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Farm-scale greenhouse gas balances, hotspots and uncertainties in smallholder crop-livestock systems in Central Kenya

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ABSTRACT

Climate-smart approaches have gained momentum in tropical, agricultural development. However, to date, few studies have examined whole-farm greenhouse gas (GHG) balances in smallholder crop-livestock systems. This study aimed to quantify GHG balances at farm-scale, identify GHG hotspots and assess mitigation options in coffee-dairy farms undergoing agricultural intensification in Central Kenya. In recent decades, decreasing farm size has forced the shift from extensive practices to zero-grazing systems and higher nitrogen (N) inputs. We hypothesised that different farm strategies and intensification levels determine the farm's GHG balance. A farm typology was constructed through principal component analysis (PCA) and hierarchical clustering from 125 farms surveyed. Four farm types were identified ranging relatively from small to large farms, low to high livestock intensities, and low to high N input rates. Whole-farm GHG balances were estimated using an adapted version of the Cool Farm Tool (CFT). Farms were found to be net sources of GHG, averaging from 4.5 t CO_2 eq ha^{-1} yr^{-1} in less intensive farms to 12.5 t CO_2 eq ha^{-1} yr^{-1} in high intensive farms. Within the farm GHG hotspots identified, methane (CH_4) from enteric fermentation processes accounted for 26–39% of total farm GHG emissions; nitrous oxide (N_2O) and CH_4 from manure management systems (MMS) for 26–38%; soil background and fertilizer induced N_2O emissions for 24–29%; off-farm production of feeds and agrochemicals for 10–22%; and crop residue management (CRM) for the remaining 1–3%. Within the mitigation practices assessed, zero-grazing stalls already lowered the livestock maintenance energy requirements, reducing enteric fermentation emissions. Stall-feeding, however, brings the necessity-opportunity to manage the manure and our results showed that MMS can be a determining factor in the GHG balance. Increasing the frequency of manure collection from stalls in favour of solid storage systems can reduce N_2O emissions by up to 75%. Furthermore, dry manure storage reduced the CH_4 emissions of liquid slurry systems by more than 70%. Further benefits in terms of carbon (C) sequestration were identified along farm types from manure and crop residues applications in soils (with averages of -1.3 to -2.3 t CO_2 eq ha^{-1} yr^{-1}) and biomass growth in agroforestry systems (-1.2 to -2 t CO_2 eq ha^{-1} yr^{-1}). Together, soils and woody biomass offset 25–36% of farm emissions. We conclude that reduced farm size and increased livestock density lead to higher emissions per unit area, though this increase is smoothed by larger negative fluxes in soils (by higher C inputs) and woody biomass (by higher tree densities) until a steady state is reached. Average yield-scaled emissions, or product carbon footprints (CFs), resulted in 1.08 kg CO_2 eq kg coffee $berry^{-1}$, 0.64 kg CO_2 eq kg $maize^{-1}$ and 1.05 kg CO_2 eq kg $milk^{-1}$ on average. CFs did not always differ between farm types and intensification levels, meaning that increases in productivity were not higher than increases in GHG fluxes from intensification. This may be due to: 1) increases in productivity are the result of more processes other than N inputs; and/or 2) emissions from N inputs are overestimated by EFs and GHG calculators. Smallholders may benefit in the near future from climate initiatives and further field characterisation, models calibration and monitoring are required to overcome critical levels of uncertainty and provide more accurate estimations of GHG balances at farm-scale.

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1. Introduction

Meeting global food demand without compromising climate goals is among the most significant challenges of the 21st Century (Smith et al., 2013; Tilman et al., 2011). The world population is expected to exceed 9 billion by 2050 (Godfray et al., 2010), and agriculture and land clearing already represent a quarter (10–12 Gt CO_2 eq yr^{-1}) of global anthropogenic greenhouse gas (GHG) emissions (IPCC, 2014). Feeding the world while reversing current trends of agricultural driven GHG emissions will require efficient intensification processes as well as minimizing food waste and shifting diets (Bajželj et al., 2014; Tilman and Clark, 2014).

Reducing the impacts that agriculture has on the climate system is particularly challenging in developing countries, where a large proportion of GHG emissions come from the agricultural sector which sustains livelihoods and economies. Complementary approaches such as sustainable intensification (SI), climate-smart agriculture (CSA) (Campbell et al., 2014; FAO, 2013; Vanlauwe et al., 2014), and transdisciplinary sciences such as agroecology (Altieri et al., 2015; Tittonell, 2014), are already addressing food security and production goals, mitigation options and resilience to a changing climate (Steenwerth et al., 2014). These approaches recognize the role that the world's smallest farms play in the global food system within the Sustainable Development Goals (SDGs) agenda. Smallholder farming systems feed most of the planet, support the most vulnerable populations and landscapes, and regulate key ecosystem services (FAO, 2016; Samberg et al., 2016).

In sub-Saharan Africa, agricultural development has primarily been based on area expansion versus intensification (Evenson and Gollin, 2003). However, lack of land for agricultural expansion, coupled with rising population densities, have caused a decline in farm size (e.g. as a result of inheritance), leading to a more intensive use of available land (Muyanga and Jayne, 2014). This intensification trend is evident in the East African Highlands, an area primarily consisting of smallholder mixed crop-livestock systems (Thornton and Herrero, 2015). Smallholder dairy farms are typically intensified by shifting from free grazing to stall feeding with semi-zero grazing (a combination of livestock kept enclosed with some period of grazing or tethered grazing) or zero-grazing systems (enclosed all the time) (Bebe et al., 2003). Semi-zero and zero-grazing systems already comprise over three-quarters of all smallholder dairy farms in the highlands of Kenya (Udo et al., 2011). Due to limited land availability, animal grazing is thus being replaced by "cut-and-carry" fodder feeding systems, often accompanied by improved dairy breeds, in a strategy to maximize the use of resources (Baltenweck et al., 1998).

The degree of interaction between crops and livestock is itself an indicator of intensification (Boserup, 1965; Mc intire et al., 1992). The shift from free grazing of livestock to the cultivation of crops and fodder increases crop-livestock interactions, causing a significant change in farm nutrient flows and efficiencies (Castellanos-Navarrete et al., 2014; Tittonell et al., 2009). Resultant changes in farm nitrogen (N) and carbon (C) cycling affect productivity as well as GHG emissions and C sequestration. To date, few studies have analysed whole-farm interactions in integrated smallholder systems (Rufino et al., 2006). Understanding whole-farm interactions is essential since changes that occur in one component of the farm system are likely to influence other components, and thus the overall farm GHG balance.

The GHG exchange between the biosphere and the atmosphere on a coffee-dairy farm is driven by five processes involving C-N fluxes between five farm components (Fig. 1). The first process is livestock feeding, consisting of a mixture of fodder; crop and weed residues and off-farm concentrates which represent an additional N source imported to the farm. During digestion, cellulose breaks down in the rumen where methanogens take up the resulting hydrogen and release methane (CH_4) during the enteric fermentation process (Johnson and Ward, 1996). As part of the second process, animal excreta (urine and dung) are mixed with feed refusals and bedding materials, serving as an input to the manure management system (MMS). Manure management systems differ depending on collection frequency from the stall, biophysical conditions in manure stores, and the length of the composting and storage phases (Lekasi et al., 2003). Such factors influence not only CH_4 but also nitrous oxide (N_2O) emissions. N_2O results directly from nitrification and denitrification processes and indirectly through ammonia (NH_3) volatilisation, deposition and nitrate (NO_3) leaching (Amon et al., 2006). The third process consists of manure, inorganic fertiliser and crop residues applications in soils, which provides N inputs inducing N_2O emissions in addition to the soil background emissions (Oenema et al., 2005). Carbon dioxide (CO_2) is also emitted from soils due to respiration processes and the breakdown of organic matter (Janzen, 2004). During the fourth process, the turnover of manure and biomass residues, together with plant root exudates, accumulates soil organic C and therefore accounts for negative fluxes (Lal, 2004). The fifth process is C fixation from plant growths, especially significant in woody biomass under agroforestry systems, which sequesters C in above and belowground plant structures (Mutuo et al., 2005).

GHG budgets that include all farming activities are necessary in order to determine whether a farm is a source or sink of GHG, identify the leverage points to reduce emissions and analyse trade-offs. For example, trees in agroforestry systems could compensate for farm emissions (Albrecht and Kandji, 2003), while providing additional benefits other than C sequestration (Vaast et al., 2016). Several studies already provide needed GHG baselines at plot scale in Kenya (Baggs et al., 2006; Hickman et al., 2014; Kim et al., 2015; Kimetu et al., 2006; Pelster et al., 2015; Rosenstock et al., 2016a). However, only few studies estimate farm-scale emissions originating from multiple farm activities (see Seebauer, 2014 for example). Management decisions are taken at the farm scale and therefore estimations that do not account for this may misrepresent mitigation opportunities.

It is unclear how intensification processes affect whole-farm GHG balances in smallholder farming systems. The aim of this study was to estimate the GHG balance of coffee-dairy farms in an advanced state of intensification (small zero-grazing farms with high N inputs) in Kenya's Central Highlands. We hypothesised that different farm management strategies and intensification levels change the whole-farm GHG balance and GHG intensities. We followed three steps: (1) building a farm typology based on an intensification gradient; (2) calculating the whole-farm GHG balance for each farm and (3) deconstructing the farm GHG balance into farm components to identify emission hotspots, assess mitigation options, and quantify uncertainties in the estimations.

2. Methods

2.1. Study area

Murang'a County is located on the eastern slopes of the Aberdare Mountain Range in the Central Province of Kenya (Fig. 2). Increased population and decreased farm sizes have already driven agriculture intensification processes such as zero-grazing, associated manure handling and increased N inputs in soils. These practices make Murang'a relevant for study, since other regions in East Africa are expected to move in this direction. Our focus area covers an altitudinal range between 1300 m and 1900 m.a.s.l., including four different agro-ecological zones (AZ) ranging from lower highlands humid (LH1) – a transition zone from tea to coffee cultivation – to upper midlands humid (UM1) – a predominant coffee zone – and all the way to upper midlands semi-humid (UM3) where coffee is becoming marginal (Fig. 2) (Jaetzold et al., 1983). Annual precipitation ranges from 1200 to 2000 mm yr^{-1}, falling in a bimodal pattern over the year, and increasing with altitude due to the prevalence of south-east trade winds. Average temperatures vary between 17 and 20 °C along the altitudinal gradient (Jaetzold et al., 1983). Well-drained deep red nitisol soils predominate in the area.