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Yield and energy balance of annual and perennial lignocellulosic crops for bio-refinery use: A 4-year field experiment in Belgium

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ABSTRACT

In densely populated regions, such as, Belgium, value chains in the bio-economy can be organized on locally produced primary feedstock, allowing cutting down transport costs and reducing greenhouse gas emissions. The energy use efficiency of three major cropping systems under two fertilizer regimes was compared side by side in a 4-year field trial, with the farm-gate as system border. The annual crops maize, sorghum, and Italian ryegrass were compared with the grassland species perennial ryegrass, cocksfoot, timothy and tall fescue, and the lignocellulosic crops miscanthus, switchgrass, common reed, reed canary grass, and willow. Maize yielded as average a dry matter of 19.6 t ha^{-1} y^{-1} at medium fertilization level. The average dry matter yield of the other crops varied between 3 t ha^{-1} y^{-1} for common reed and 21.1 t ha^{-1} y^{-1} for *Miscanthus* × *giganteus*. However, the highest energy use efficiency was obtained for switchgrass and willow. The factors with the most important impact on the total energy input (EI) were fertilizer application, up to 79% for perennial ryegrass, and the preparation of starting material (e.g., up to 81% of the total EI is attributed to the production of miscanthus rhizomes). Targets for further improvement of the sustainability of the primary feedstock production are the development of resource efficient varieties, e.g., fertilizer use efficient maize varieties or seed-based miscanthus varieties, or the inclusion of energy efficient crops into the rotation system, such as energy beet instead of Italian ryegrass. This study provides interesting insight in the energy balances at the farm level for both the farmer and the industrial actors in the locally organized bio-refinery chains.

1. Introduction

Environmental concerns, the limited availability of fossil fuel, and associated high energy prices, have awakened the interest in developing products from renewable resources and have triggered the interest of governments worldwide to support the transition to a bio-based economy. Biomass, primarily from crops as well as residues from agriculture and from industry, can be used as a renewable substitute for fossil-based raw materials (Sanders and van der Hoeven, 2008). Large quantities of biomass are needed to meet the increasing demand for primary biomass resources; this tendency is expected to increase even further in the future (Carus and Dammer, 2013). The sustainable production of biomass, thus, plays a central role in a bio-based economy (Bentsen and Felby, 2012) and agriculture faces great challenges to meet this increasing demand for biomass (Offermann et al., 2011; McCormick and Kautto, 2013), without compromising food production. These developments may represent economic benefit for the farmer in form of new markets for the agricultural sector, and possibly higher or more stable income per hectare (Carus and Dammer, 2013).

In general, efficient bio-based value chains such as, anaerobic digestion or small scale biorefinery have a marked regional character. The production of feedstock and (pre-) processing steps are ideally located within regional scale, allowing efficient use of the resources available, cutting down transport costs and consequently reducing greenhouse gas emissions (Bruins and Sanders, 2012). An additional factor to consider is the limited availability of arable land, what can result in competition among the production of food, feed, bio-based industries, and landscape conservation. Thus, in the path toward a bio-based economy the optimization of the agricultural systems for locally produced biomass at the highest sustainable level is essential (Bentsen and Felby, 2012).

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Here, we present an evaluation of different crops and cropping systems for the production of biomass at a regional scale (Flanders, Belgium). This analysis can assist the primary feedstock chain to select the most suitable crop(s) to supply certain value chains, and assist the industrial actors to identify feedstock that are (or can become) available at regional scale. The selection of studied crops and cropping systems was based on four characteristics of an appropriate crop for the production of renewable resources, such as, bio-energy and green chemicals in areas with arable farming systems in temperate regions of Western Europe. These characteristics are high yield of utilizable biomass, production systems that avoid competition with food, crops that can be cultivated with low inputs and that are highly resistant to pests and diseases (Dubois, 2011). Crops traditional in European agricultural systems and novel lignocellulosic crops were retained. (i) Maize is currently the most important energy crop cultivated in temperate regions such as, Belgium, mainly for co-digestion with manure in biogas installations (1430 ha in 2009, www.statbel.fgov.be). (ii) Although monoculture is increasing in popularity, it is unsustainable thus, maize monoculture should be avoided and was compared to a cropping system with a 3-year rotation scheme (maize Italian ryegrass and sorghum). (iii) Managed grasslands represent a major acreage in Europe, mainly as a source of in-farm produced feed for ruminants (Peeters, 2009). Perennial ryegrass is the most important cultivated species in grassland and is compared to three other species: tall fescue, cocksfoot, and timothy (in monoculture and in mixture with clovers). Although these latter species cannot compete with perennial ryegrass with respect to nutritional value for ruminants, they can achieve high yields and might become relevant in combination with an alternative valorization chain (Pannecoucque et al., 2012). (iv) As novel biomass crops, the lignocellulosic crops reed canary grass, switchgrass, *Miscanthus* spp, common reed, and willow were chosen.

As basis for comparison we calculated the energy balances, an approach that is increasingly used to assess the energy input and productivity of agricultural systems (Bhoemel et al., 2008; Castoldi and Bechine, 2010; Felten et al., 2013). This comparison takes into consideration the land use efficiency (LUE) and the energy use efficiency (EUE) of the crop management system applied. Energy inputs and outputs are, thus, both taken into consideration. To calculate the energy balance, we used the methodology described in Bhoemel et al. (2008), in which the farm gate is used as system border, without incorporation of any further processing because this can vary depending on factors outside the agricultural system, and may require separate case-by-case evaluation.

Specific objectives of the experiment presented were (i) to compare dry matter yield of the different cropping systems under low and medium input conditions over several growing seasons, (ii) to get insight into the energy consumption and the energy use efficiencies associated to the different cropping systems, and (iii) to generate knowledge concerning the performance of novel lignocellulosic crops in comparison to currently cultivated crops under Belgian climatic conditions and more general to similar agricultural regions in Western Europe,

2. Material and methods

2.1. Field experiment

A long-term field experiment was established in May 2007 at the Institute for Agricultural and Fisheries Research (ILVO), in Melle (51°0′N, 3°48′E), Belgium on a light sandy loam soil. The climate in this region is temperate maritime with mean rainfall of 800 mm per year and mean temperature of 10.5 °C over the past 10 years. Before the initiation of the experiment this field had been used since 2004 to cultivate maize, with rye sown as winter catch crop. The field was plowed in the spring of 2007. Before planting, compost was added at a rate of 25 t ha^{-1} (137N, 6P_2O_5, and 14K_2O kg ha^{-1}).

Three groups of cropping systems were considered: (i) annual crops, (ii) perennial grassland, and (iii) lignocellulosic crops. The experimental layout of the field trial was a randomized split-plot block design with three replications. Each replicate (block) was divided in three sub-blocks, corresponding to the three cropping systems defined above. The position of the sub-blocks within each replicate was randomized, and the crops were randomized within the sub-blocks. The plots within the sub-blocks of cropping systems 'annuals crops' and 'perennial grassland' were divided into two sub-plots, referring to two fertilizer treatments (low *F* and medium *F*). The fertilizer doses were in all cases below the maximum allowed in Flanders for sandy loam soils as described below.

Season 2007 was considered as an establishment year. Only for the lignocellulosic crops, data from season 2007 were included in some of the calculations as described below.

2.2. Annual crops

Each sub-block of annual crops consisted of four plots: one plot with monoculture maize, and three plots trialing a 3-year rotation of one season maize, one season Italian ryegrass, and one season with one spring cut of Italian ryegrass followed by sorghum. At the start of the experiment, plots with monoculture maize and each crop of the rotation were established. For each crop, two cultivars (Table 1) were sown in the same plot to reduce cultivar effects. This resulted in 4 plots of 42 m^2 in each sub-block of annual crops, each divided in two sub-plots (low *F* and medium *F*).

Maize (monoculture and rotation) was sown on May 7th in 2008, April 23rd in 2009, and April 29th in 2010 with a between-row spacing of 0.75 m and at a density of 10 plants m^{-2}. Fertilizers were applied 10 days after sowing (low *F* (kg ha^{-1}): 90N, 12P_2O_5, and 150K_2O; medium *F* (kg ha^{-1}): 150N, 20P_2O_5, and 250K_2O). Herbicides were applied 2 days later at a ratio of 2 l ha^{-1} Stomp (BASF Crop Protection) and 1.4 l ha^{-1} Frontier (BASF Crop Protection). Maize was harvested at a dry matter content of approximately 30% (w/w), at the end of September or beginning of October with a three-row maize harvester C2200 (Kemper).

Italian ryegrass was sown after the harvest of maize in October, at a density of 1400 germinating seeds m^{-2}, with a between-row spacing of 0.13 m. Fertilizers were applied in March, May, and June, and 4th time in March of the following year before the spring cut (low *F* (kg ha^{-1}): 218N, 246K_2O, and 10P_2O_5; medium *F* (kg ha^{-1}): 304N, 432K_2O, and 20P_2O_5). No herbicides were applied in this case. Italian ryegrass was mown four times the year of sowing, with one final cut the following spring, using a grass harvester Haldrup-F55 (J. Haldrup, Løgstor, Denmark).

Sorghum was sown in the second half of May after a final cut and plowing of Italian ryegrass, at a density of 40 seeds m^{-2} with a between-row spacing of 0.75 m. Herbicides (6 l ha^{-1} Ramrod–Monsanto) were applied at the end of May 5 days after fertilizer application (low *F* (kg ha^{-1}): 72N, 12P_2O_5, and 150K_2O, medium *F* (kg ha^{-1}): 120N, 20P_2O_5, and 250K_2O). The crop was harvested in October at a dry matter content of 30% (w/w), using a three-row maize harvester C2200 (Kemper).

2.3. Perennial grassland

Each sub-block of perennial grassland consisted of six plots of 15.6 m^2 each: five pure grass stands and one grass–clover mixture (Table 1). All plots were sown in May 2007 at a density of 30 kg seeds ha^{-1}, and 0.13 m spacing between rows. Plots without clover were treated with 5 l ha^{-1} Bofix® (herbicide, Dow AgroScience, Indianapolis, IN, USA) at the end of June 2007. Fertilizers (low *F*