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Effect of irrigation and nitrogen fertilization on the production of biogas from maize and sorghum in a water limited environment

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ABSTRACT

The expansion of biogas production from anaerobic digestion in the Po Valley (Northern Italy) has stimulated the cultivation of dedicated biomass crops, and maize in particular. A mid-term experiment was carried out from 2006 to 2010 on a silt loamy soil in Northern Italy to compare water use and energy efficiency of maize and sorghum cultivation under rain fed and well-watered treatments and at two rates of nitrogen fertilization. The present work hypothesis were: (i) biomass sorghum, for its efficient use of water and nitrogen, could be a valuable alternative to maize for biogas production; (ii) reduction of irrigation level and (iii) application of low nitrogen fertilizer rate increase the efficiency of bioenergy production. Water treatments, a rain fed control (I0) and two irrigation levels (I1 and I2; only one in 2006 and 2009), were compared in a split–split plot design with four replicates. Two fertilizer rates were also tested: low (N1, 60 kg ha^{-1} of nitrogen; 0 kg ha^{-1} of nitrogen in 2010) and high (N2, 120 kg ha^{-1} of nitrogen; 100 kg ha^{-1} of nitrogen in 2010). Across treatments, sorghum produced more aboveground biomass than maize, respectively 21.6 Mg ha^{-1} and 16.8 Mg ha^{-1} ($p < 0.01$). In both species, biomass yield was lower in I0 than in I1 and I2 ($p < 0.01$), while I1 and I2 did differ significantly. Nitrogen level never affected biomass yield. Water use efficiency was generally higher in sorghum (52 kg ha^{-1} mm^{-1}) than in maize (38 kg ha^{-1} mm^{-1}); the significant interaction between crop and irrigation revealed that water use efficiency did not differ across water levels in sorghum, whereas it significantly increased from I0 and I1 to I2 in maize ($p < 0.01$). The potential methane production was similar in maize and sorghum, while it was significantly lower in I0 (16505 MJ ha^{-1}) than in I1 and I2 (21700 MJ ha^{-1}). The only significant effect of nitrogen fertilization was found in the calculation of energy efficiency (ratio of energy output and input) that was higher in N1 than in N2 ($p < 0.01$). These results support the hypothesis that (i) sorghum should be cultivated rather than maize to increase energy efficiency, (ii) irrigation level should replace up to 36% of ETr and (iii) nitrogen fertilizer rate should be minimized to maximize the efficiency in biomass production for anaerobic digestion in the Po Valley.

1. Introduction

Energy production is the largest source of greenhouse gases (IPCC, 2013), and global energy demand will increase by one-third from 2010 to 2035 (IEA, 2012). On these premises mitigation of climate change will inevitably pass through a profound modification to the energy supply system, based on a progressive shift toward renewable energy sources. In this regard, biomass crops and biomass conversion to bioenergy may represent a valuable option to combine energy production with atmospheric CO_2 sequestration (Lopez-Bellido et al., 2014). Energy crops can be cultivated both on fertile and marginal land (Campbell et al., 2008), but it is particularly in the latter case or when low-input practises are used that bioenergy production is efficient (Amaducci et al., 2004; Agostini et al., 2015).

Among annual crops maize (*Zea mays* L.) and sorghum (*Sorghum vulgare* pers.) are currently used to feed biogas plants (Zegada-Lizarazu and Monti, 2011; Mahmood and Honermeier, 2012). Sorghum is a suitable option in drought-prone environments (Barbanti et al., 2006) and in low-input cultivation systems thanks to its deep and dense root system (Stone et al., 2001; Farré and Faci, 2006; Ananda et al., 2011) and to its high photosynthetic efficiency under drought (Zegada-Lizarazu et al., 2012). Where water is scare sorghum can be a viable biomass crop in alternative to

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maize (Mastrorilli et al., 1999; Farré and Faci, 2006; Schittenhelm and Schroetter, 2014), that has a relatively shallow root system (Himmelbauer et al., 2010).

From an economic point of view, the profitability of energy plants fed with dedicated bioenergy crops is strictly dependent on the price of agricultural raw materials and the economic analysis must consider the water consumption as one of the chief aspect driving the production cost (Donati et al., 2013). The reduction of water use can be achieved by increasing WUE, and particularly by shifting to crops capable of producing acceptable yields under deficit irrigation.

As the future trend of the European Union policy is to cut down public incentives supporting the biogas production from dedicated energy crops, the reduction of production costs is becoming even more important to enhance the whole system productivity.

The main objective of this paper was to compare sorghum and maize for biogas production, under contrasting nitrogen and irrigation levels, in a mid-term experiment in Northern Italy. Accordingly, a mid-term field trial was carried out to test three hypothesis: (i) biomass sorghum could be a valuable alternative to maize in biogas production; (ii) the reduction of irrigation level and (iii) low nitrogen fertilizer rate can result in profitable biomass production. The irrigation level was calculated as a rate of the maize and sorghum actual evapotranspiration (ETr), and a simplified energy balance was calculated to identify critical steps in biogas production from maize and sorghum.

2. Materials and methods

2.1. Field trials

Field trials were carried out in Gariga di Podenzano (PC) at the Vittorio Tadini experimental farm, Italy (latitude 44° 59′) in 2006–2010 comparing biomass production, WUE and energy balance of two energy crops, maize and sorghum, under different irrigation levels and nitrogen availability in factorial combinations. The soil is a Chromic Luvisol, with a silt loamy texture (sand 12%, silt 64%, and clay 24%), according to soil taxonomy (FAO, 2006). The soil has a low percentage of carbonates, a subacid to neutral pH (6.9) and the CEC is 14.9 meq/100 g.

The experiment layout was a split–split-plot design with four replicates (only three in 2009). Main plots were irrigation levels (I0–I2), genotypes (maize hybrid Arma—Syngenta FAO class 700; sorghum hybrid Biomass133—Syngenta) were in subplots and nitrogen levels (60 or 120 kg ha^{-1}) in sub-subplots. Sub–sub plots were 24 m^2 (4 × 6 m).

Irrigation schedule was based on water depletion due to the ETr, taking also into account for the water availability due to rainfall (see Section 2.4). Over the 5-year period, the amount of irrigation water varied from 17 to 52% and 28 to 59% of ETr for treatment I1 and I2, respectively. No irrigation was provided to the rain fed treatment I0. Daily values of mean temperature, solar radiation, rainfall and wind speed were recorded by an automatic weather station located within the farm-site (Fig. 1). Irrigation levels were three in 2007, 2008 and 2010 (I0–I2) and two in 2006 (I1 and I2) and 2009 (I0 and I1). Water was supplied by drip irrigation using a piping system at low pressure with a device for volume control.

In Table 1 all treatments and levels of irrigation applied in the five years of experiment are presented.

Soil preparation was carried out in all years with a combination of operations that is typical for the area: Soil ploughing was carried out after the harvest of the preceding crops (wheat or processing tomato), seedbed was prepared with a rotary tiller immediately before sowing. Sowing was carried out with an experimental mechanical seed drill (Vignoli) using an inter-row distance of 0.7 m for both sorghum and maize. Target planting density was 7 and 12 plants m^{-2} for maize and sorghum, respectively.

Sowings were carried out between 20th and 25th of April for maize and approximately 20 days later for sorghum. Sowing date were defined in accordance with the common practises of local farmers, which entailed the optimal planting dates occurring from the second half of April up to the first half of May, excepted in 2010, when sowing was delayed to June 5th due to the adverse meteorological conditions.

Nitrogen fertilization was carried out at sowing time via distributing 60 kg ha^{-1} of nitrogen in all plots as urea. An additional dose of 60 kg ha^{-1} of nitrogen was distributed manually on randomised N1 plots immediately prior to hoeing, which was carried out with a row crop cultivator. Weed control was carried out chemically by spraying a mix of *S*-metolachlor and terbuthylazine immediately after sowing with a boom-type sprayer and mechanically at the beginning of the stem elongation phase with the row crop cultivator.

2.2. Soil and crop measurements

In 2007 and 2008 a self-constructed "Shelby" tube sampler was used to take 1.2 m deep soil core samples (7.4 diameter) from each plot at sowing and at harvesting (Amaducci et al., 2008). Each core was then divided into 0.1 m and 0.2 m samples, for the first 0.7 m of the soil profile and for the deeper layer from 0.7 m to 1.2 m, respectively; subsequently volumetric water content was calculated for each sample from gravimetric water content and soil bulk density measurements. Volumetric water content data were calculated before and after the cultivation to estimate the soil water consumption of maize and sorghum at different soil depths by applying the method proposed by Farré and Faci (2006). Such a method consists in monitoring soil water content gravimetrically in each 0.2 m layer till 1.0 m depth. Soil water depletion was then estimated from soil water contents at sowing and maturity of both maize and sorghum. Soil water contents (m^3 m^{-3}) were calculated from gravimetric soil water contents and bulk density. ETr of maize and sorghum was calculated from the water balance components as the sum of irrigation, rainfall and soil water depletion between sowing and maturity.

Maize and sorghum harvesting was carried out at approximately dough maturity.

Three rows per sub-subplot (8 m^2 in total per sub-subplot) were harvested with a single-row chopper. The biomass harvested from each row was weighed directly on-field with a balance mounted on the chopper. A subsample of biomass per each sub-subplot was then collected to determine dry matter content (oven dried at 70 °C). A selection of samples of biomass from maize and sorghum harvested in 2006 and 2007 were fermented according to the method DIN 38414-S8 to evaluate the potential methane production.

2.3. Rainfall, crop evapotranspiration (ETr) and water use efficiency (WUE)

Daily values of mean temperature, solar radiation, rainfall and wind speed were recorded with an automatic weather station located within the farm-site (Fig. 1). Large differences of total rainfall and distribution were observed in the central months of the crop cycle over the 5-year period (2006–2010) (Fig. 2). The rainfall pattern did not deviate substantially from the data measured by the Regional Meteorological Service (Dexter, Emilia-Romagna). The lowest amount of rain was observed in 2009 (<100 mm) and the highest in 2007 (386 mm).

For the whole period the WUE was computed as the ratio of total biomass (kg ha^{-1}) to total water use (i.e., crop evapotranspiration, ETr, mm). ETr was estimated with the CropSyst simulation model