Trade-offs between agricultural product carbon footprints and land use: a case study from Tanzania

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ABSTRACT

A case study comparing extensive, low-yielding smallholder maize production with an intensified, high-yielding production system ('sustainable intensification') is used to illustrate potential trade-offs between agricultural product carbon footprints (PCFs) and land use (LU). In the comparative analysis the extensive systems had lower PCFs so the conclusion may be that these systems should be encouraged as a climate mitigation strategy. However, if LU and the potential for land use change as a consequence of the extensive systems' low yields are also considered, then the conclusion changes in favour of the intensified, high-yielding system. Our conclusion is that an assessment of the success of sustainable intensification with regard to climate mitigation needs to also include indirect effects at a larger spatial scale than individual farms in order to avoid misinterpreting PCF results.

Keywords: sustainable intensification, maize, greenhouse gas emissions, extensive farming, land use change

1. Introduction

The agricultural sector is key for addressing various interconnected challenges, including food security, land use and climate change. Significant yield reductions are predicted over the next decades in many regions of the world as a result of climate change (IPCC 2007). At the same time, agricultural activities contribute to global warming by releasing greenhouse gases (GHGs) at all stages of agricultural value chains. The application of sustainable practices along entire food supply chains is essential for reducing GHG emissions, ensuring continued agricultural production, increasing global food security and feeding the growing world population (Beddington et al. 2012). The concept of sustainable intensification, i.e. the production of more food from the same area of land while reducing associated environmental impacts, is of particular importance in this respect (Beddington et al. 2012).

Product carbon footprints (PCFs) estimate the amount of GHGs emitted during the life cycle of goods and services. They are reported per unit of product and aim at maximising input-output ratios, where high input-high output systems can have low PCFs, i.e. low levels of GHG emissions per unit of output. Despite the importance of GHG accounting per unit of product for assessing efficiencies and potential leakage effects, such analyzes are lacking for many agricultural production systems and agroecological and socio-economic contexts (Smith and Wollenberg 2012).

Our case study on the PCF of maize cultivation in smallholder production systems in Tanzania is part of a project investigating sustainable intensification practices. So far, little information has been reported on the GHG emissions from smallholder production as previous analyzes have focused on large export oriented farms (e.g. Edwards-Jones et al. 2009). Our analysis includes extensive, low-yielding farming systems as practiced widely in the region, and an improved, more intensive management system which aims at increasing yields by applying more targeted inputs. The PCF of these two systems are compared and their respective climate impacts discussed. The hypothesis is that raising yields by applying more targeted inputs under the concept of sustainable intensification can reduce the climate impact from maize production.

2. Methods

2.1. PCF calculation

For the calculation of farm gate PCFs we used data on smallholder maize production in Tanzania generated as part of a larger public-private partnership project implemented by the Norwegian University of Life Sciences, Sokoine University of Agriculture in Tanzania, Syngenta and Yara International. Field trials were conducted on five smallholder farms located in the Njombe and Morogoro regions of Tanzania. At each site, paired treatments were established where the farmers continue with their traditional management ('farmer practice', FP treatment) on one plot. On a second plot more targeted farm inputs are applied, following a protocol devised by the project partners ('YSS treatment'). At all sites soil samples were taken at the beginning of the trials in order to develop a balanced and crop-specific nutrition program.

The system boundary of the PCF analysis included the production and transport of farm inputs and all relevant on-farm processes up to the farm gate for one project year. Primary data on the amounts of fertilizers, agro-chemicals, yields and crop residues were available for each treatment. Direct N_2O emissions from soils as a result of nitrogen inputs (mineral fertilizers, crop residues) were estimated using the IPCC (2006) Tier 1 method. Indirect N_2O emissions were calculated using the Bouwman et al. (2002) model for ammonia volatilisation and a nitrogen balance approach to identify potential nitrate leaching losses. Mineral NPK fertilizers used in the YSS treatment were produced in Norway and transported to Dar es Salaam by container ship. Mineral fertilizers applied on FP plots were assumed to be produced in China and Morocco and shipped by bulk. Emission factors for the production of inputs were obtained from Yara International, Brentrup and Pallière (2008), IFA (2009), Saling and Kölsch (2008) and PE International's GaBi 4 database.

2.2. Description of the case study farms

All field operations on the case study farms were carried out manually. The YSS treatments received 138 kg N ha^{-1} $year^{-1}$, 57 kg P_2O_5 ha^{-1} $year^{-1}$, 34 kg K_2O ha^{-1} $year^{-1}$ and micronutrient applications. On two of the FP plots, no fertilizer was applied at all whereas some nitrogen (11-79 kg N ha^{-1} $year^{-1}$) and phosphorus (28-57 kg P_2O_5 ha^{-1} $year^{-1}$) was applied on the other three FP plots. Weed control was mainly done manually on the FP plots whereas plant protection agents were applied on the YSS plots as and when necessary. Grain yields achieved on the YSS plots ranged between 2.1 and 6.3 t ha^{-1}. Grain yields on FP plots were considerably lower (1.8-4.0 t ha^{-1}). Stover yields were 1-5 times greater on most YSS plots, leading to a greater return of organic residues to the soil.

2.3. Land use (LU)

A second indicator, land use (LU), was calculated to compare the paired treatments and highlight trade-offs between PCFs and LU. We define LU as the area of land required to produce a unit of output (Tuomisto et al. 2012), i.e. as the inverse of the yield.

2.4. Potential land use change (pLUC)

If low-yielding maize production systems as in our FP treatment are expanded to meet growing demands for Tanzania's rapidly increasing population (UN 2010), this will cause GHG emissions outside of the farms studied due to land use change (LUC). Therefore, it is not direct LUC (dLUC) taking place on the farms analyzed. Although it is an indirect effect of the extensive farming system outside of the PCF system boundary, we suggest not to calculate these indirect impacts using established methods for estimating indirect LUC (iLUC) emissions. Such iLUC occurs outside of the product system being assessed as a result of the conversion of land due to changes in agricultural land use elsewhere in the world. Modelling iLUC impacts is complex and based on assumptions about economics, market factors, pre-conversion land use types and other factors (Prins et al. 2010). In our case study region, in contrast, it is likely that LUC will be induced by an expansion of extensive farming to increase production under a business-as-usual scenario (FAO 2012). This LUC occurs nearby in order to meet growing demands for the same crop in the same region. We call this form of land use change 'potential LUC' (pLUC) and estimate associated GHG emissions based on the available land use type in the region for an extended FP system, FP_{ext} (Brentrup and Pallière 2008). First, we calculate the amount of land that needs to be converted to produce the same amount of maize harvested in YSS under the current FP management. This additional area of land is then assumed to be subject to LUC, leading to the emission of 12.4 t CO_2e ha^{-1} and year (IPCC 2006, Tier 1) if emissions are allocated evenly across 20 years (BSI 2011). In the case study area tropical shrubland is potentially available to support this expansion. These emissions, scaled by the yield on each FP plot, are added to the FP PCF for the amount of land that needs to be converted to match the YSS yield.

3. Results

3.1. Farm gate PCF

The farm gate PCF of maize varied greatly between 102 and 963 kg CO_2e t^{-1} grain. A comparison of the results for the paired YSS and FP systems reveals that in most cases the FP systems had lower PCFs (Fig. 1a). The main emissions sources on all farms were related to fertilization and crop residues. On the YSS plots, the production and transport of mineral fertilizers to the farm, direct N_2O emissions from soils, and N_2O emissions from crop residue management were the main emissions sources. On the FP sites, N_2O from crop residues was the main source of emissions with the exception of Farms A and B, where the production and transport of mineral N fertilizer was the greatest contributor, closely followed by direct N_2O emissions from soils. On the two FP plots that did not receive any mineral fertilization (Farms D and E), the only sources of emissions were N_2O from crop residue management and the production of seeds.

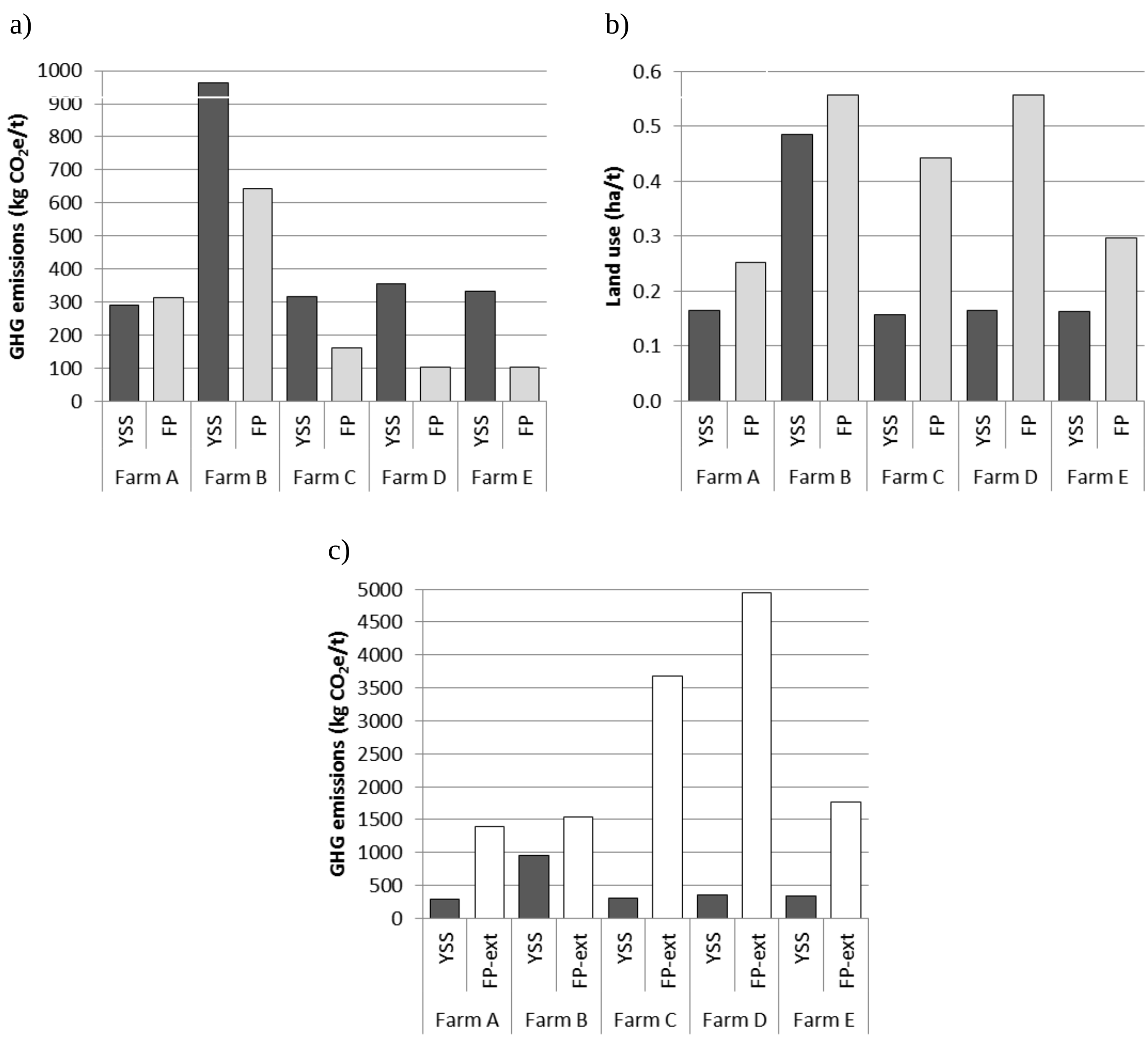

Figure 1. Results for maize production at five sites of paired management treatments: a) Product carbon footprint (PCF) up to the farm gate; b) Land use; and c) PCF including potential land use change. The black bars denote the intensified YSS management system, the grey bars the widespread farmer practice (FP) and the white bars the expanded FP system that matches YSS yields, including potential land use change on the additional land needed to produce this yield (FP_{ext}).

3.2. Land use

The LU of the case study farms ranged between 0.16 ha t^{-1} and 0.56 ha t^{-1} (Fig. 1b). Contrary to the PCF results where the YSS farms generally were associated with greater GHG emissions per t of maize than the FP farms with their extensive management, the LU indicator shows the exactly opposite pattern: for all pairs of YSS vs. FP management LU is lower and therefore more favourable for the YSS systems. The transition from FP to YSS thus indicates a move towards a lower LU and a more efficient use of land. In order to produce one ton of maize, the FP plots needed between 1.1 and 3.8 times more land than the paired YSS plots.

3.3. Indirect impacts from land use change

If GHG emissions arising from FP_{ext} from an area large enough to match the paired YSS yields (including pLUC for the additional area) are considered, the conclusions drawn from considering the farm gate PCF only change dramatically (Fig. 1c), with GHG emissions related to FP_{ext} between 2.4 and 48 times greater than the FP PCFs up to the farm gate.

4. Discussion

4.1. Smallholder maize production

The present study demonstrates the significant potential for achieving yield increases in smallholder systems by addressing limitations to productivity and applying targeted inputs of fertilizers and agro-chemicals. The wide range in PCFs between farms and within paired treatments also shows the impact of individual farm management decisions and location specific conditions such as soil pH or soil nutrient supply. Nutrient deficits and soil degradation which limited yields on smallholder farms were identified and improved, leading to significantly increased yields in the YSS system. For most FP systems, nutrient mining was observed which explains their low yields but also shows that these systems are not sustainable in the long run without increasing the input of plant nutrients in the form of organic or mineral fertilizers.

4.2. Trade-offs between PCFs and land use

If LU is considered, the conclusions differ from those based on the farm gate PCF where the extensive FP systems which use very little inputs might be taken for more environmentally friendly. When looking at the land area needed to produce a ton of maize, the FP plots clearly exert a much greater pressure on land resources than the intensified systems, which is likely to lead to land use change in the region to satisfy growing demands. This trade-off can lead to significant indirect impacts beyond the farm gate which are important to consider before concluding on the respective climate friendliness of the contrasted systems. LU can draw attention to this trade-off and should be considered whenever systems with great yield differences are compared. Out of two farms or production systems with similar PCFs but a high LU for one and a low LU for the other, the latter should be preferred.

The UK Royal Society (2009) defined sustainable intensification as “the production of more food on a sustainable basis with minimal use of additional land”, clearly recognising the need to reduce LUC and the continuing expansion of agricultural areas while meeting the challenge of increasing global food production. Our study illustrates the potential climate change impact of expanding the present low-yielding maize systems. The results emphasize the need for meeting increasing food demands without further LUC by carefully intensifying current production systems. The analysis of pLUC also highlights the need for more integrated assessments and policies, e.g. on land use and climate change, and a wider landscape scale approach to assessing the environmental impacts of farming systems and comparing the climate impact of different production systems. This is particularly important in regions where low-yielding systems dominate and increasing demands are likely to be met by converting land locally (pLUC).

5. Conclusion

The present case study highlights the risks associated with the interpretation of single issue indicators such as PCFs. In contrast, in a full LCA, trade-offs within the same system boundary become evident (e.g. Tuomisto et al. 2012). Our results show that raising the productivity and long-term sustainability of the systems analyzed by applying more targeted inputs and addressing nutrient limitations can result in a greater climate impact than the current low-yielding systems within the system boundary of a farm gate PCF. However, the benefits of sustainable intensification should be assessed at a greater spatial scale. In order to achieve food security for current and future populations, large increases in food production are necessary. Against this background, an assessment of the climate impact of extensive vs. intensive agricultural systems with significant differences in yield levels should consider trade-offs between PCFs, yields and LU. In such cases it is important to consider indirect impacts that may occur beyond the farm gate before concluding on the climate friendliness of one or the other system. A comparison of the LU indicators of the different systems can highlight the risk of LUC and help interpret PCF results. If this is not done, there is a risk that PCF results may be misinterpreted and agricultural systems that have low PCFs but exert a large pressure on land resources may be encouraged, unintentionally causing significant carbon emissions due to land conversion to agriculture.

In conclusion, the success and benefits of sustainable intensification on existing agricultural land should not be assessed based on direct impacts only. There is a need to also consider indirect impacts and larger spatial scales and to develop appropriate policy responses to ensure positive results (Garnett et al. 2013). In our analysis of the climate mitigation potential of two agricultural systems a consideration of indirect land use effects can help resolve potential conflicts between climate impacts on farm and in the wider landscape, with the benefit of sustainable intensification becoming obvious at a larger spatial scale.

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