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Nitrogen balances of innovative cropping systems for feedstock production to future biorefineries☆

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HIGHLIGHTS

- Biomass nitrogen (N) of novel cropping systems for biorefinery feedstock was examined.
- The largest biomass N was achieved by fertilised and unfertilised perennial systems.
- Optimised rotation with annual crops also held high potential for biomass N supply.
- The novel systems had lower nitrate leaching compared to the conventional systems.
- Soil N balance of the systems was overall negative, except for grass-legume systems.

GRAPHICAL ABSTRACT

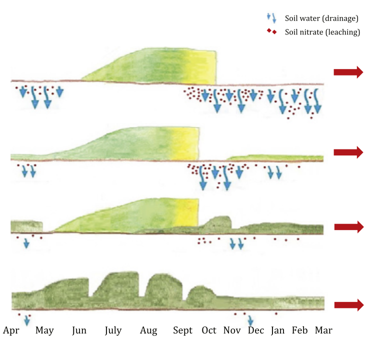

Figure from Elly M. Hansen, Aarhus University (modified).

System	Harvest	Leaching
	Kg N ha^{-1}year^{-1} sandy loam/coarse sand	
Traditional maize (continuous, monoculture)	200/100	100/180
Traditional titicale (continuous, monoculture)	170/-	60/-
Optimised rotation with annual crops	190/160	40/110
Perennial grasses		
Highly fertilised	450/320	15/50
Unfertilised	250/200	18/20

Values are means of three-years. Dash denotes no data

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ABSTRACT

Future biorefineries will prefer crops with high biomass yields, thus may precipitate fundamental changes to the agricultural landscape and the biomass production systems. Understanding the fate of nitrogen (N) in novel agricultural land uses is vital for product optimisation and environmental protection. This work reports and investigates the first multi-annual N balances for novel cropping systems optimised for high biomass production compared to traditional systems under North European climate and soil conditions.

In a three-year study, two types of novel systems, *i*) a rotation of annual crops optimised for maximum biomass production (maize, beet, hemp/oat, triticale as main crops, and winter rye and winter oilseed rape as "second" - cover crops), and *ii*) perennial grasses (intensively fertilised (festulolium, reed canary grass, tall fescue and cocksfoot), low-fertilised (miscanthus) and unfertilised (grass-legume mixtures)), were compared with *iii*) traditional systems (continuous maize or triticale, and a cereal crop rotation) at two sites in Denmark varying in temperature, rainfall and soil type (sandy loam and coarse sand). Harvested biomass N and soil nitrate dynamics, as well as model-supported nitrate leaching and field surface N balance (input minus output) of the systems were compared.

At each study site, the fertilised perennial grasses outperformed all other systems by doubling biomass N and reducing nitrate leaching by 70–80% compared to the traditional systems. Compared to continuous maize monoculture, the optimised rotation supplied 70% more biomass N and 40% less nitrate leaching on coarse sandy soil, whereas on sandy loam soil it yielded about 10% less biomass N with 50% less nitrate leaching. Field surface N balances were overall neutral/positive, except for festulolium and continuous maize monoculture that slightly mined the soil for N. When N losses by leaching, denitrification and volatilisation were included, soil total N stocks were estimated to decline for the majority of the systems at both sites.

☆ Capsule: Agro-environmental analysis of novel cropping systems for biorefinery in Denmark – Aarhus University Centre for Circular Bioeconomy, http://cbio.au.dk/en/.

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1. Introduction

In Europe, biorefining is central to the European Union (EU) strategy for reindustrialisation to a "bioeconomy", aiming to stimulate sustainable growth and increase competitiveness. Biomass is already being converted to transportation fuel and heat or refined to chemical building blocks for the industry (Gandini, 2016). Various food and feed ingredients may also be produced from biomass, e.g., water-soluble carbohydrates, minerals, organic acids and protein (Hermansen et al., 2017; Jørgensen and Lærke, 2016; Kamm et al., 2016). The EU is only 30% self-sufficient in protein feed, with a heavy dependence on environmentally costly import of soybean meal and an increasing demand for domestic/local protein sources. Although agriculture may supply biomass with annual renewability to biorefineries (Gylling et al., 2016), two major issues arise. Firstly, to supply sufficient biomass requires substantial increases in crop productivity, and realising this potential would necessitate fundamental changes to existing agricultural land use in terms of high-yielding crops, more intensive management, etc. (Larsen et al., 2017). Secondly, compared to non-cultivated soils, agricultural soils are large emitters of nitrous oxide (N_2O) and large amounts of nitrogen (N) may also leach from the soils into groundwater, drainage ditches, streams, rivers and eventually estuaries, contributing to eutrophication and indirect N_2O emissions (Reay et al., 2012). Therefore, to ensure environmental sustainability, increased agricultural production should take place in parallel with reduced losses of reactive N to the environment.

Peer-reviewed quantitative studies of the fate of N after agricultural land use changes targeting feedstock production for biorefineries are scarce. The few existing multi-criteria decision analyses and life cycle assessments point to perennial grasses being promising, i.e., highly productive with low nitrate leaching (Hamelin et al., 2012; Parajuli et al., 2015; Robertson et al., 2017). Other biofuel/bioenergy studies using simulation modelling also reported lower nitrate leaching for perennial grasses compared to annual crops (Chamberlain et al., 2011; Gentry et al., 2009; Lesur et al., 2014). The capabilities of perennial grasses to exploit the entire growing season and to do this for several years without re-establishment (e.g. Manevski et al., 2017) underline their potential in a sustainable intensification of biomass production based on increasing N input, N uptake and total harvested N while concurrently reducing N losses, compared to traditional crop production. Sustainable intensification is herein interpreted as increased production with lower environmental impact by relying on efficient use of external inputs. The potentials of productive grassland have been demonstrated by, among others, Pugesgaard et al. (2015) who harvested annually 353 kg N ha^{-1} in a fertilised grass-legume sward (perennial) compared to 130 kg N ha^{-1} in fertilised winter wheat (annual) in a field experiment on sandy soil in Denmark, whereas the respective nitrate leaching was 5 and 57 kg N ha^{-1} annually. Grass-legume mixtures also have an important competitive advantage at low N fertiliser inputs compared to pure grasses due to biological N fixation by the soil microbes associated with the leguminous plants, providing opportunities for sustainable extensification, whereby production is limited/maintained with lower environmental impact and low external inputs (van Grinsven et al., 2015). In a field study on sandy loam soil in Denmark, Hauggaard-Nielsen et al. (2016) harvested 380–480 kg N ha^{-1} from unfertilised N-fixing clovers, thus saving the around 325 kg N ha^{-1} fertiliser normally used to harvest about 300 kg N ha^{-1} from ryegrass. Combinations of sustainable intensification and extensification that minimise environmental impacts while increasing or maintaining production are thus preferred, depending on local conditions and requirements of the supply chains (van Grinsven et al., 2015).

Annual crops are equally interesting as a biomass feedstock for biorefineries if productivity is increased and N losses are minimised compared to traditional crop production. Implementing novel management practices that include photosynthetically efficient crops on the field throughout the year have been suggested (Manevski et al., 2017). Biorefineries may pave the way for early harvest of an immature main crop before significant leaf senescence, thus opening a time window for earlier establishment of a second crop (Hansen et al., 2007). Today, the system of an annual main crop followed by a second = cover crop is often used in regions with a temperate, wet climate to reduce nitrate leaching. Mineralisation of the cover crop ploughed into the soil in spring can be an important N source for the following crop, but may also induce notable N_2O emissions, depending on cover crop quality and soil moisture regime (Basche et al., 2014; Pugesgaard et al., 2017). Thus, its early establishment in late summer and harvest in autumn and spring, rather than ploughing into the soil, may increase overall system N uptake and reduce emissions (Hansen et al., 2007; Li et al., 2015).

The field surface N balance is a mass balance defined as the difference between N fluxes entering and leaving the field surface, i.e., inputs of inorganic/organic fertiliser, biological fixation and atmospheric deposition on the one side and outputs of harvested biomass on the other. The surface N balance is a widely adopted indicator of N loss potential, although there is uncertainty regarding this relationship due to effects of changes in soil organic N stocks. The potential for N losses by leaching, denitrification or volatilisation is for many systems related to the surface N balance (e.g., Pugesgaard et al., 2017; van Beek et al., 2003). In order to achieve sustainable biomass production with reduced N losses, there is a need for robust information on surface N balances and losses for current and new cropping systems.

The objective of this study was to quantify N balances for annual and perennial crops grown in novel systems optimised for biomass supply to future biorefineries, in a side-by-side comparison with traditional systems practised in Denmark. The following research questions were explored:

1) How does N harvested in biomass and leached below novel annual and perennial systems compare with traditional systems under a temperate wet climate and sandy soils?
2) What does the N balance and its components mean for the environmental impacts of the introduction of novel biorefinery cropping systems?
3) What is the implication for sustainable intensification of highly fertilised cool-season C3 perennial grasses, and for sustainable extensification of unfertilised grass-legume mixtures, with respect to N?

2. Materials and methods

2.1. Study sites, field experiments and management

Field experiments started in 2012 at two sites in Denmark at Foulum (56°30′ N, 9°35′ E) on a sandy loam soil (78.2% sand, 10.7% silt, 8.0% clay and 3.1% organic matter at 0–25 cm depth; mostly rainfed) and at Jyndevad (54°54′ N, 9°46′ E) on a coarse sand soil (87.0% sand, 4.3% silt, 4.0% clay and 4.7% organic matter at 0–25 cm depth; irrigated). The climate is temperate and wet, with a mean annual temperature and precipitation of, respectively, 7.8 °C and 740 mm at Foulum, and 8.9 °C and 950 mm at Jyndevad. Potential evapotranspiration is about 600 mm $year^{-1}$. At each site, three cropping systems were established: an optimised rotation for biomass production, perennial grasses and traditional crops. Tables 1 and 2 summarise the systems with crops and their N fertilisation. The optimised rotation was a four-year rotation at Foulum and involved maize (*Zea mays* L.), sugar beet (*Beta vulgaris* L.), hemp (*Cannabis sativa* L.) and winter triticale (*Triticosecale*) as "major" crops, as well as winter rye (*Secale cereale* L.) or grass-clover (*Festuca rubra* L.-*Trifolium repens* L.) as "second" crops between the major crops, or a three-year rotation at Jyndevad involving maize, winter rye and hemp, with winter rape (*Brassica napus* L.) as a second crop. Based on the duration, the optimised rotation was repeated four times at Foulum and three times at Jyndevad, each year starting with a different crop so that each crop occurred every year. Triticale after hemp in optimised rotation 1, and winter rye after maize in optimised rotation 3 were harvested in 2016, thus not considered in the present study.