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Eco-efficiency of forage production in Northern Germany

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Abstract. A 2-year field experiment was conducted at two sites in Schleswig-Holstein, northern Germany, to quantify and evaluate the carbon footprint of arable forage cropping systems (continuous silage maize, maize-wheat-grass rotation, perennial ryegrass ley) as affected by N fertilizer type and N amount. Total greenhouse gas emission showed a linear increase with N application, with mineral N supply resulting in a higher slope. Product carbon footprint ranged between -66 and 119 kg CO2eq/(GJ NEL) and revealed a quadratic or linear response to fertilizer N input, depending on the cropping system. At N input required for achieving maximum energy yield, perennial ryegrass caused lower emission per product unit than continuous maize or the maize-wheat-grass rotation. The data indicate potential for sustainable intensification when crop management options are adopted to increase resource use efficiency.

Keywords: Carbon footprint, cropping system, silage maize, perennial ryegrass, N fertilization, N fertilizer type.

Introduction

Sustainable intensification of agricultural production, *i.e.* maximization of production without compromising a system's ability to sustain its productive capacity, is currently debated as a pathway to cope with a growing population and climate change (Spiertz 2012). The rise of intensive livestock production is a major cause of environmental damage. Greater efficiency in use of resources along the production chain, especially in forage production, which contributes the major share of greenhouse gas (GHG) emission, will be a key to reduce 'livestock's long shadow'. So far, only few studies have examined the carbon footprint, *i.e.* the total GHG emission per product unit, of forage production systems under variable management. The objective of the current study therefore was to quantify the eco-efficiency of arable forage production systems in terms of their carbon footprint for two typical Northern German landscapes, which are representative for a range of northwestern European regions.

Material and Methods

Based on a 2-year field trial (April 2007- March 2009) conducted at two sites (Hohenschulen, HS; Karkendamm, KD) in northern Germany, the yield, N leaching, emission of climate relevant gases, as well as the consumption of energy of different forage production systems (maize, grassland, maize rotations) was analyzed. Site HS is characterized by a sandy loam soil (pseudogleyic Luvisol, pH 6.7), a long-term annual precipitation of 750 mm and a mean annual temperature of 8.3°C. The annual precipitation at site KD averages 844 mm with a mean annual temperature of about 8.3°C. The soil is classified as a gleyic Podzol (pH 4.5-5) of sandy structure. Three cropping systems were investigated; continuous silage maize (R1) and a maize–whole crop wheat–Italian ryegrass (cover crop, 2 cuts) rotation (R2) at HS, while continuous maize (R1) and a four-cut perennial ryegrass ley (R4) were investigated at KD. Nitrogen fertilizer was applied at four levels (maize, wheat: 0, 120, 240, 360 kg N/ha; ley: 0, 160, 320, 480 kg N/ha; Italian ryegrass: 0, 160, 160, 160 kg N/ha) and different N types. Calcium ammonium nitrate (CAN) and digestate from an anaerobic digestion was applied at KD and HS, whereas cattle slurry was additionally applied at KD and pig slurry at HS. Forage energy concentration was quantified in terms of net energy lactation (NEL, MJ (kg/DM) according to GfE (2009) and Weissbach *et al.* (1996). Total GHG emission was calculated taking direct and indirect emissions related to plant cultivation (seed, fertilizer, liming, plant protection, machines, diesel), transport (8 km distance field-farm) and storage (installation of silo, silage cover, diesel, machines) into account. The calculations were based on observed yields (Sieling *et al.* 2013) and the energy input by Claus *et al.* (2011), supplemented by measured data of N_2O emissions (Senbayram *et al.* 2009), NH_3 emissions (Gericke 2009) and nitrate leaching (Svoboda 2011). Changes in soil carbon stocks were considered according to German Cross Compliance commitments, *i.e.* annual losses of -280 kg C/ha (wheat) and -560 kg C/ha (maize) or gains of 120 kg C/ha (Ital. ryegrass) and 600 kg C/ha (ley), as well as a C input of 5-10 kg C/t liquid organic fertilizer applied. With respect to organic fertilizers, emissions from storage (90 days) but not from its production were allocated to crop production. Soil N release from mineralization, estimated from N uptake of zero N treatments, was accounted for as mineral N input.

A regression analysis was applied to investigate the

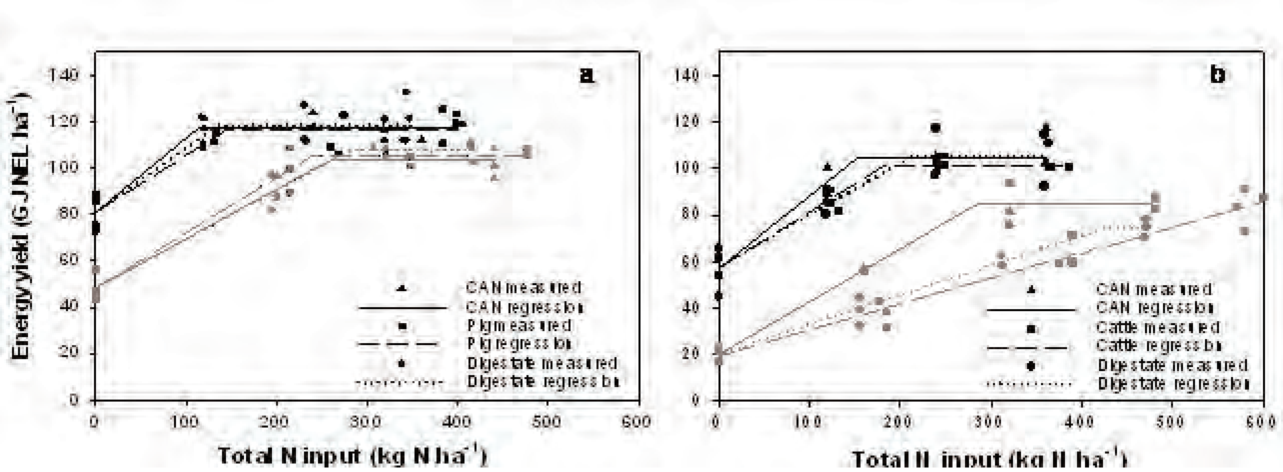

Figure 1. Average annual energy yield (GJ NEL/ha; losses due to harvesting and ensiling not considered) of (a) cropping systems R1 and R2 at site HS and (b) systems R1 and R4 at site KD as affected by N fertilizer type and N amount; R1: continuous silage maize (black lines), R2: silage maize – winter wheat for whole crop silage – Italian ryegrass as a double crop (grey lines, a), R4: 4-cut perennial ryegrass ley (grey lines, b); CAN (calcium ammonium nitrate): triangles and solid lines, pig or cattle slurry: squares and dashed lines, digestate: circles and dotted lines

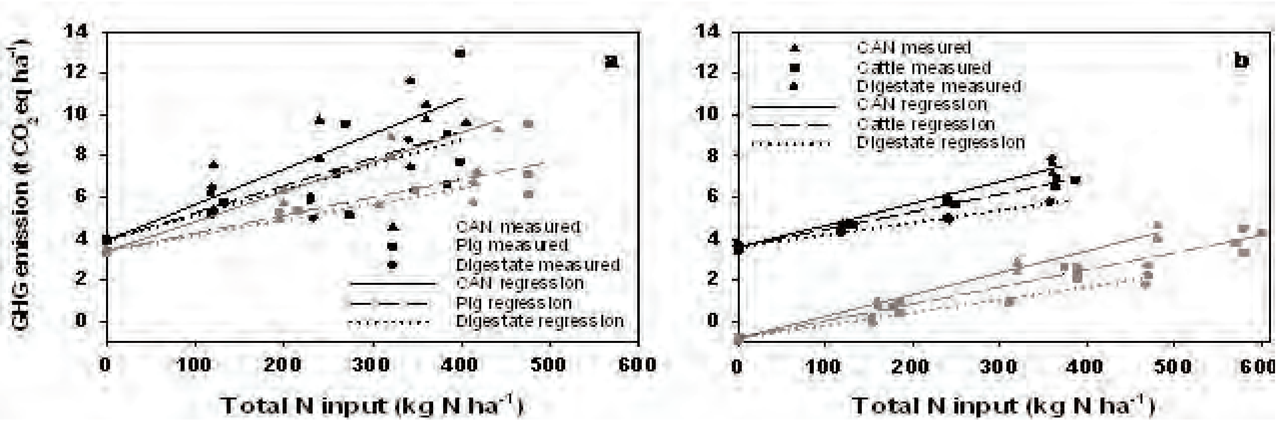

Figure 2. Average annual GHG emission (t CO_2eq/ha) of (a) cropping systems R1 and R2 at site HS and (b) systems R1 and R4 at site KD as affected by N fertilizer type and N amount; R1: continuous silage maize (black lines), R2: silage maize – winter wheat for whole crop silage – Italian ryegrass as a double crop (grey lines, a), R4: 4-cut perennial ryegrass ley (grey lines, b); CAN (calcium ammonium nitrate): triangles and solid lines, pig or cattle slurry: squares and dashed lines, digestate: circles and dotted lines.

relationship between fertilizer N input and energy yield (GJ NEL/ha), total GHG emission (kg CO_2eq/ha) and product carbon footprint (PCF, kg CO_2eq/(GJ NEL)), using Proc Nlin of SAS 9.2 by assuming a linear-plateau (energy yield), linear (total GHG emission) or quadratic (PCF) model. Before analysis, the data of the single crops were added to obtain a cumulative value for each crop rotation and were then averaged over both years. Nitrogen response curves were calculated separately for each N type and crop rotation and function parameters were compared by a modified t-test.

Results and Discussion

Nitrogen input substantially contributes to the PCF of crop production (Hillier *et al.* 2009), but is essential to ensure high productivity, which is of utmost importance in case of shortages of farmland. In the current study, estimated energy yield varied between 20 and 119 GJ NEL/ha and was substantially affected by N supply, site and cropping system. At site HS, continuous maize (R1) achieved 81 GJ NEL/ha without any fertilization and attained its maximum energy yield of 117-119 GJ NEL/ha at an N input of 115 to 145 kg N/ha (Fig. 1a). Maximum yield of R2 (maize-whole crop wheat-Ital. ryegrass) was significantly lower (104-108 GJ NEL/ha) and required a higher N supply of 238 to 283 kg N/ha. At site KD, R1 significantly outperformed the perennial ryegrass ley, which achieved a plateau only in the CAN and digestate treatments (Fig. 1b). N fertilizer type only had an affect on the ryegrass ley, where the maximum energy yield of the digestate treatment (75 GJ NEL/ha) differed to CAN (85 GJ NEL/ha) and cattle slurry (89 GJ NEL/ha). Furthermore, digestate (428 kg N/ha) and cattle slurry (623 kg N/ha) required higher N input than CAN (285 kg N/ha) for achieving the maximum yield due to a lower N fertilizer value (Sieling *et al.* 2013), resulting in a lower slope.

Total GHG emissions increased linearly in N input, with 6 to 17 kg CO_2eq/ha for each kg N applied (Fig. 2). As expected, CAN treatments tended to have a stronger increase in GHG emission per unit of N applied than organic fertilizers, because of the higher energy

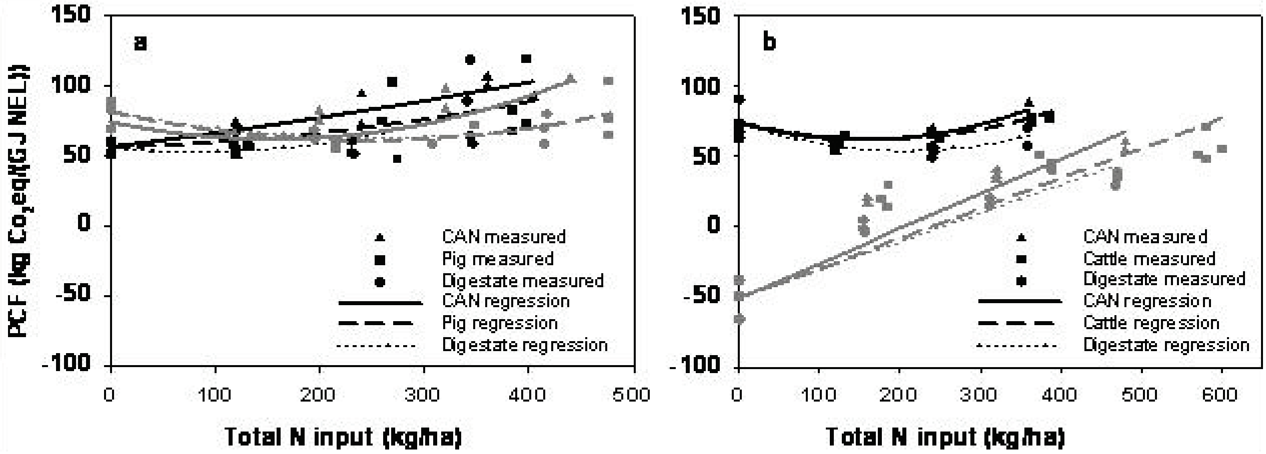

Figure 3. Average product carbon footprint (PCF, kg CO_2eq/(GJ NEL)) of (a) cropping systems R1 and R2 at site HS and (b) systems R1 and R4 at site KD as affected by N fertilizer type and N amount; R1: continuous silage maize (black lines), R2: silage maize – winter wheat for whole crop silage – Italian ryegrass as a double crop (grey lines, a), R4: 4-cut perennial ryegrass ley (grey lines, b); CAN (calcium ammonium nitrate): triangles and solid lines, pig or cattle slurry: squares and dashed lines, digestate: circles and dotted lines. Losses during harvesting and ensiling were assumed to be 12 %

input associated with mineral N application (Hillier *et al.* 2009). A significant impact of N fertilizer type, however, was only found in R2 where the slope was higher for CAN than pig slurry or digestate at HS, and at site KD where all N types differed in both cropping systems. Cropping system R1 showed a greater increase in GHG emissions than R2 for all N fertilizer types at site HS, whereas at site KD, no significant differences were detected between R1 and R4. The slopes found in our study for the minerally fertilized R1 and R2 at site HS agree well with values of 15.6 to 16.4 kg CO_2 eq/ha reported by Ma *et al.* (2012) for grain maize grown in different rotations. The substantially higher total emission level found in our work may be attributable to different system boundaries, e.g. soil C stock changes and emissions resulting from storage not covered by Ma *et al*. (2012), which is a general challenge when comparing life cycle assessment studies. We found, however, good accordance of the GHG emission at N input required for maximum energy yield with eddy covariance based GHG balances reported for various crops by Ceschia *et al.* (2010).

The relationship between product carbon footprint (PCF) and fertilizer N input revealed a pattern specific to the cropping system/site (Fig. 3). For R2 at site HS and R1 at site KD, PCF initially decreased before increasing again in the higher N input range, and the N input at a minimum PCF agreed well with the N fertilizer amount required to achieve maximum energy yield, except for R2 supplied with CAN. The production potential thus can be exploited without causing a higher PCF of forage production, indicating a potential for sustainable intensification. In contrast, a linear relation was detected for R1 at site HS and R4 at site KD, *i.e.* a trade-off between energy yield and PCF. In the case of R1 this is most likely due to the high soil mineral N release (average over two years: 123 kg N/ha), which was accounted for as fertilizer N input, and considerably exceeded the N release of R2 (74 kg N/ha) and R1 at site KD (73 kg N/ha). For the perennial ryegrass ley, negative values of the zero N treatment caused by credits for carbon sequestration outweighed the production related emissions and resulted in a linear model. Replacing fertilizer N by biological N fixation would offer the opportunity to combine high productivity and forage quality with low PCF (Ledgard *et al*. 2009). The introduction of maize-legume rotations would also be an option to improve the PCF of arable forage production, as indicated by Ma *et al.* (2012), finding lower PCF for grain maize following red clover or alfalfa compared to continuous maize. The overall level of PCF for R1 and R2 was substantially higher in our study compared to values reported by Adom *et al.* (2012) for dairy feeds produced in different US regions or by the Ecoinvent database for Swiss silage maize production. As mentioned earlier, this is probably due to different system boundaries and may also explain the different ranking of cropping systems found in our study. Contrary to our expectations, R2 achieved lower energy yield and a similar PCF as R1, which can be attributed partially to an earlier maize hybrid with a lower yield potential used in R2 and experimental conditions causing low yield of whole crop wheat. In agreement to the aforementioned study we found a lower variation of PCF due to site conditions than to cropping systems.

The focus of our study was on the PCF of forage cropping systems. When, however, comprehensively addressing sustainability, not only climate change impact has to be considered, but potential trade-offs to other environmental objectives, such as the conservation of water, soil, air or biodiversity, should also be accounted for, as well as ecosystem services cropping systems may provide. The provision of clean drinking water is a key determinant of quality of life with a strong local dimension and it therefore seems appropriate to evaluate forage cropping systems in terms of their area-based nitrate load. In this respect, grassland (R4) was characterized by a significantly lower pollution risk than silage maize grown at site KD. Cropping systems R1 and R2 at site HS showed similar leaching loss (20 kg NO_3-N/ha/yr) up to the N input required for maximum energy yield, above which leaching loss rose more sharply for continuous maize (Svoboda 2011). This might be effectively mitigated by introducing a catch crop. With respect to NH_3 emission after organic fertilizer application, maize cultivation was found to cause lowest emissions due to a lower leaf area compared to grass and wheat and immediate incorporation after spreading (trailing hose system), which was not possible in wheat and grass (Gericke 2009). Various studies have confirmed shallow slurry injection as an effective measure to avoid excessive NH_3 volatilization and to increase the N fertilizer value (Webb *et al*. 2010; Klop *et al*. 2012), but the success of reducing NH_3 volatilization is correlated to the energy requirements for injection. Furthermore, there was some evidence for a trade-off between NH_3 and N_2O emission when injecting liquid organic fertilizer into grassland. Our studies conducted on a heavy clay grassland soil over a 2-year period, however, found similar N_2O emission for injection and trail hose application (unpublished).

Conclusion

Achieving sustainable dairy production will require a reduction in the environmental burden of forage production. The present study indicates that high yielding arable forage production and eco-efficiency must not be conflicting. A range of crop management measures at the operational and tactical level, *e.g.* replacing mineral fertilizer by biological N fixation and use of innovative slurry application techniques, is at hand to further improve the resource use efficiency and environmental performance of forage production. At the strategic management level, the introduction of well-managed pasture-based dairy farming is regarded an effective measure to improve the PCF of milk. Sustainable intensification may provide a win-win option for dairy farmers and the environment, but requires concerted policy actions (climate/energy, agriculture, nature protection) and priority-setting among environmental objectives at the regional level.

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