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Biomass productivity and radiation utilisation of innovative cropping systems for biorefinery

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ABSTRACT

In order to supply future biorefineries there is a need to sustainably intensify the biomass production on current agricultural land. The aim of this work was to determine biomass yield and associated radiation utilisation for novel perennial grasses and annual crops in rotations optimised for biomass production, and compare their performance with traditional cropping systems commonly used in northern European agriculture. Measurements of biomass yield from 2012 to 2015 at two Danish sites differing in soil type and climatic conditions were conducted in three main cropping systems: *i*) optimised rotation of annual crops (maize, beet, hemp/oat, triticale, winter rye and winter rapeseed), *ii*) perennial crops intensively fertilised (festulolium, reed canary, cocksfoot and tall fescue), low-fertilised (miscanthus) or unfertilised (grass-legume mixtures) and *iii*) traditional systems (continuous monocultures of maize and triticale, and a rotation of spring barley – winter barley – winter rapeseed).

The results showed that on sandy loam soil, the highest biomass yield (mean of three years following the establishing year) was achieved by festulolium (20.4 Mg ha^{-1}), followed by tall fescue (18.5 Mg ha^{-1}), optimised rotation (16.7 Mg ha^{-1}), reed canary (15.9 Mg ha^{-1}) and cocksfoot (15.2 Mg ha^{-1}). On coarse sandy soil, the highest biomass was achieved by tall fescue (17.7 Mg ha^{-1}), followed by cocksfoot (15.9 Mg ha^{-1}), reed canary (14.3 Mg ha^{-1}) and optimised rotation (13.9 Mg ha^{-1}). The biomass yield of traditional cropping systems varied between 11 and 18 Mg ha^{-1}, with continuous maize being the most productive. Although traditional maize produced similar or higher biomass yields than the novel cropping systems, the novel systems are expected to reduce environmental impact and have positive effects on biodiversity.

The fraction of intercepted photosynthetically active radiation (*flpar*), the accumulated intercepted photosynthetically active radiation (*Ipar*) and the radiation use efficiency (*RUE*) were determined from canopy radiations measured biweekly for three years. These results showed a higher annual *Ipar* (800–1200 MJ m^{-2}) but lower *RUE* (1.0–2.0 g MJ^{-1}) for the most productive perennial crops than for the most productive annual crops such as maize and beet (*Ipar* = 600–750 MJ m^{-2}, *RUE* = 2.3–3.0 g MJ^{-1}), with variations depending on crop species, management actions and prevailing meteorological conditions. The lower aboveground *RUE* of perennial crops than of annual crops indicates differences in photosynthesis efficiencies and partitioning of assimilates to non-harvested plant parts and calls for further breeding of the perennial crops to improve their *RUE*.

1. Introduction

Indirect land use change (ILUC) is a strong argument against production of dedicated energy crops on agricultural land. Although the size of ILUC effects is uncertain, it can increase greenhouse gas emission or even cause negative greenhouse gas balances for the crop production and associated energy use (López-Bellido et al., 2014). Therefore, the most promising strategy is to increase biomass productivity on existing agricultural land and maintain the current food production while simultaneously increasing biomass availability for the bio-industry. However, increasing the productivity by making fundamental changes to the cropping strategy

Abbreviations: *PAR*, Photosynthetically active radiation, in MJ per m^2 ground area; f_{Ipar}, Fraction of intercepted photosynthetically active radiation, dimensionless; *Ipar*, Intercepted photosynthetically active radiation, in MJ per m^2 ground area; *CIpar*, Crop Ipar accumulated in the growing season, in MJ per m^2 ground area; *AIpar*, Annual Iparaccumulated from 1 January to 31 December, in MJ per m^2 ground area; *RUE*, Radiation use efficiency, in g of dry biomass per MJ *Ipar*.

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requires changes in current agricultural supply chains, and biorefining may be one key to facilitate such a change and to utilise high-yielding crops in new ways for food, feed and bioenergy production (Parajuli et al., 2015). For instance, a potential option is to extract protein feed from grass and legume crops in order to replace the import of soybean products for monogastric animals (Dale et al., 2009; Jørgensen and Lærke, 2016), while the fibrous fraction of the crops can be used for ruminants or energy production.

Current regulations and general sustainability awareness of the public and industry will require that increased productivity is followed by lower emissions of reactive nutrients to the environment. Increasing crop yield without adverse environmental impact or need for conversion of additional non-agricultural land has been defined as 'sustainable intensification' of the agricultural system (Petersen and Snapp, 2015). It has mostly been practised in tropical regions, where reviews of the implementation in agricultural and agroforestry systems show twofold increases in crop grain yields at time scales varying from 3 to 10 years (Pretty and Bharucha, 2014; Pretty et al., 2011). It has yet to be demonstrated whether sustainable intensification can take place under temperate climate, where agricultural chains are already optimised (Firbank et al., 2013). Although the low-hanging fruits in the European agriculture have been picked and limited yield increase is possible with further sustainability improvements (van Grinsven et al., 2015), the potential for a change into more resource-efficient cropping systems and for reviewing their utilisation in the context of the emerging bioindustry and bioeconomic thinking is largely unexplored. Kuyper and Struik (2014) concluded that sustainable agriculture is a contested concept and its intensification requires a radical rethinking of the production. Since sustainable intensification does not articulate or favour any particular vision or method (Pretty and Bharucha, 2014), a wide range of biophysical and management approaches, ranging in scale and scope, as well as candidate crops for biorefining can be investigated.

Annual crops such as maize, winter wheat and winter rapeseed are currently grown on large areas to supply biomass for the bioindustry (e.g. for biofuel; Koçar and Civaş, 2013). They can provide acceptable biomass yields under traditional field management practices (e.g. maize, Schittenhelm, 2008), yet their cultivation for biomass is debated because of ILUC effects (López-Bellido et al., 2014) and sustainability issues such as losses of unutilised nitrogen (N) to the environment (Manevski et al., 2015; Zegada-Lizarazu et al., 2010). Perennial crops might be a better option since they cover the soil all year round and utilise solar radiation for a longer period, potentially giving larger biomass yields than annual crops (Pugesgaard et al., 2015). They produce moderate to high yields of biomass on medium- to low-fertility or abandoned land while having lower production costs and soil nutrient losses (Monti et al., 2009; Zegada-Lizarazu et al., 2010). Yet, numerous aspects of the production agronomy, physiology and ecology for perennial crops grown as industry crops are unexplored. There is also a motivation for improving the drawbacks associated with growing monocultures and perennial crops for biomass, such as monotonous landscapes, and a reduction in biodiversity and the farmer's income. Well-designed and diverse crop rotations may be able to mitigate some of these drawbacks and may maximise the biomass yield needed for a green biorefinery. For instance, the use of cover crops is either recommended or legally required in many countries under a temperate climate in order to reduce nutrient losses and fulfil (inter)national environmental policies. Cover crops typically produce 0.5–1.0 Mg ha^{-1} biomass, which is not economical to harvest and which is why they are ploughed under before the next crop is sown. If the main crop is harvested earlier, either as a green whole crop or by stripper harvesting and air-tight storage, the production of the cover crop may be increased (Hansen et al., 2007; Schwarte et al., 2005) and turned into a harvestable crop, which further increases the annual productivity.

Prolonging the field coverage with crops also increases the annual amount of intercepted solar radiation because the dynamics in canopy development and the course of senescence affect the duration and penetration of light across the green foliage and the net photosynthesis over time (Ceotto et al., 2013). The fraction (*f*) of photosynthetically active radiation intercepted by the canopy (*Ipar*) is one of the key parameters in studying biomass production (Hamzei and Soltani, 2012; Struik et al., 2000; Strullu et al., 2013). For instance, non-optimal conditions due to lack of nutrients or low temperatures reduce the amount of green canopy, leading to lower f_{Ipar}, which, in turn, reduces production of photosynthates and dry matter and lowers radiation use efficiency (*RUE;* g dry matter MJ^{-1} *Ipar*). It is especially important not only to characterise the typical values for *Ipar* or *RUE* of plant species, but also to identify their variability and the probable sources of such variability. f_{Ipar} can be derived from vegetation indices (VIs), which are easy to measure by handheld or remote sensors, and are useful indicators of how radiation interception and use by the plants vary with time and respond to weather variability (Andersen et al., 1996; Jørgensen et al., 2003). However, directly comparable field measurements of light interception and utilisation as well as yields for biomass crops compared with traditional agricultural crops are very limited.

The objectives of the study were to determine light interception, biomass yield and *RUE* of annual and perennial crops grown in innovative cropping systems optimised for biomass production, and compare with crops traditionally grown by farmers in Denmark. To evaluate the sustainability of the novel systems, N balance, soil carbon development and pesticide use were also measured in all treatments and will be reported in follow-up papers.

2. Materials and methods

2.1. Study sites and experimental design

Field experiments started in 2012 in Denmark at two sites belonging to Aarhus University. One site is located at Foulum (56°30′N, 9°35¨′′E) on a sandy loam soil (Typic Hapludult) and another site at Jyndevad (54°54′N, 9°46′′E) on a coarse sandy soil (Orthic Haplohumod). Both soil types are deemed to be free-draining and the average percentages of clay, silt, fine and coarse sand in the top 25 cm are 8, 11, 42 and 36, respectively, at Foulum, and 5, 4, 17 and 71 at Jyndevad. The climate is temperate and wet, characterised by mild summers and cool to cold winters, with moderate seasonal temperature variation. Although Jyndevad has an overall warmer and wetter climate, the low water holding capacity of the coarse sand soil necessitates irrigation, whereas in Foulum the agricultural systems are mostly rainfed. Weather data were obtained from weather stations located at the experimental sites.

A range of perennial grasses, namely reed canary, tall fescue, cocksfoot, two grass-legume mixtures, miscanthus (*M.* × *giganteus* at Foulum and *M. sinensis* at Jyndevad) and festulolium (only at Foulum), were grown together with a crop rotation optimised for high yields at each site (Table 1). The cycle of the optimised rotation at Foulum is completed every four years and includes maize, beet, hemp, triticale, and grass/clover and winter rye sown as cover crops in between the major crops. At Jyndevad, the cycle of the optimised rotation is completed every three years and includes maize, winter rye, winter rapeseed (cover crop), and hemp (or oat replacing failed hemp).

They were compared with traditional systems in the Danish (i.e. north European) agriculture, namely continuous maize monoculture, continuous triticale monoculture (only at Foulum) and a crop rotation of spring barley, winter barley and winter rapeseed (only