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First or second generation biofuel crops in Brandenburg, Germany? A model-based comparison of their production-ecological sustainability

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ABSTRACT

We assessed and compared the production-ecological sustainability of first and second generation biofuel production systems in the state of Brandenburg, Germany. Production ecological sustainability was defined by a limited set of sustainability indicators including net energy yield per hectare, GHG emissions, N leaching, soil organic carbon and soil erosion, and several resource use efficiencies. The assessed first generation fuels are biodiesel and bioethanol produced from rapeseed (*Brassica napus* L.) and sugarbeet (*Beta vulgaris* L.) feedstock, respectively. Assessed second generation systems are based on feedstock from *Miscanthus* (*Miscanthus* × *giganteus* Greef et. Deu. ex Hodkinson et Renvoize) and black locust (*Robinia pseudoacacia* L.); for both crops conversion into cellulosic ethanol and Fischer Tropsch Diesel was assessed. In the assessment, computer models were used for simulating crop growth, soil organic carbon dynamics and several other relevant biophysical processes. Second generation biofuel production systems based on *Miscanthus* and black locust perform substantially better than first generation systems based on rapeseed and sugarbeet. They contribute much more to GHG emission reduction, had much higher net energy yields and better resource use efficiencies; soil erosion and N leaching were also lower. *Miscanthus* performed better than black locust, except for its N use efficiency; it is the most water-efficient species, which is important in a region with declining groundwater tables. However, in Brandenburg, low temperatures during winter and early spring are often threatening to survival of first-year *Miscanthus* plantings; there have been disastrous experiences in the past. The drawback of black locust is that it has invasive characteristics; this risk may be controllable however (cf. Motta et al., 2009). Of the first generation systems, rapeseed has low net energy yields and large N requirements per unit of energy produced; it also performed poorly for N leaching. Erosion hazard in rapeseed is especially present after the seedbed has been prepared at the end of summer. Greatest erosion risk was calculated for sugarbeet however, due to its late canopy closure.

1. Introduction

From a production-ecological perspective and assuming no cost at the expense of ecosystems, first-generation biofuels produced from tropical crops such as sugarcane (*Saccharum officinarum* L.) and oil palm (*Elaeis guineensis* Jacq.) are more sustainable than from temperate crops such as sugarbeet (*Beta vulgaris* L.) and rapeseed (*Brassica napus* L.) (De Vries et al., 2010). This is due to their favourable harvest indices, C4 photosynthesis and perennial nature. However, energy crops exist that possess similar features and yet can be grown in temperate areas; examples are *Miscanthus* (*Miscanthus* × *giganteus* Greef et. Deu. ex Hodkinson et Renvoize), willow (*Salix* spp.), poplar (*Populus* spp.) and black locust (*Robinia pseudoacacia* L.). Unlike first-generation crops, these species contain no plant oil, sugar or starch that can easily be converted into biodiesel or bioethanol. They largely consist of ligno-cellulosic compounds and hence require more advanced (second generation) processing methods. Cellulose may be converted into ethanol along biological pathways, using modified yeasts (Ragauskas et al., 2006), while biodiesel from ligno-cellulosic biomass is mostly obtained by gasification and consecutive Fischer Tropsch synthesis ('Biomass to Liquid', BtL; cf. van Vliet et al., 2009). At present, the production of such fuels is not cost-effective because there are a number of technical barriers that need to be overcome before their potential can be realized (Naik et al., 2010). Virtually all biofuels are therefore produced with first-generation technology (OECD and FAO, 2011). In Germany for instance, the country with the largest biodiesel production volume in the world (US-EIA, 2011), biodiesel is almost exclusively produced from rapeseed (FNR and BMELV, 2011a), while bio-ethanol is produced from wheat (*Triticum aestivum* L.),

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rye (*Secale cereale* L.) and sugarbeet (FNR and BMELV, 2011b). Rapeseed, wheat and sugarbeet require good quality agricultural land (LVLF, 2010). Replacing these feedstocks with ligno-cellulosic crops that can be grown on lower quality land and have higher net energy yields could substantially reduce indirect land use change by releasing sugarbeet and rapeseed production for food purposes. It could also be more favourable for soil carbon sequestration.

Miscanthus is such a ligno-cellulosic crop and has enjoyed considerable attention from researchers in Germany over the years (cf. Jones and Walsh, 2001). Of more recent origin is the interest in black locust for biomass (Grünewald et al., 2009). This legume species has habitat-forming characteristics and is often planted in poor and loose sandy soils to fix and enrich them (Rahmonov, 2009). Fast growth, good resprouting ability after cutting and high wood density proved to be particularly useful for the production of woody biomass for bioenergy in areas with marginal soils (Böhm et al., 2011). Marginal soils can be defined as soils on which cost-effective production is not or hardly possible; it is an economic term (Schroers, 2006). Black locust is mentioned as a feedstock for BtL (CHOREN, 2011a). It is native in North America. Since the early 1600s, when black locust seeds were first sent to France, it has been extensively planted throughout Europe, U.S.S.R., Korea and China. There are now over one million hectares of black locust plantations, making it second among broad-leaved species only to *Eucalyptus* spp. on the basis of world-wide planted area (Boring and Swank, 1984).

In this paper, we assess and compare the production-ecological sustainability of biofuel production chains based on *Miscanthus* and black locust (‘second generation’) with production chains based on sugarbeet and rapeseed (‘first generation’) in the state of Brandenburg. Brandenburg was selected because of its relatively low population density, large-scale agriculture and general interest in renewable energy. Rapeseed, sugarbeet and *Miscanthus* were assumed to be grown on agricultural land; black locust production was assessed on reclaimed mine soils. Ca. 77,000 ha land in the southeast of Brandenburg (*Lausitz*/Lusatia) are affected by large-scale open-cast lignite mining operations (Grünewald et al., 2009). After removal of the overburden sediments up to 120 m depth and consecutive extraction of the lignite, it is required by law (Bundestag, 2004a) to ‘recultivate’ the land: ‘to achieve a natural, pre-industrial landscape’ (Vattenfall, 2009, 2011). One of the most important issues for restoration of ecosystems in post-mining landscapes is soil formation through accumulation of organic C in the surface layers of the spoil material (Keskin and Makineci, 2009). To supply this organic C, over the years planting of different tree species has been carried out. Under deciduous trees, organic matter with higher bioactivity and better water and nutrient balance is found than under pine and larch (Katzur and Haubold-Rosar, 1996). As part of a 170-ha project, the mining company Vattenfall Europe Mining started with the establishment of *R. pseudoacacia* on mining substrates in 2005 (Grünewald et al., 2009).

Brandenburg may be considered representative of the agro-ecological conditions prevalent in large parts of Poland, Hungary, Rumania, Bulgaria, Slovakia and the Czech republic, with precipitation below 600 mm y^{-1} (Nellesteijn and Dekker, 1998) and mostly sandy soils with low base saturation (dystric cambisols; FAO/UNESCO, 2007). In a climatic stratification of the environment of Europe (Metzger et al., 2005), these areas are grouped under the continental zone. In our assessment, we used a set of indicators to characterize the production-ecological sustainability of biofuel production systems that was defined in preceding work (De Vries et al., 2010, 2011). It focuses on resource-use efficiency, net energy production and greenhouse gas (GHG) emissions and the quality of soil and water resources and their ability to sustain agricultural production. Some of these indicators are of legal importance in the case study area: soil erosion and soil organic matter content are part of the German Ordinance on Direct Payments (Bundestag, 2004b) while GHG emission reduction is part of the Sustainability Decree for Biofuels (Bundestag, 2009). Although it is not a full Life Cycle Assessment (LCA), with these indicators, the analysis goes beyond the field level and integrates impacts of the production of inputs upstream and of conversion to energy downstream.

In the assessment, models were utilized for simulating relevant biophysical processes such as crop growth, soil organic carbon dynamics, changes in soil water content, soil erosion, N leaching and the emission of GHGs.

2. Methods

2.1. Soils

Soils in Brandenburg are predominantly sand and loamy sand; less than 20% of the arable land consists of better quality sandy loam and sandy loess soils (Holsten et al., 2009; Wechsung et al., 2000) whilst loam and clay soils constitute only 3% of the area (LVLF, 2010). We assessed sugarbeet production on loam (soil data from SEAMLESS project; Hazeu et al., 2010) since in Northern Europe, sugarbeet is often grown on heavier soils (Elzebroek and Wind, 2008). Production of rapeseed and *Miscanthus* is assessed for the predominant loamy sand (Table 1). They can both be grown on a wide range of soils, as long as they are well-drained (Elzebroek and Wind, 2008; Lewandowski et al., 2003). Black locust cultivation was assessed on reclaimed mine soils; these have loamy sand and sandy loam textures (Grünewald et al., 2007), similar to the agricultural soils; in the assessment we used loamy sand (Table 1). SOC content of ∼0.5% is also similar to that of the agricultural soils (Bungart and Hüttl, 2004). The main differences between agricultural soils and reclaimed mine soils are soil chemical properties such as acidity and nutrient availability and the absence of soil aggregates. Further, part of the total C in these soils can be assigned to lignite (Rumpel et al., 1998). These issues are not explicitly taken into account by our models, but are accounted for by using actual yield data from production systems on reclaimed mine soils.

2.2. Crop production

For rapeseed and sugarbeet, agricultural input usage and crop and crop residue yields from agricultural practice in Brandenburg were used (LVLF, 2010). Since *Miscanthus* and black locust cultivation in Brandenburg are still in the experimental phase, for these crops we used data from experiments. Furthermore, for all of the assessed crops, we used dynamic crop growth models for obtaining daily values of leaf area index (LAI, m^2 m^{-2}) and evapotranspiration (mm d^{-1}) during the season as these were required for calculating soil erosion and water productivity. We ran the models for water-limited production, assuming that all systems are entirely rainfed and that no limitation from nutrient shortages occurs. However, for black locust on reclaimed mine soils, we calibrated a crop growth model so that simulated yields matched with actual biomass yields in trials (Grünewald et al., 2009); in these soils, nutrient limitations are likely to occur. Daily weather data from the SEAMLESS project (Hazeu et al., 2010) for Brandenburg were available for 25 years (1982–2006) and used as model input; soil data were derived from the same source. For calculating soil erosion and water productivity, we used averaged daily model results of LAI and evapotranspiration over the 25 years of simulation. A summary of the cultivation systems and of the crop growth models used is given below for each of the four feedstock crops.

Miscanthus stands are established through vegetative propagation by rhizome pieces or by plants grown from callus culture. We considered planting from rhizomes since this is more favourable