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Identifying secure and low carbon food production practices: A case study in Kenya and Ethiopia

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ABSTRACT

The world population is projected to increase to 9–10 billion by 2050, during which time it will be necessary to reduce anthropogenic greenhouse gas emissions to mitigate climate change. The particular challenge this places on agriculture is to identify practices which ensure stable and productive food supply that also have a low greenhouse gas (GHG) intensity. Maize is the principle staple crop in many parts of Africa with low and variable yields, averaging only 1.6 t/ha in sub-Saharan Africa (SSA). Food security and increasing crop yields are considered priorities in SSA over impacts of food production on GHG emissions. Here we describe an approach that can be used to inform a decision support tree for optimal interventions to obtain sufficient food production with low GHG intensity, and we demonstrate its applicability to SSA. We employed a derivative of the farm greenhouse gas calculator 'Cool Farm Tool' (CFT) on a large survey of Kenyan and Ethiopian smallholder maize-based systems in an assessment of GHG intensity. It was observed that GHG emissions are strongly correlated with nitrogen (N) input. Based on the relationship between yield and GHG emissions established in this study, a yield of 0.7 t/ha incurs the same emissions as those incurred for maize from newly exploited land for maize in the region. Thus, yields of at least 0.7 t/ha should be ensured to achieve GHG intensities lower than those for exploiting new land for production. Depending on family size, the maize yield required to support the average consumption of maize per household in these regions was determined to be between 0.3 and 2.0 t/ha, so that the desirable yield can be even higher from a food security perspective. Based on the response of the observed yield to increasing N application levels, average optimum N input levels were determined as 60 and 120 kg N/ha for Kenya and Ethiopia, respectively. Nitrogen balance calculations could be applied to other countries or scaled down to districts to quantify the trade-offs, and to optimise crop productivity and GHG emissions.

1. Introduction

The world population is projected to increase to 9–10 billion by 2050 (Godfray et al., 2010), during which time it will be necessary to reduce anthropogenic greenhouse gas emissions to mitigate climate change (Smith et al., 2008). The particular challenge this places on agriculture is to identify agricultural practices which ensure stable and productive food supply combined with food of low greenhouse gas intensity (Garnett et al., 2013; Godfray et al., 2010; Mueller et al., 2012; Smith et al., 2013; Tilman et al., 2011). In the developed world, access to water, nutrient resources (e.g. fertilisers), and crop protection chemicals have raised yields since 1965 (Foley et al., 2011). In contrast, yield increases in the developing world have been limited, so that there is substantial potential to increase food production (Mueller et al., 2012).

Mueller et al. (2012) identify sub-Saharan Africa as one of the world regions showing considerable 'low-hanging' intensification opportunities for major cereals, stating also that closing maize

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yield gaps to 50% of attainable yields (defined as the area-weighted 95th percentile of observed yield within zones of a similar climate) primarily requires addressing nutrient deficiencies, but that additional gains require both an increase in irrigated area and nutrient application over most of the region (Mueller et al., 2012).

Tittonell and Giller (2012) discuss the need to increase soil fertility in sub-Saharan Africa and develop options to achieve this. The potential for yield improvement has also been demonstrated by the national subsidy programme for fertiliser and improved seeds in Malawi, which resulted in a doubling of national yields (Denning et al., 2009; Hickman et al., 2011). However, this comes at a cost by also increasing GHG emissions. During the 2000s, agriculture contributed between 10 and 12% to global anthropogenic greenhouse gas (GHG) emissions, consisting mainly of nitrous oxide and methane (Smith et al., 2008). These are projected to increase further, with one of the highest growth rates in emissions predicted in sub-Saharan Africa, due to increased fertiliser input and livestock numbers (Reay et al., 2012; Smith et al., 2007). Therefore, food supply needs to be improved whilst minimising the environmental impact (Garnett et al., 2013), which is a strategy that has been termed 'sustainable intensification'. There has been much debate about the precise definition of this term (Tilman et al., 2011; Smith et al., 2013). In order to make this term practically usable, quantifiable measures – such as GHG emissions per unit of production – are needed for evidence-based assessment of practices. Although in many developed countries, improvement in this measure can be achieved with modest increases in production in conjunction with reduced emissions – through for example precision agriculture – in developing countries the focus and benefits will be more on increasing the efficiency of production through good agronomic practices (e.g. Mueller et al., 2012; Van Groenigen et al., 2010).

Total GHG emissions from croplands are a sum of background emissions from the field (e.g. soil gaseous emissions from the breakdown of residual soil organic matter), and emissions from the production and application of pesticides, synthetic and organic fertilisers, and from the management of residues. Field measurements of GHG emissions are often expressed on a per hectare basis and may not report observed yield (Linquist et al., 2012). GHG emissions per hectare have a strong relationship to the amount of fertiliser N supplied, and are usually linked to yield (Hillier et al., 2009; Van Groenigen et al., 2010). The relationship between GHG emissions and agronomic productivity can be illustrated by calculating the yield-scaled emissions (Linquist et al., 2012; Mapanda et al., 2011; Mosier et al., 2006; Van Groenigen et al., 2010). This enables the identification of best management options in terms of GHG emissions as a function of N input (Van Groenigen et al., 2010) in addition to other variables.

Current estimates of GHG emissions for African regions are mainly based on the IPCC Tier 1 emission factor approaches, which are often considered to be too simplistic for informative site-level assessments (Hickman et al., 2011). In contrast, the use of more complex models is hampered by a lack of data. These include soil and weather data used as inputs, but also the dearth of GHG emissions measurements available for model validation (Hickman et al., 2011). The capacity to assess the impact of practices on GHG emissions on working farms is relatively recent. Although for example, Smith et al. (2008) list many mitigation options for agriculture together with an estimate of the per hectare GHG impact, until relatively recently decision support capacity has been lacking at the site level (Hillier et al., 2011a). This has led to the development of several "GHG calculators", some examples of which were recently reviewed (Whittaker et al., 2013). These models enable the analysis of typically collated farm survey data and so can capture mitigation options at a scale, and with a degree of representativeness, not possible with models that are more data demanding. Such tools are generally not sensitive to seasonal climatic variation or subtle variation in soil properties. However, some allow an assessment of GHG emissions as a function of management practice, and enable the user to examine and optimise different management options (Hillier et al., 2011b) at the desired scale (e.g. Hillier et al., 2012).

In this study we used a derivative of one such model – the Cool Farm Tool (CFT; Hillier et al., 2011b) – to estimate GHG emissions of smallholder maize in Kenya and Ethiopia to assess best practice. Kenya and Ethiopia represent countries in SSA where maize is the dominant staple crop in both countries with smallholder farmers occupying about 75% of the total maize land area (CSA, 2013; Kang'ethe, 2011). Kenyan smallholders usually have complex intercropping regimes with two or three different crops grown in a single plot, whereas maize is mainly planted on its own as a sole crop in rotation with other crops by smallholders in Ethiopia. In this study, we have restricted the analysis to mono-cropped maize to avoid issues of allocation of emissions to different crops on the same plot. Both countries are representative of maize-based smallholder farming systems in SSA. According to FAOSTAT, Ethiopia is a country almost self-sufficient in maize (FAOSTAT, 2014). An integrated livestock system is part of Ethiopian culture, reflected in it having the highest livestock population in Africa. In contrast, Kenya produces only ~60% of the maize required for its own needs (FAOSTAT, 2014). Both countries are characterized by erratic rainfall and hence are prone to drought (Mulwa et al., 2013; Muricho et al., 2012).

The CFT was chosen partly because it does not exclusively adopt a Tier 1 emissions factor approach. As such it can produce site and technology sensitive estimates of GHG emissions as a function of management practice, but at the same time, it is relatively data-light in comparison to many process-based models.

We hypothesise that farm survey data and a version of the CFT are sufficient to identify optimum levels of N input (the key driver of GHG emissions in croplands) based on currently observed attainable yields (defined as the 95th percentile of surveyed observed yield), for sustainable food production in sub-Saharan Africa. Datasets from Kenya and Ethiopia are used as representative of smallholder maize growing systems in the region. We further show that the method is generalizable, and scalable for screening approaches to identify best practice to guide sustainable intensification on a regional basis.

2. Materials and methods

2.1. Data

Data were derived from household surveys conducted by the Kenyan Agricultural Research Institute (KARI) and the Ethiopian Institute of Agriculture Research (EIAR) in collaboration with the International Maize and Wheat Improvement Centre (CIMMYT) as part of the 'Sustainable Intensification of Maize–Legume Systems for Food Security in Eastern and Southern Africa' (SIMLESA) programme. In this survey, 613 and 896 households were interviewed on a multitude of farm and general social aspects in 5 Kenyan, and 9 Ethiopian districts, respectively (Mulwa et al., 2013; Muricho et al., 2012) (Fig. 1). The survey also included farmer experiences of stresses such as "waterlogging". This study makes use of 376 mono-cropped plots from 187 households in Kenya, and 1433 mono-cropped plots from 765 households in Ethiopia.

2.1.1. Calculation of GHG emissions

GHG emissions on smallholder farms were calculated using a derivative of the CFT. Particular features of the tool are that it has a