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Soil organic matter underlies crop nutritional quality and productivity in smallholder agriculture

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ABSTRACT

Global crop yield gains have not be associated with increases in the many macro- and micro-nutrients needed for a balanced human diet. There is thus growing interest in improving agricultural practices to increase nutrient availability to people. Because nutrients in crops come from soil, soil management—such as building soil organic matter—could be a tool in managing agriculture to produce more nutritious food. To understand the relationship between soil organic matter and nutritional quality, we measured soil organic matter fractions, crop yield, and wheat nutrient composition on smallholder farms along a land-use and land-cover gradient in Ethiopia. We found that wheat yields and protein content were related to organic matter nitrogen, and zinc content was related to organic matter carbon. Increasing organic matter carbon by 1% was associated with an increase in zinc equivalent to the needs of 0.2 additional people per hectare; increasing organic matter nitrogen by 1% was associated with an increase in protein equivalent to the daily needs of 0.1 additional people per hectare. Soil organic matter—and its associated fractions—was greatest in soils closest to a state forest and in home gardens (as opposed to in wheat fields). Wheat fields closer to the forest had elevated soil organic matter fractions relative to wheat soils closest to the market town. Our results indicate that realistic gains in soil organic matter could make human-health-relevant increases in wheat nutrient content. Soil organic matter management can therefore be an additional tool for feeding the world well.

1. Introduction

Global yields of staple grains increased significantly starting in the early 1960s, even on a per capita basis as populations have grown (DeFries et al., 2015; Hazell and Wood, 2008). Production of the many nutrients required for a balanced human diet, however, has not kept pace with the growth in yield and calories, and even fallen for some nutrients (DeFries et al., 2015). In addition, there is growing evidence that increasing CO_2 concentrations could further suppress crop micronutrient content (Myers et al., 2014). Evidence from a more-than-century-old cropping trial suggests that this has already happened due to existing changes in atmospheric CO_2 concentrations (Fan et al., 2008). Ensuring food is nutritious, and not just calorically adequate, will therefore be important to future advances in agriculture.

The threat of decreasing crop nutrients—or decreasing crop nutrients per capita—raises concerns about hidden hunger, which is the high burden of vitamin and mineral deficiency around the world. To date, most nutrition interventions have focused on dietary supplementation, dietary diversification, and to a lesser degree biofortification of existing crops. Largely missing from this nutritional toolkit has been management of the environment conditions in which crops grow, such as soil properties, to optimize nutrient concentrations. Despite this absence, it is established that soils can contribute to nutrients in crops in sufficient levels to impact human wellbeing (Barrett and Bevis, 2015; Bevis, 2015). For instance, crops grown on soils with low levels of selenium have been shown to lead to selenium deficiencies in people consuming these crops (Chilimba et al., 2011; Hurst et al., 2013).

There is a need to combat hidden hunger by increasing the nutrient composition of crops and one avenue to do this is through integrated soil fertility management, which emphasizes building up the organic and inorganic nutrients needed by plants through land management and mineral fertilizer use (Bado and Bationo, 2018; De Valença et al., 2017). A key aspect of integrated soil fertility management is soil organic matter (SOM). Going back to the earliest work in agroecology, there have been claims that building SOM is associated with more

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nutritious food (Howard, 2010). Soil organic matter provides macronutrients for protein building in plants, as well as cation exchange capacity for the exchange of micronutrients. Despite a long history of this supposition, there is strikingly little quantification of the link between SOM and crop nutrient content. There are some specific examples, mostly for horticultural crops, such as higher levels of flavonoids in tomatoes under organic production (Mitchell et al., 2007).

The main goal of this study was to assess if SOM was associated with nutrient composition of wheat in a smallholder farming setting in Ethiopia. We focused on SOM because it is known to impact nutrient availability through elevated cation-exchange capacity, and also because it is a manageable soil property (unlike texture, which is also related to cation-exchange capacity). We measured SOM fractions—-mineral-associated and particulate—on the expectation that particulate organic matter would be more associated with nitrogen (N) release and mineral-assosciated organic matter would be more associated with cation-exchange capacity (Wander, 2004).

Our first objective was to determine the drivers in wheat yields and nutrient content across a landscape characterized by a gradient of distance to a state forest. We hypothesized two competing patterns in wheat yields. First, we expected that yields would be greatest for households closer to the market town (and thus having greater access to mineral fertilizers and other inputs) where farmers had also transformed their surrounding landscape the most for crop production (e.g., low tree cover; Baudron et al., 2017). Secondly, we expected that wheat yields would be greatest for farms with the greatest level of native SOM, suggesting agroecological—rather than conventionally intensive—approaches would be optimal for production. For wheat nutrients, we expected that nutrient content could be impacted by mineral fertilizers or native organic matter, when statistically controlling for soil type.

Our second objective was to determine the drivers in soil properties that we hypothesized could be important predictors of wheat yield and nutrient status. We posed two competing hypotheses for drivers in SOM—particulate and mineral organic matter as well as microbial biomass. First, we expected that SOM would decrease with distance from a state forest on the expectation that households closer to vegetation patches would have greater inputs of organic matter to their soil—mainly from manure from grazing cattle (see Baudron et al., 2017). Second, we hypothesized that patterns in SOM would be dominated by immediate land use—whether a soil sample was taken from a wheat field or home garden—regardless of distance to forest or grazing land. Because home gardens have high levels of organic inputs from household waste and household livestock, we expected this would wash out any distance-decay spatial pattern in SOM.

2. Material and methods

2.1. Site description

Nationally, Ethiopia is at severe risk of hidden hunger (Muthayya et al., 2013). Our study site was located in the *woreda* (district) of Arsi Negele, located in the Oromia region of Ethiopia (Baudron et al., 2017; Duriaux Chavarría et al., 2018). We studied six villages in an area of about 100 km^2 in three *kebele* (sub-district). Each village was selected to lie along a distance gradient from the state forest of Munesa (Baudron et al., 2017). Households were grouped into three geographical clusters: near-to-forest, middle, and near-to-main-market. The furthest villages from the state forest lie about 11 km from the forest area. The near-to-forest, middle, and near-to-main-market villages lie about 16, 11.5 and 6.5 km from the main market in Arsi Negele town (Fig. 1).

The study area lies between 2050 and 2214 m above sea level. Its climate is characterized by a mean annual rainfall of 1075 mm and a mean annual temperature of 15 °C. There are three main seasons: a short rainy season from March to May; a long rainy season from July to September; and a dry season from October to February. The natural vegetation is classified as dry Afromontane forest. Prior to land reform that took place in the mid-1970s, the landscape was largely forested and people were mainly pastoralists. Resident tenants only cultivated small fields. Today, the area outside of the state forest has been largely deforested for mixed crop-livestock agriculture. The main crops are wheat (*Triticum* sp. L.), maize (*Zea mays* L.), potato (*Solanum tuberosum* L.), and enset (*Ensete ventricosum* (Welw.) Cheesman). Soils are loam and clayey loam (Fig. S1). Most farmers keep livestock in the form of cattle, sheep, goats, horses, donkeys and chickens. Residents of villages neighboring the forest use the forest for grazing and collection of fuelwood. Middle villages are about 3 km from the forest and do not use it for grazing and fuelwood. They do, however, have access to a large communal grazing area for livestock grazing and fuelwood collection. Villages furthest from the forest—and closest to the market town—do not have access to any common land for livestock grazing and fuelwood collection. More site information can be found in Baudron et al (2017) and Duriaux Chavarría et al. (2018).

2.2. Field sampling and household surveys

Household surveys were conducted with 266 households—representing all of the households in each zone—between December 2014 and February 2015. Questions were asked regarding household composition, assets, income sources, crop and livestock production, forest use, market access and trading (Duriaux Chavarría et al., 2018). Based on survey results and a farm typology delineated through self-categorization exercises (Duriaux Chavarría et al., 2018), a stratified sample of nine farms per zone was selected for in-depth sampling and analysis.

Crop measurements—yield and nutrient content—were only collected for wheat fields while soils were collected from wheat fields, home gardens, and the municipal forest. Wheat yields were estimated by dividing the quantity of grain harvested from the field – as recalled by the head of the farm during the interview – and dividing it by the area of the field – as measured by a handheld GPS. Most farmers harvested their wheat field with a combine harvester (custom hire services) and thus had accurate records of their harvest. Because of the large diversity of crops in homegardens (enset, vegetables, coffee, maize, etc.), it was not possible to acquire data on the productivity of these other crops. Wheat samples were collected in November 2016, immediately after harvest. We collected about 500 g of wheat, which was sub-sampled from each farm's harvest after it was brought back to the household.

Soil samples were collected in December 2016 with a 2-cm probe. For each sample, we collected fifteen subsamples to 15 cm depth and aggregated and homogenized the subsamples to a single sample.

2.3. Crop analyses

Crude protein, iron and zinc contents of wheat grain were analyzed at Bless Agri Food Laboratory Services P.L.C. in Addis Ababa, Ethiopia (a ISO 17025-2005 accredited laboratory). Crude protein content was determined using Kjeldahl method (AOAC979.09) and iron and zinc contents were determined using atomic absoption spectrophotometry after microwave digestion (AOAC999.10).

2.4. Soil analyses

We analyzed soil for texture (% sand, silt, and clay), pH, microbial biomass, and carbon (C) and N of two SOM fractions: the particulate ($> 53\ \mu m$) fraction and the mineral-associated ($< 53\ \mu m$) fraction. Texture and pH analysis were done at the University of Connecticut soil testing facility. Microbial biomass was estimated using a modified substrate-induced respiration assay (Bradford et al., 2008a; Fierer et al., 2003). Briefly, we added 4 mL of autolyzed yeast to 4 g of dry-weight equivalent soil in 50-mL centrifuge tubes. We shook tubes on a bench-top shaker table for one hour, after which tubes were capped and