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Forage production in rotational systems generates similar yields compared to maize monocultures but improves soil carbon stocks

Ralf Loges, Inga Bunne, Thorsten Reinsch*, Carsten Malisch, Christof Kluß, Antje Herrmann, Friedhelm Taube

Grass and Forage Science/Organic Agriculture, CAU Kiel, Hermann-Rodewald-Straße 9, 24118 Kiel, Germany

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ABSTRACT

Ruminant livestock in agriculture is one of the largest contributors to anthropogenic greenhouse gas (GHG) emissions. One GHG mitigation strategy is to maintain or increase soil carbon stocks. However, the estimation of the impact of agricultural production systems on soil carbon stocks is often difficult due to lack of data regarding the above- and belowground allocation of the net primary production of plants. Hence, in a 7-year field experiment in northern Germany, the aboveground net primary productivity and carbon budget of three different forage production systems (a crop rotation (grass-clover, maize and winter wheat); continuous maize; and continuous grassland) were quantified, with belowground net primary productivity being determined in two production years. While the net primary production was similar across all systems and ranged between 12.2 and 13.3 t organic matter ha^{-1}, the belowground fraction of the NPP was higher in grasslands with up to 35%, compared to 18 and 23% in continuous maize and the crop rotation. Accordingly after deduction of harvest removal also the carbon inputs as predicted by the soil carbon model were much higher in grassland and carbon stocks are projected to increase by +413 kg C ha^{-1} a^{-1} in fertilized grasslands, yet are projected to decrease by −183 kg C ha^{-1} a^{-1} in unfertilized continuous maize. However, the best option with respect to both carbon inputs and harvestable yields was the crop rotation, obtaining almost identical yields with the continuous maize with nearly balanced carbon stocks independent of the fertilization.

1. Introduction

Carbon sequestration describes the capacity of an ecosystem to absorb CO$_2$ from the atmosphere and store it as soil organic matter (SOM) in the soil (Lal 2004). Thus, carbon sequestration has received a lot of attention as a mechanism to achieve a negative greenhouse gas (GHG) balance (Rees et al., 2005; Lal 2003). Root growth and the turnover rate of the plant roots are the driving variables for the carbon amount that is sequestered. However, large differences exist in the performance of these two factors among various agricultural systems.

Grasslands, for example, are characterised by a dense, fibrous root system and a substantially larger belowground biomass production than annual crops. Rees et al. (2005) compared different studies to find that the residual plant C from cereal roots into the soil was on average 1.3 t C ha^{-1}, and thus less than half of the C input of perennial ryegrass, which was 2.8 t C ha^{-1}. Moreover annual crops are linked to soil tillage, which reduces the ability of soils to sequester high rates of carbon in the mid- and long-term perspective (Johnston et al., 2009a,b; Six et al., 2000; Reinsch et al., 2018). Accordingly, continuous grasslands compose one of the largest terrestrial C pools (Gobin et al., 2011). However, grasslands in intensive agricultural production in northwest Europe produce lower herbage yields compared to annual crops such as maize grown for silage (Muylle et al., 2015; Propheter et al., 2010) and the same can be seen for metabolic energy yields. This resulted in a large decrease of permanent grasslands, mainly in dairy production areas, which were predominantly substituted by maize cultivation (Souchère et al., 2003; Taube et al., 2014). Nevertheless, despite these developments being driven by an optimization of the systems for aboveground net primary productivity (ANPP), both the ANPP and belowground net primary productivity (BNPP) are important, with the ANPP being a major concern for economic viability of the production, while the BNPP is relevant for regulating ecosystem services, such as climate change mitigation. The ratio between the two can be expressed in the belowground fraction of the overall net primary production (NPP), also called the f$_{\mathrm{BNPP}}$. The f$_{\mathrm{BNPP}}$ is dependent on plant species, but also on environmental changes and management operations, e.g. nutrient or water availability (Skinner and Comas, 2010), as under favourable growing conditions, growth is primarily allocated to shoots

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* Corresponding author.
E-mail address: treinsch@gfo.uni-kiel.de (T. Reinsch).

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(Dodd and Mackey, 2011).

Despite the importance of both, ANPP and BNPP formation, and the large differences among cultivation systems, studies that compare those regarding to different crops and cropping systems are rare, despite these data being the prerequisite for modelling the development of carbon stocks in the future. Hence, to enable a better understanding of the differences in f_{BNPP} and C input of different production systems, a field experiment was conducted with three different forage production systems, which represent a perennial system (i.e. grassland), a complex annual system (i.e. crop rotation) and a simple annual system (i.e. continuous maize), as well as two levels of fertilization. With this general setup, this work aimed at answering the following questions: what is i) the above- and belowground performance of each system, ii) the amount of plant residual C of each crop, and iii) the resulting long-term impact on soil carbon stocks?

2. Material and methods

2.1. Experimental site and design

The field experiment was established at the organically managed research farm „Lindhof“ of Kiel University (N 54°27′55 E 9°57′55; 15 m a.s.l.) in autumn 2010. Soil samples were taken until 2017 to determine changes in soil carbon content. Measurements regarding the ANPP and BNPP of the crops were conducted in two years only, namely between April 2012–March 2013 (P_I) and April 2013–March 2014 (P_{II}). Soils at the research farm are classified as either *Eutric Luvisol* or *Cambisol*. The soil texture comprised 61% sand, 26% silt and 13% clay, with 1.2% organic carbon in the 0–30 cm soil depth (Table S1). The historical management of the site prior to the establishment of the experiment in 2010 was a long-term arable cropping system with a 4-year crop rotation. The climate at the research station is oceanic with a mean long-term (1981–2010) annual temperature of 8.9 C and a mean annual precipitation of 778 mm (Table 1).

Weather data (temperature and precipitation) were obtained from a weather-station in Kiel-Holtenau, located 8 km in a direct line to the experimental field. The first experimental period (April 2012 to March 2013; P_I) was characterised by a long cold period in winter, with an average temperature between December 2012 and March 2013 of 0.8 °C, compared to the long term mean of 2.2 °C (Table 1). Contrary to that, the second experimental period (April 2013 to March 2014; P_{II}) exhibited high temperatures in winter, with a mean temperature of 4.9 °C between December 2013 to March 2014. Precipitation was low during the observation period, with 664 mm and 646 mm, for P_I and P_{II}, respectively, in comparison to 778 mm for the long-term mean. The experiment was designed as a two-factorial split-plot design with three replicates, using the following factors:

1 Forage production system

- A crop rotation, consisting of grass-clover – maize – winter wheat (with grass-clover undersown)
- Continuous silage maize
- Continuous grassland (henceforth called ‘grassland’)

2 N-Fertilization

- 0N
- 240N (240 kg N ha^{-1} a^{-1}, applied as cattle slurry)

The grassland was sown in autumn 2010 with a standard mixture (consisting by weight of 67 % perennial ryegrass (*Lolium perenne*), 17 % timothy grass (*Phleum pratense*), 10 % smooth meadow grass (*Poa pratensis*) and 6 % white clover (*Trifolium repens*)) at a sowing density of 30 kg ha^{-1}. Maize (*Zea mays* cv. Ronaldinio) was sown after rotary cultivation and ploughing of grass clover swards in the crop rotation or ploughing of preceding maize stubble in the continuous maize system each year in the first half of May at a seed rate of 12 plants m^{-2} and a row distance of 0.75 m. Winter wheat (*Triticum aestivum* cv. Mulan) was sown between late October and mid-November with 350 grains m^{-2}. In the crop rotation, a grass-clover mixture with predominantly red clover was used, that was undersown in winter wheat with 20 kg ha^{-1} perennial ryegrass, 8 kg ha^{-1} red clover (*Trifolium pratense*) and 2 kg ha^{-1} white clover and continued to grow during the subsequent year (Table S2). This treatment is subsequently called grass-clover to distinguish it from the grassland. Weed control occurred by spring time harrowing in winter wheat and inter-row hoeing in maize. Maize was harvested as silage maize with a target dry matter content of 300–350 g kg^{-1}. Winter wheat was harvested as whole crop silage in the soft dough stage. Grass-clover was cut once in autumn two months after the wheat harvest, while in the subsequent year it was cut four times in unison with the grassland.

Slurry application in the N-fertilized treatment was split in four dressings for grassland (80/60/60/40 kg N ha^{-1}; Table S3) and three dressings for winter wheat and maize (80/80/80 kg N ha^{-1}). Slurry was applied with trailing hoses and had an average C/N-ratio of 6.9. The grass-clover was not fertilized because it was in itself considered as significant N-source in the crop ration. All plots were fertilized with phosphorous (45 kg P ha^{-1}), potassium (100 kg K ha^{-1}), magnesium (24 kg Mg ha^{-1}) and sulphur (68 kg S ha^{-1}) in the form of rock phosphate and potassium-magnesium sulphate. Liming occurred every two years with 1 t ha^{-1} calcium carbonate (23 % Ca and 1.4 % Mg). Each crop in the rotation was present in three replicates in each experimental year. The plot size was 12 m × 6 m.

2.2. Above- and belowground biomass

Aboveground biomass samples were taken at each harvest during the vegetation period. Herbage yield on grass plots was measured using a forage plot harvester (Haldrup, Løgstør, Denmark), to a residual sward height of 5 cm. Maize plots were harvested by a Haldrup harvester at a stubble height of 20 cm. Weight of total fresh harvested biomass was directly determined. DM weight was measured after oven drying of fresh samples taken during the Haldrup harvest at 58 °C until constant weight. To determine the residual biomass, after each harvest the stubbles were cut at soil level in subsampling plots of 0.25, 0.5, and

Table 1
Mean monthly air temperature (°C) and precipitation (mm) for the two experimental periods (PI and PII), as well as the long-term average (1981–2010).

Temperature (°C)	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Year
PI (2012/2013)	6.9	12.2	13.6	16.3	17.3	13.5	9.6	6.3	1.1	1.7	0.4	−0.1	8.2
PII (2013/2014)	6.7	11.8	14.7	18.2	17.8	13.7	11.5	6.4	5.4	2.0	5.2	6.8	10.0
1981–2010	7.6	11.9	14.8	17.3	17.0	13.6	9.7	5.2	2.2	1.5	1.5	4.0	8.9

Precipitation(mm)	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Year
PI (2012/2013)	55	40	103	120	55	52	55	41	49	70	21	4	664
PII (2013/2014)	15	93	65	37	51	60	99	50	60	53	42	22	646
1981–2010	40	54	71	84	74	67	77	70	67	70	47	57	778