar beet are not suitable for second-generation biofuels, because the accumulation of large amounts of lignocellulose can delay the harvest time, with the consequent loss of biomass (i.e., dead leaves and relocation of sugar from roots to new leaves). For other crops such as sorghum, the harvest time at full maturity can compromise the field operations and/or the sowing time of the autumn species that follows. Finally, the cultivation of sucrose crops for feed has dramatically declined in Italy over past years (72% decrease from 2001 to 2012; ISTAT 2015, [18]), because of the European policies (EU Regulation 320/2006); however, the use of these crops can provide diversification of the farm income using the expertise and machinery available on the farm.

Assessment of the energy performance of various crops has been carried out using different parameters and/or at different stages of the supply chain. Koga (2008) [19] reported the energy balance at the field scale as the difference between the gross energy output from sugar beet and the energy cost for its cultivation. Other studies [20] have defined the *EROI (*energy return on the energy investment) as the ratio of the quantity of energy delivered by a biofuel society to the energy used as an input in the process to produce the energy, with a comparison of *EROI* of bioethanol obtained from corn and lignocellulose materials.

Most of the studies that have analysed energy crop performances have been limited to a single species [8,21] or a single growing season [22], or have been based on literature data [23], rather than applied to a specific environment. Moreover, in Italy, field experiments have been mainly carried out in central or northern regions [24,25], with pedo-climatic condition that are relatively dissimilar to the typical climate of the Mediterranean area of the present study. In addition, the system boundaries are often limited to the farm, thus excluding the cost of transportation and the conversion of biomass into biofuel, although the energy for transport is not negligible and can reach up to 23% of the total energy cost [26].

Comparisons of the energy performances of sucrose crops for bioethanol production under different cropping systems (e.g., with modulation of soil tillage and nitrogen supply) under specific pedo-climatic conditions that are prolonged over several years need to be investigated. Thus, the present study was designed to: (i) determine the biomass and sugar yield of sweet sorghum and sugar beet in southern Italy cultivated for first-generation biofuel; and (ii) compare the energy performances between these two crops under different management (i.e., conventional and no tillage practices, and different nitrogen levels), with consideration also of the flow along all of the supply chain (i.e., from farm to bioethanol conversion plant).

2. Materials and methods

The field experiment was carried out over a 3-year period from 2009 to 2012 in Foggia (latitude, 41°88′7″N; longitude, 15°83′05″E; altitude, 90 m a.s.l.), in the Apulia region of southern Italy. The soil was a vertisol of alluvial origin, Typic Calcixeret [27] classified as silty-clay, with the following characteristics: organic matter, 2.1%; total nitrogen, 0.122%; $NaHCO_3$-extractable phosphorus, 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}; and available soil water, 202 mm m^{-1}. The climate was 'accentuated thermo-Mediterranean' [28], with temperatures below 0 °C in winter and above 40 °C in summer. The annual rainfall (mean, 550 mm) was mostly concentrated in the winter months. The class 'A pan' evaporation was 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 at a meteorological station located at the same experimental farm.

2.1. Field experiment

Sweet sorghum (*cv* 'Sucro 506') was sown at the beginning of May, in rows 0.5 m apart and at a distance of 0.08 m between the seeds in each row (i.e., 250,000 seeds per hectare). The crop was harvested before heading (mid-August) to maintain an adequate plant water content (75%), as necessary for the fermentation process. Sugar beet (*cv* 'Autave') was sown between late November and early December, with row spacing of 0.5 m, and plant-to-plant spacing of 0.20 m (i.e., 100,000 seeds ha^{-1}). The crop was harvest at the beginning of August, when the plant achieved a good compromise between water content and root sugar content.

Irrigation of both of these crops was managed according to the water consumed by the plants, as estimated by the gravimetric method (at 0–0.8 m soil depth). Each time the water used by the sweet sorghum and sugar beet reached 60 mm and 30 mm, respectively, the irrigation was triggered. To ensure uniform water distribution, a drip irrigation system was used, with one line for each plant row, and drippers with a 4 L h^{-1} flow. The total amount of water applied for the irrigation of the sorghum was 120 mm, 176 mm and 300 mm for the first, second and third experimental years, respectively, with rainfall of 79 mm, 73 mm and 68 mm during the growing seasons in 2010, 2011 and 2012, respectively. For the sugar beet, 90 mm, 65 mm and 108 mm of irrigation water were applied in the first, second and third growing seasons, respectively, with the total rainfalls of 473 mm, 399 mm and 236 mm during the growing seasons in 2010, 2011 and 2012, respectively.

For both of these crops, the soil management was carried out according to *CT* (conventional tillage) and *NT* (no tillage). For *CT*, shallow ploughing (soil depth, 25 cm) was performed with a five-furrow plow, followed by disc harrowing, power harrowing, and seeding with a precision driller. For *NT*, no soil practice was scheduled, with only direct seeding with a Gaspardo No-Till 1040, which ensured light and shallow tillage in the strip area affected by the furrowers. For *NT*, before seeding, 5 L ha^{-1} glyphosate was applied for weed control.

Mineral nitrogen fertilisation was managed with 75 kg ha^{-1} (*N75*) and 150 (*N150*) kg ha^{-1} nitrogen in the form of ammonium nitrate (34%), as compared with no nitrogen fertilisation (*N0*). The nitrogen fertilizer was split into two doses, one as basal dressing before sowing, and the second as top dressing in the middle of May for sugar beet, and between the end of June and the beginning of July for sorghum. Phosphate fertilizer was applied before sowing (100 kg ha^{-1} P_2O_5).

The main treatment of these crops was related to soil tillage, while the secondary treatment was for the different nitrogen supplies. The experimental design was a split-plot design with three replications. The area of each subplot was 84 m^2. In the 2-year