Science of the Total Environment 626 (2018) 328–339

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Multi-scale measurements show limited soil greenhouse gas emissions in Kenyan smallholder coffee-dairy systems

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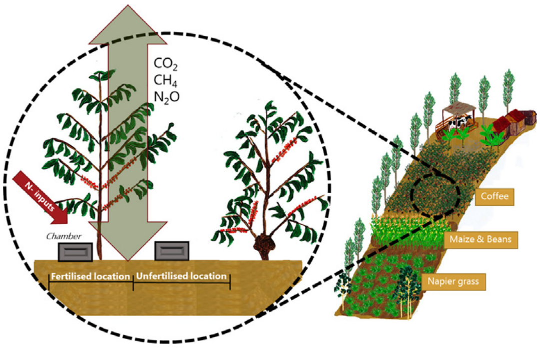
HIGHLIGHTS

- Smallholder coffee-dairy farms have low soil GHG emissions in Central Kenya.
- The inherent complexity of smallholder systems challenge GHG measurements.
- Stratification among farms, fields, and field locations can capture spatial variability.
- Sampling should match seasonal events to account for temporal variability.
- Fertilised spots in coffee plots registered the highest emissions during wet periods.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 10 October 2017
Received in revised form 17 December 2017
Accepted 21 December 2017
Available online xxxx

Editor: Jay Gan

Keywords:
Carbon dioxide
Nitrous oxide
Methane
Hotspots
Hot moments
Mixed crop-livestock systems

ABSTRACT

Efforts have been made in recent years to improve knowledge about soil greenhouse gas (GHG) fluxes from sub-Saharan Africa. However, data on soil GHG emissions from smallholder coffee-dairy systems have not hitherto been measured experimentally. This study aimed to quantify soil GHG emissions at different spatial and temporal scales in smallholder coffee-dairy farms in Murang'a County, Central Kenya. GHG measurements were carried out for one year, comprising two cropping seasons, using vented static chambers and gas chromatography. Sixty rectangular frames were installed on two farms comprising the three main cropping systems found in the area: 1) coffee (*Coffea arabica* L.); 2) Napier grass (*Pennisetum purpureum*); and 3) maize intercropped with beans (*Zea mays* and *Phaseolus vulgaris*). Within these fields, chambers were allocated on fertilised and unfertilised locations to capture spatial variability. Cumulative annual fluxes in coffee plots ranged from 1 to 1.9 kg N_2O-N ha^{-1}, 6.5 to 7.6 Mg CO_2-C ha^{-1} and $^{-}3.4$ to -2.2 kg CH_4 -C ha^{-1}, with 66% to 94% of annual GHG fluxes occurring during rainy seasons. Across the farm plots, coffee received most of the N inputs and had 56% to 89% higher emissions of N_2O than Napier grass, maize and beans. Within farm plots, two to six times higher emissions were found in fertilised hotspots – around the perimeter of coffee trees or within planted maize rows – than in unfertilised locations between trees, rows and planting holes. Background and induced soil N_2O emissions from fertiliser and manure applications in the three cropping systems were lower than hypothesized from previous studies and empirical models. This study supplements methods and underlying data for the quantification of GHG emissions at multiple spatial and temporal scales in tropical, smallholder farming systems. Advances towards overcoming the

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https://doi.org/10.1016/j.scitotenv.2017.12.247

dearth of data will facilitate the understanding of synergies and tradeoffs of climate-smart approaches for low emissions development.

1. Introduction

Agriculture's carbon debt has considerably increased over the past two centuries (Sanderman et al., 2017). The sector – comprising agriculture, forestry and other land use (AFOLU) — currently contributes about a quarter of global anthropogenic greenhouse gas (GHG) emissions (Smith et al., 2014), of which more than a third result from soil GHG fluxes (Tubiello et al., 2013). Further agricultural expansion and intensification, driven by ongoing trends of population increases and dietary changes, are expected to result in the clearance of an additional one billion hectares of forest and increase agricultural GHG budgets by up to 80% by 2050 (Tilman et al., 2011). Meeting global food demand without increasing agricultural land and associated GHGs emissions will require transdisciplinary approaches such as sustainable intensification for yield gaps closure (Mueller et al., 2012); increase resource use efficiency (Foley et al., 2011); soil carbon restoration efforts (Lal, 2004); minimisation of food waste (Bajželj et al., 2014); and a shifting diets (Tilman and Clark, 2014), among others.

Crucial agricultural breakthroughs are thus needed to achieve the Sustainable Development Goals (SDGs) agenda (United Nations General Assembly, 2015). In Africa, targets to end poverty (SDG1) and end hunger, achieve food security and promote sustainable agriculture (SDG2), are of vital importance given the rapid population growth and rises in food demand, particularly in sub-Saharan Africa (Van Ittersum et al., 2016). Increased production largely depends on innovations within the AFOLU sector, which already releases >60% of the continental emissions (Valentini et al., 2014). Most of the SSA countries have ratified the Paris Agreement and made GHG reduction commitments for low-carbon development (UNFCCC, 2016). The lack of empirical data obliges these countries to report using Tier 1 default emission factors (EFs) (Hickman et al., 2014a, 2014b; Ogle et al., 2014), which were developed from global average data based primarily on monoculture cropping systems in temperate areas (Hickman et al., 2014a, 2014b; Olander et al., 2014).

Relatively few field studies have hitherto measured GHG emissions in agricultural soils in sub-Saharan Africa (Kim et al., 2016; Rosenstock et al., 2016a; Pelster et al., 2017). Insufficient, sparse empirical data present a challenge in evaluating the accuracy of the estimations (Kim et al., 2016), and may therefore lead to misdirected mitigation or regulation interventions (Rosenstock et al., 2013). For instance, there are no experimental data on common agroecosystems such as smallholder coffee systems, which in Kenya alone support >600,000 households (Monroy et al., 2012). Furthermore, the available accounting tools for carbon footprinting, such as GHG calculators, rely on EFs and empirical models that have not been calibrated for these regions. Since marketing low carbon products may benefit smallholder farmers producing global commodities such as coffee, accurate estimations are needed. Given the need for more data to inform programming and policy, efforts have recently made to develop harmonised low-cost methods to build EFs and parameterise models (Rosenstock et al., 2013).

While carbon dioxide (CO_2) from soils is produced by plant roots, soil fauna and microbial respiration, agricultural soils also emit or take up two major non-CO_2 gases: methane (CH_4) and nitrous oxide (N_2O). The former is emitted by methanogens under the anaerobic conditions in submerged soils – mainly in rice cropping systems (Zhang et al., 2016) – and taken up by methanotrophs in aerobic systems (Le Mer and Roger, 2001). The latter, N_2O, is currently the most important ozone-depleting gas (Ravishankara et al., 2009). N_2O is produced by nitrification and denitrification in microbial-mediated processes. Nitrification involves the aerobic oxidation of ammonium (NH_4^+) to nitrite (NO_2^-) and nitrate (NO_3^-) (Webster and Hopkins, 1996), whereas denitrification causes the anaerobic reduction of NO_2^- and NO_3^- to N_2O and gaseous nitrogen (N_2) (Robertson and Tiedje, 1987). The amount of nitrogen cycled, together with environmental parameters such as climate (*e.g.* temperature, atmospheric pressure and rainfall) and soil factors (*e.g.* soil texture, moisture and oxygen content, drainage, soil organic-C and pH), control the nitrification and denitrification rates (Firestone and Davidson, 1989; Davidson et al., 2000; Bouwman et al., 2002; Butterbach-Bahl et al., 2013). Inorganic fertilisers and animal manure are the major contributors for N_2O production (Mosier, 2001).

The inherent heterogeneity of smallholder farming systems makes the design of GHG sampling approaches complicated (Rosenstock et al., 2016b). Complex landscapes of small farms, with multiple farm components (*e.g.* several crops), management practices (*e.g.* fertilisation) and seasonal events, accentuate spatial and temporal variabilities of GHG emissions (hotspots and hot moments). Hotspots are those precise spatial locations, within a determined scale (*e.g.* the landscape level), which show higher emissions rates than the surroundings (McClain et al., 2003). N_2O hotspots in agricultural fields depend on the interaction of nutrient patches and physical factors which controls oxygen diffusion and consequently denitrification (Groffman et al., 2009) Thus, the allocation of resources (*e.g.* N inputs), together with biophysical factors (*e.g.* plant and soils), needs to be considered in experimental designs. Hot moments, however, are temporal events that cause the convergence of factors (*e.g.*, drying-rewetting) with high emissions rates (Groffman et al., 2009). Targeting sampling periods within the day, season or year, under particular weather conditions (*e.g.* precipitation and temperatures) or farmers' practices (*e.g.* fertilisation periods), are critical to overcome temporal variability.

Smallholder mixed farming systems – characterised by the integration of crops and livestock – are the backbone of African agriculture (Thornton and Herrero, 2001). The coexistence and redundancy between different farm components (*e.g.* crops, livestock, and trees) allow these systems to diversify farm production, promote resource interactions and increase farm resilience. For instance, livestock manure plays a crucial role in maintaining soil fertility by recycling plant nutrients removed by different crop residues and fodder (Rufino et al., 2007). At the same time manure quality depends on livestock feeding and manure management, which ultimately may affect soil N_2O emissions after manure application. In comparison with low-input systems (Pelster et al., 2015; Rosenstock et al., 2016a), integrated small farms with high livestock densities have relatively higher N inputs. Although previous studies have measured GHG at the field level, this is an attempt to upscale at farm-level by stratifying the farm on its different components, from the farm to the field and then to the specific location in the field (*e.g.* fertilised and unfertilised locations) (Fig. 1). Furthermore, despite the important role of manure as an endogenous resource in African smallholder systems, few studies have investigated N_2O emissions from manure handling and application. The present study aims to provide empirical measurements of soil GHG fluxes at multiple spatial and temporal scales in smallholder integrated coffee-dairy farms in Central Kenya.

2. Methods

2.1. Study area

Murang'a County is situated on the eastern slopes of the Aberdare Mountain Range in Central Kenya, one of the main coffee regions of