Soil organic matter depletion as a major threat to agricultural intensification in the highlands of Ethiopia

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ABSTRACT

Agriculture is considered as the backbone of Ethiopian economy. The government promotes rural development through policies that enhance intensive and commercially-oriented agriculture. Soil quality may be the bottleneck of these ambitions as more than half of the agricultural land shows signs of land degradation. Soil organic carbon (SOC) contents are a key aspect of soil quality, where relatively high SOC contents indicate better water holding capacity, nutrient retention capacity and better structure of the soil. In this research, SOC balances were used as indicator for short and midterm changes in SOC contents. SOC balances were calculated using data collected from 6914 fields for three years (2012-2014) using a simple input-out approach. On average, SOC balances were three tons per hectare per year. This equals 4 to 7% of the total soil organic carbon stock, which varied according to regions and cropping systems. SOC depletion rates were high in the mountainous and high cultivation intensity sites in central and northern Ethiopia where cereal based cropping systems dominates. Under the current practice, soils will eventually become exhausted and lose their productivity. This alarming trend could be reversed by integrating organic matter and nutrient management strategies and by providing alternative sources for feed and fuel supply of the community.

Keywords: Soil Fertility, Sustainability, Farming system, MonQI

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INTRODUCTION

The agricultural sector in Ethiopia is rapidly developing but it still lags behind the demand for food, feed and fibre. Low agricultural productivity caused by soil degradation is a serious challenge in Ethiopian highlands (Amare Haileselassie *et al.,* 2006). At the same time, population increase with 2.6% y^{-1} (World Bank, 2006) has increased pressure on the natural resources, especially in agricultural areas (Hadgu *et al.,* 2009; Woldie Mekuria *et al*., 2009). The highlands of Ethiopia (>1500 masl elevation) occupy 44% of its area and are home for 90% of the country's human and for 75% of its livestock population (Amare Haileselassie *et al*., 2006). Another consequence of the increasing population is a decrease in land tenancy size with a negative trend falling from 1.7 ha per household in 1964 to less than 1 hectare in 2006 (World Bank, 2006). According to Corbeels *et al*. (2000), decreased land holding size causes loss of soil fertility because farmers are unwilling to allow land to stay fallow in order to naturally restore and recharge soil fertility. This situation, combined with sustained and improper agricultural management such as crop residues removal, steep slope cultivation, deforestation, use of animal manure (manure cake) as source of energy for cooking and excessive livestock pressure, has led to a great extent to soil organic matter depletion and eventually to the abandonment of land. Although farmers are aware of the problems of permanent and intensive cropping and of the need for organic inputs to restore soil fertility, they have a few alternatives at their disposal because of the persistent lack of inputs and alternative energy sources (Mulat Demeke *et al*., 1997; Alemu and Kohlin, 2008; EIAR and TARI, 2011). Soil organic matter (SOM) is an important soil quality parameter. Relatively high SOM contents indicate relatively high buffer capacities for water and nutrients, good soil structure, increased water holding capacity and friability (Rees, 2001; Loveland and Webb, 2003). Moreover, decomposition of SOM releases nutrients that may be taken up by crops which in turn highly contribute to the natural soil fertility (El Titi, 2003; Pekrun *et al*., 2003).

Changes in SOM contents are so difficult to monitor that they often only become apparent after some decades (Corral-Nunez *et al.,* 2014). As an alternative, SOC balances can be determined to indicate eventual changes in SOM contents. In this paper, SOC balances were determined for 6914 fields in Capacity Building for Scaling up of Evidence-Based Best Practices in Agricultural Production in Ethiopia (CASCAPE) intervention *woredas* (districts) for three years using on-farm monitoring surveys. The results were related to agro-ecological conditions, and prospects were discussed with regard to intervention mechanisms to maintain and restore the productive capacity of the soils.

MATERIALS AND METHODS

Selected sites

The present study is part of a broader study in the CASCAPE project (www.cascape.info). This project operates in 30 *woredas* assigned by the Agricultural Growth Program (AGP) distributed over 6 teams (clusters) hosted at local universities (Figure 1).

The *woredas,* whose details are published (van Beek *et al.*, 2017), represent different farming systems, agro-ecological zones and soil types. In each cluster, SOC balances were determined for all fields of approximately 60 farms per cluster for three years (2012-2014) with a total of 6914 unique combinations of fields and years.

Monitoring farm management with the MonQI toolbox

SOC balances were calculated as the net differences of nutrient inputs and output flows using the Monitoring for Quality Improvement (MonQI) toolbox. The MonQI toolbox is a method for monitoring management and performance of small-scale farming systems world-wide. MonQI has been used in the tropics for over 30 years (www.monqi.org; Vlaming *et al.*, 2012; Smaling *et al.,* 2013). So far, MonQI included macro nutrients (NPK), but the basic approach applies to all matter. In the current study, the MonQI toolbox was extended with a module on organic C circulation.

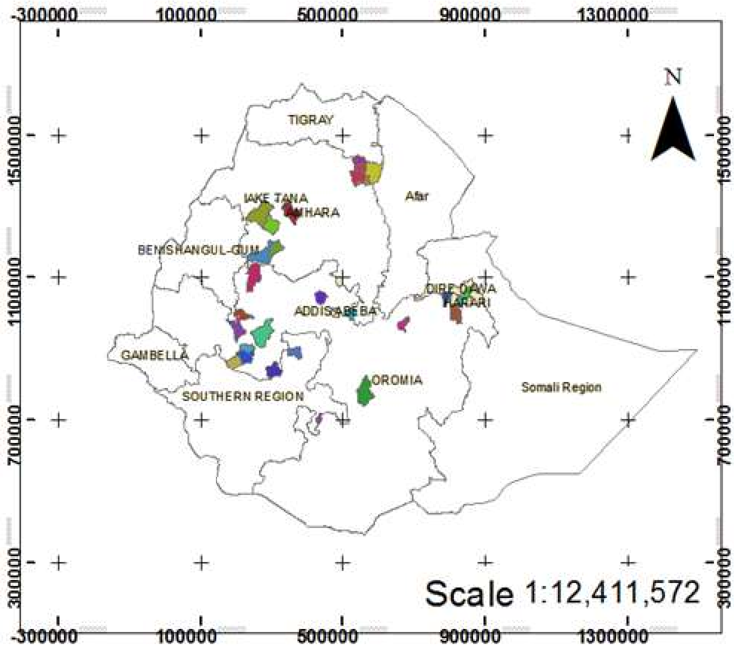

Figure 1. CASCAPE intervention *woredas*

Carbon input flows include farmer managed flows such as compost application. Output flows include removal of organic carbon by harvests, leaching, mineralization and erosion. Mineralization was estimated using a mineralization rate of 1% y^{-1} as suggested by Lesschen (2007). Leaching and erosion were calculated using pedo transfer functions (Lesschen, 2007). Farm management data were collected using structured farm surveys with questions on farm structure, crop management, livestock management and compost management for nutrients and cash. Data collection started in 2012 for all *woredas*. A total of 360 farmers who were beneficiaries of the CASCAPE project were selected as research participants on the basis of their representativeness of their respective region.

Data analysis

Soil organic C depletion rates were calculated by dividing soil nutrient balances by relevant *woreda* average soil nutrient pools, using soil properties of the topsoil (0-70 cm). Outliers, defined as SOC balances of less than -100 tons $ha^{-1}y^{-1}$ or more than 10 tons ha^{-1} y^{-1} were removed from the dataset. These outliers were often due to difficulties of farmers to estimate on-farm inputs such as organic residues to small fields (typically less than 100 m^2). For these flaws, wrong estimations in original data were checked again and the data were converted to hectares.

RESULTS

Average annual C removal rates were three tons $ha^{-1}y^{-1}$, with the lowest depletion in the dry areas of North (Tigray) and East (Haramaya) (Figure 2). Variability in SOC balances between *woredas* and between fields was high, and the relative standard deviation of the entire dataset was 458%. Relative standard deviations were high for the mountainous *woredas* in Mekelle, Hawassa and Addis Ababa clusters (Figure 3). Yet, variability in SOC balances were only slightly lower between fields within specific farms compared to variability between *woredas* or regions (Figure 4). SOC balances varied between crops. Especially wheat showed major depletion rates while beans had a slightly positive organic C balance (Figure 5). The main loss pathways were volatilization, leaching and erosion, and only Jimma cluster had substantial organic inputs (Figure 6). Although no significant trends were observed in regions such as Jimma and Bahir Dar, SOC balances declined with an average of 37% per year, with major decreasing rates recorded/noted in Mekelle and Hawassa regions (Figure 7).

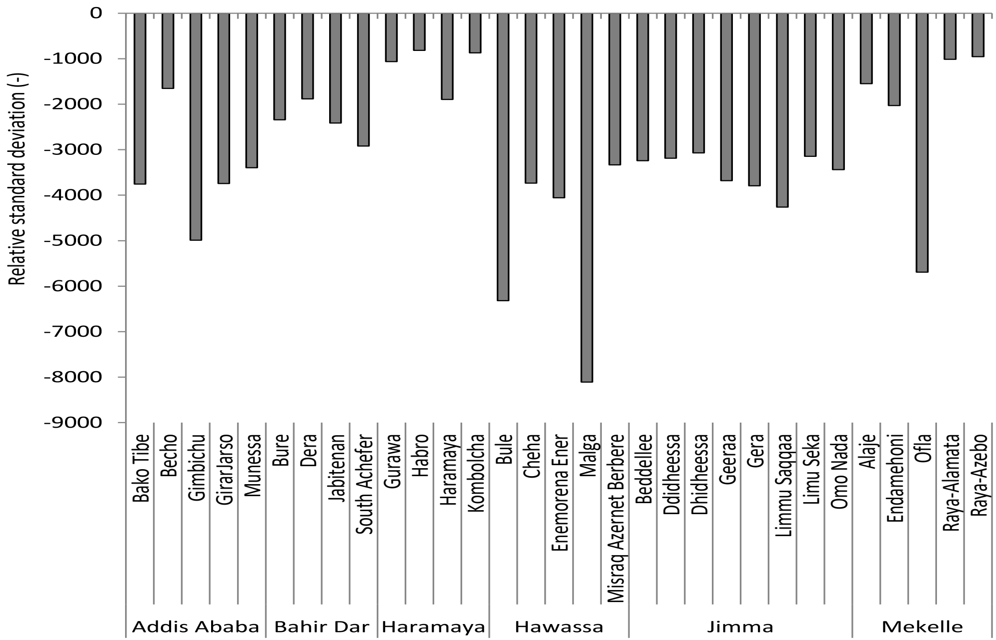

Figure 2. Average soil organic C balances per woreda (n=651-1494 depending on location).

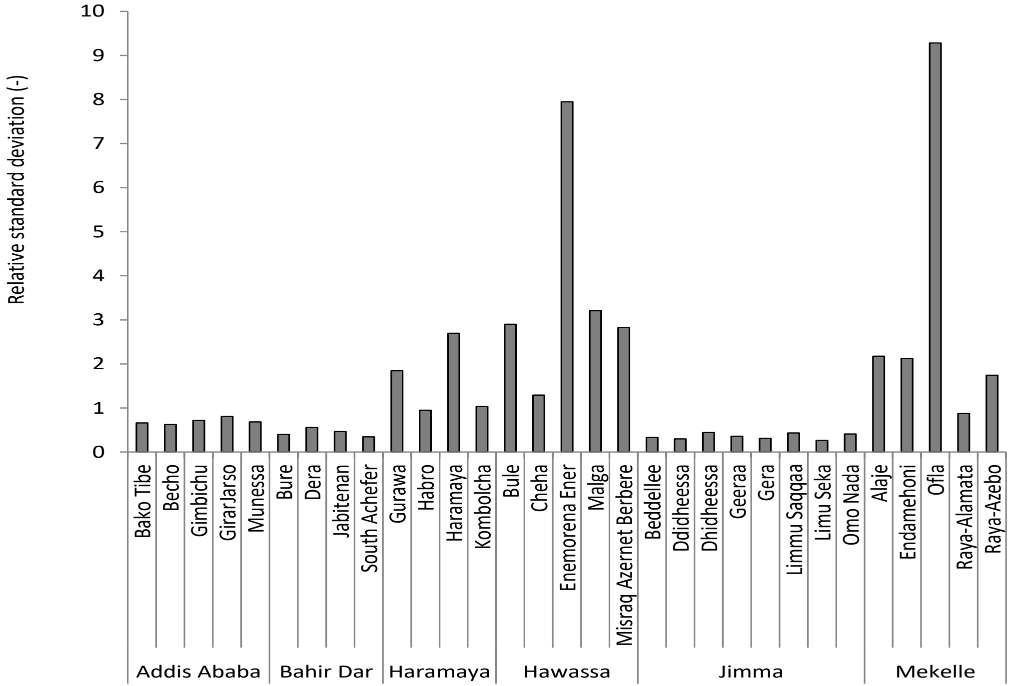

Figure 3. Relative standard deviation of organic C balances per *woreda*.

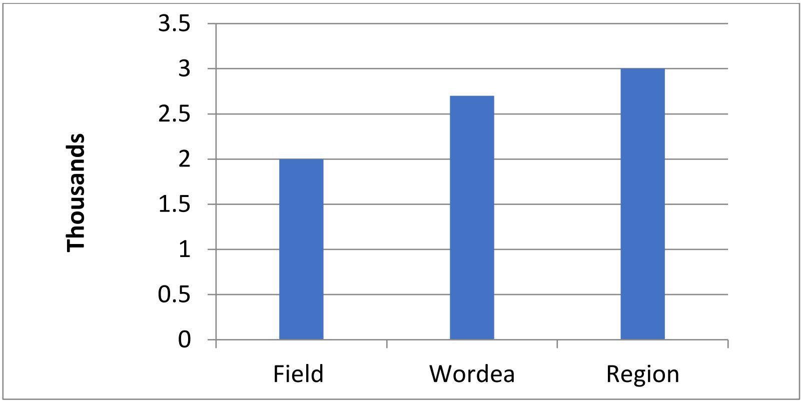

Figure 4. Average standard deviations of organic C balances between fields of individual farms, between *woredas* of a specific region and between regions.

DISCUSSION

Soil carbon balances strongly differed between fields, *woredas* and regions (Figure 3). The cause of the variation, however, was different for each spatial scale. At field level, differences in soil organic C balances were mainly caused by different cropping systems (Figure 5). At regional level, differences in climate (rainfall and temperature) and soil types were the main causes of variability. The highest depletion rates were found in Mekelle and Haramaya clusters (Figure 2), because both were semi-arid areas with low biomass production that precipitates little options for organic matter circulation.

Main loss pathways were volatilization and erosion (Figure 5). Volatilization, which occurs after mineralization of organic matter, is favoured by moist and warm conditions, typically for Jimma and Hawassa areas. Erosion is favoured by steep and long slopes, typically for Bahir Dar, Hawassa and Jimma areas. Consequently, losses were high in Jimma and Hawassa, but this was not always the case (Figure 2). The difference between Jimma and Hawassa is explained by the high organic matter inputs in Jimma compared to Hawassa. Farming systems in Jimma were dominated by coffee-based, mixed systems, whereas those in Hawassa were cereal based. Consequently, in Jimma more organic residues were available for composting that was applied to the fields.

In general, Figure 5 shows that, apart from Jimma, the negative SOC balances were caused by the absence of organic C inputs. Amare Haileselassie *et al.* (2006) reported that organic matter related parameters like N and P contents were higher in the perennial crop (*enset*) based system.

This could have been the result of management, i.e., more inputs of organic residues in the perennial system than in the annual crop (*teff*) based system. Similarly, conversion of native forest and subsequent cultivation reduced the amount of SOC in South-Eastern Highlands of Ethiopia because of lower supply and return of organic matter into the soil system (Fentaw *et al.*, 2007). On average, soil organic matter balances decreased by 37% per annum. This was about 4% to 7% of the total soil organic carbon stock, depending on the organic carbon content of the particular soil, a rate that was alarming by any standards.

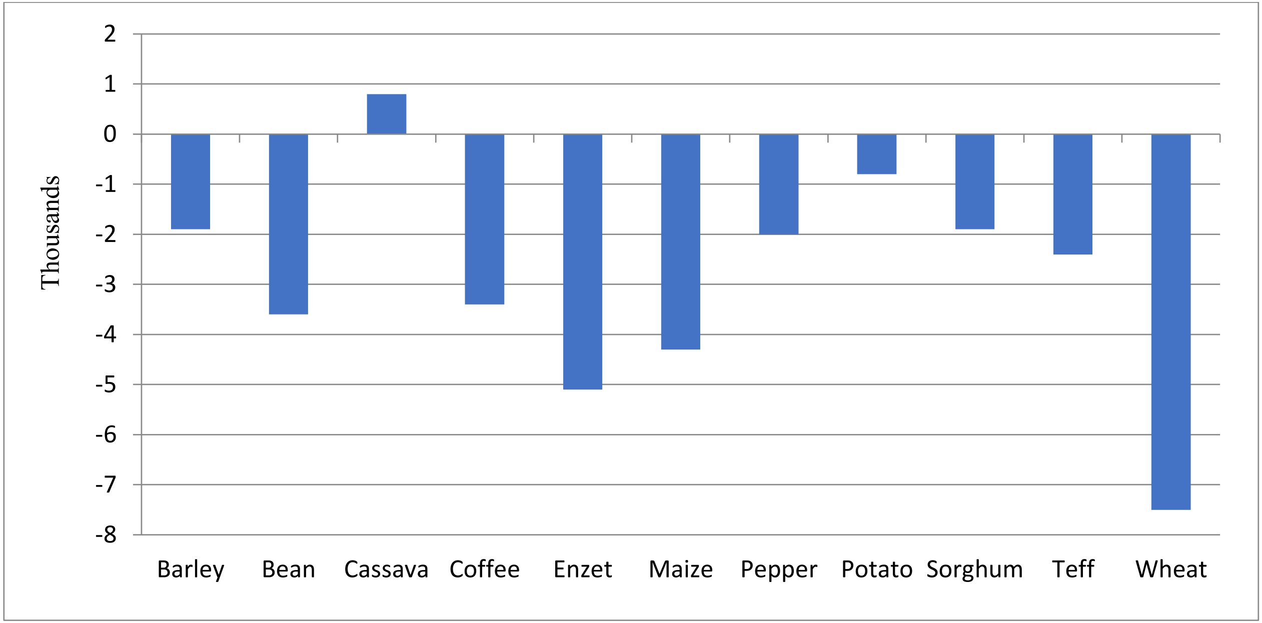

Figure 5. Soil organic C balances (kg/ha/y) for different crops (average for all regions)

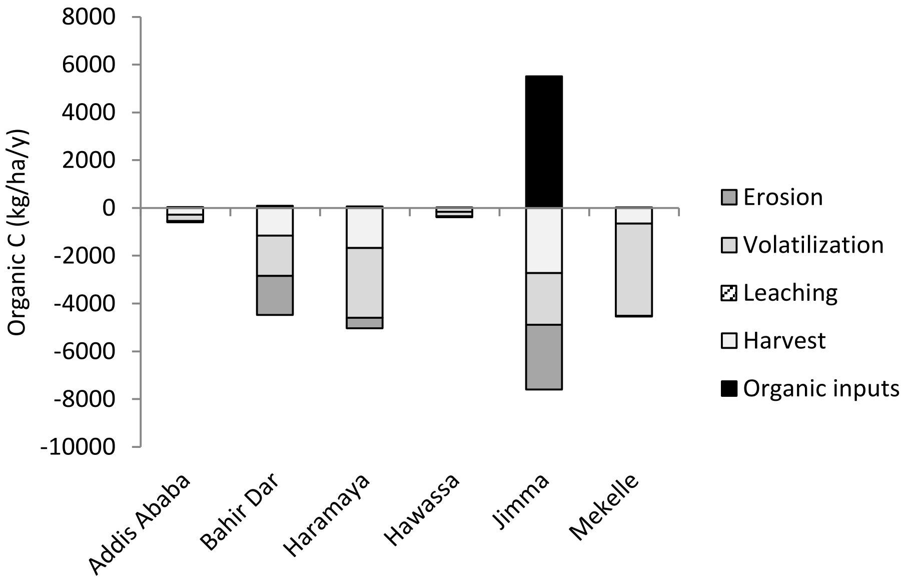

Figure 6. Average balance entries of the soil organic C balance per region

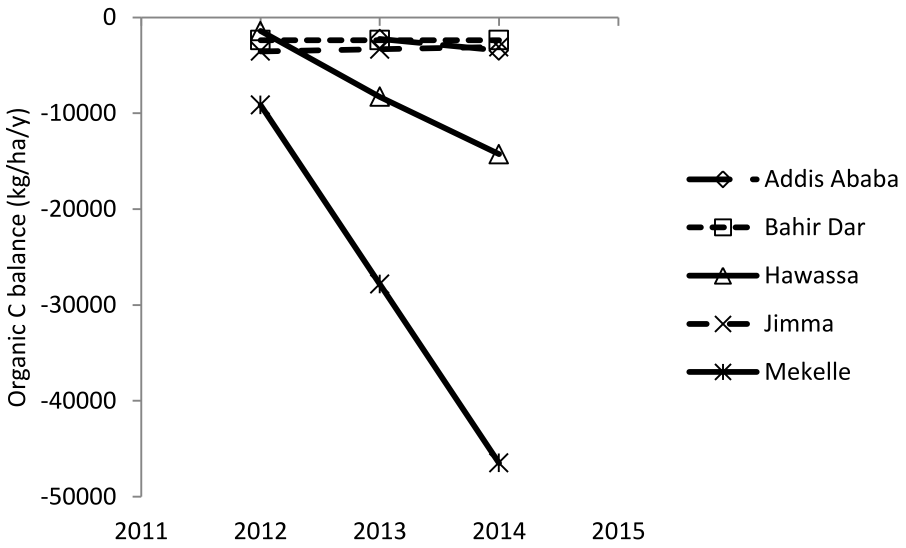

Figure 7. Trends in organic C balances per region for only those woredas with multiple years of monitoring

Yet, Lemenih (2005) reported still higher rate, i.e., 74.6%, after deforestation in the Southern highlands of Ethiopia. Corral-Nuñez *et al.* (2014) confirmed the declining trends for Northern Ethiopia under business as usual scenarios while Abegaz *et al.* (2005) also showed that organic fertilizer input levels were much lower than required to maintain a dynamic equilibrium in soil organic matter content. Declining trends for Jimma and Hawassa were more severe than for other areas (Figure 7). During the study period, less crop residues were applied to the fields which could explain the decreasing trend. However, it could not explain why crop residue management changed in such small time period, apart from the overall trend towards intensification and the competing claims for organic matter for feeding and fuel.

Unbalanced organic C and nutrient balances in agricultural soils can be a precursor of land degradation and, eventually, land abandonment. The continuous soil mining results in lower soil organic matter content consequently reducing the nutrient and water holding capacity, and the biological activity of the soil. After prolonged depletion, soils fall prey to erosion and desertification or become unproductive and abandoned, which could no longer render the ecosystem service of carbon sequestration. This downward spiral is commonly known as the poverty trap. This is not an unthinkable scenario for Ethiopia where, especially in the central rift valley, land is degraded and productivity has declined (Woldeamlak Bewket *et al*., 2013). In northern Ethiopia, forest cover seems to be improving which may increase SOM contents (Nyssen *et al.,* 2009), but it is unclear how this relates to land pressure of the agricultural lands (Corral-Nuñez *et al*., 2014). Pulleman *et al*. (2000) also compared SOC accumulation in conventional-arable, conventional-grass, organic-arable and organic-grass lands. They found that there was significantly higher organic carbon accumulation in the grass lands than in the arable lands.

Soil organic matter is commonly regarded as a potential solution to climate change as carbon sequestration in soil is the largest potential sink for CO_2 (Lal, 2004; Lal, 2010). Yet, in the agricultural soils of Ethiopia, with the common trends in soil organic C balance, C is not sequestrated. When balances are negative, organic C is released as CO_2 directly contributing to greenhouse gas emissions. We could not quantify the exact CO_2 emissions based on the soil organic C balance data because, for example, dissolved organic C in erosion may or may not be emitted to the atmosphere. Taking the two extremes of all released C emitted as CO_2 and only mineralization emitted as CO_2 gives a range of 7-14 tons of CO_2 $ha^{-1}y^{-1}$.

CONCLUSION

Soil organic matter balances were negative in the intensive but subsistence farming systems of the highlands of Ethiopia. On average, soil organic C balances were -3.7 tons $ha^{-1}y^{-1}$ that steadily decreased with time. Intervention strategies should include adapted cropping systems and soil conservation practices. Such an integrated strategy will also contribute to adaptation to climate change by making the farming system more robust and resilient to erratic weather patterns. Under the current practices, soils will eventually become exhausted and lose their productivity. This worrisome trend could be turned around by integrating organic matter with inorganic nutrient management and by devising alternative sources for feed and fuel.

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