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Intensifying rotations increases soil carbon, fungi, and aggregation in semi-arid agroecosystems

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ABSTRACT

Increasing soil organic carbon (SOC) is a critical but daunting challenge in semi-arid agroecosystems. For dryland farmers, low levels of SOC and aggregation exacerbate the risks of farming in a water-limited environment − risks that will compound with climate change. Many dryland farmers in semi-arid climates use year long periods called summer fallow, where no crops are grown and weeds are controlled, to store rainwater and increase the yield of the following crop. In semi-arid climates around the world, dryland farmers are increasingly replacing summer fallow with a crop, a form of cropping system intensification. Cropping system intensification has the potential to increase SOC, but the drivers of this effect are unclear, and may change based on environmental conditions and management strategy. We quantified SOC, water-stable aggregates, and fungal and microbial biomass on 96 dryland, no-till fields in the semi-arid Great Plains, USA, representing three levels of cropping system intensity from wheat-fallow to continuous (no summer fallow) rotations along a potential evapotranspiration gradient. Cropping system intensity was positively associated with SOC, aggregation, and fungal biomass, and these effects were robust amidst variability in environmental and management factors. Continuous rotations averaged 1.28% SOC at 0–10 cm and had 17% and 12% higher SOC concentrations than wheat-fallow in 0–10 cm and 0–20 cm depths, respectively. Aggregate stability in continuous rotations was about twice that in wheat-fallow rotations. Fungal biomass was three times greater in continuous rotations than wheat-fallow, but was not significantly different from mid-intensity rotations. Using structural equation modeling, we observed that continuous cropping, potential evapotranspiration, % clay content, and fungal biomass together explained 50% of the variability in SOC, and that SOC appears to enhance aggregation directly and as mediated through increases in fungal biomass. Overall, the model suggests that cropping system intensity increases SOC both directly, through greater C inputs to soil, and indirectly, by increasing fungal biomass and aggregation. Our findings suggest that continuous cropping has the potential to provide gains in SOC and soil structure that will help offset C emissions and enhance the resilience of dryland agroecosystems.

1. Introduction

Increasing soil organic carbon (SOC) in semi-arid agroecosystems is a critical sustainability challenge for the 21st century. Semi-arid regions, defined as regions with a precipitation to potential evapotranspiration (PET) ratio of 0.2–0.5 (UN, 2011), constitute 20% of Earth's land surface and support a large agricultural population that is under increasing pressure from land degradation and desertification (Bot et al., 2000; Koohafkan and Stewart, 2008). Dryland farming in these regions depends solely on precipitation and uses no supplemental water, which presents a need for, and a challenge in increasing SOC. Warmer temperatures under future climate scenarios will further exacerbate water limitation in semi-arid climates (Ko et al., 2012; USGCRP, 2014). Dryland agriculture contributes to climate change through energy use during its life cycle (e.g. fertilizer production) and emissions of greenhouse gases from soils, but agricultural soils can also sequester carbon dioxide from the atmosphere. Not only are dryland soils an underutilized resource for enhancing C sequestration to mitigate climate change (Lal, 2004), but increasing SOC is also a key climate change adaptation strategy for dryland farmers. Increasing SOC has the potential to mitigate the risks associated with increasing water limitation by enhancing water infiltration and storage (Franzluebbers, 2002). Greater SOC can also enhance soil functions like nutrient provision and retention, substrate provision for biodiversity, and erosion control (Wall, 2012), but increasing SOC in dryland systems is constrained by high erosion rates, low C inputs, and accelerated

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mineralization from tillage (Plaza-Bonilla et al., 2015).

Environmental constraints on C inputs are further exacerbated by the common practice of a year-long period called summer fallow, where no crops are grown and weeds are controlled so that the soil can accumulate rainwater and increase the yield of the following crop. Summer fallow periods have historically helped stabilize wheat yields, but they are inefficient and management intensive. Precipitation storage efficiency is typically less than 35% under best management (Nielsen and Vigil, 2010), and fallow periods require frequent tillage and/or herbicides for weed control. No-till management (where weeds are controlled through herbicides instead of tillage) enhances water storage and enables dryland farmers to replace summer fallow periods with a crop, a form of cropping system intensification. Within no-till systems, cropping system intensification may increase SOC by increasing overall productivity relative to more traditional crop-fallow systems, where a crop is only grown once every two years (Sherrod et al., 2003; Peterson and Westfall, 2004). In semi-arid agroecosystems around the world, dryland farmers are undergoing transitions from crop-fallow to intensified cropping systems (Maaz et al., 2018), in what has been called a revolution in semi-arid cropping (Smith and Young, 2000). This widespread transformation in dryland agroecosystems may have significant implications for C sequestration and enhancing the resilience of dryland agriculture through gains in SOC. However, the mechanisms and extent to which cropping system intensity increases SOC independent of shifts in tillage practices are unclear and may be influenced by climate, soil type, and management strategy.

Given the limited productivity and associated amount of available C inputs to dryland soils, understanding the mechanisms and drivers of how C becomes stabilized is important to slow or reverse losses of SOC. Accrual of SOC can occur when C is protected from decomposition, either through adsorption on soil mineral surfaces, or when it is physically bound in soil aggregates (Jastrow, 1996). Protection of SOC in soil aggregates is a primary mechanism of SOC stabilization in agroecosystems and is highly sensitive to management (Tisdall and Oades, 1982). Several studies have observed the accumulation of SOC in aggregate pools as a significant driver of C accrual during the conversion from conventional till to no-till systems (Six et al., 1999). Similarly, cropping system intensification contributes greater C inputs to soil by replacing fallow periods with a growing crop, and has been associated with greater macroaggregation, microbial biomass, and SOC (Shaver et al., 2003; Peterson and Westfall, 2004; Sherrod et al., 2005; Mikha et al., 2010). Greater root biomass may enhance aggregation via root and associated rhizosphere microbial polysaccharides that contribute to aggregate formation and stabilization (Jastrow et al., 1998).

In addition to the direct influence of greater C inputs on SOC accrual, cropping system intensification may also indirectly enhance SOC through changes in the microbial community (Fig. 1). Fungi, in particular, can contribute to SOC stabilization by physically entangling soil particles in hyphae to form aggregates and by secreting cohesive substances like glycoproteins that enhance aggregation (Wilson et al., 2009). In addition to their role in aggregation, some evidence suggests that fungi may have a higher C use efficiency, and thus retain more C in the soil during the decomposition process relative to bacteria (Waring et al., 2013; Kallenbach et al., 2016; Malik et al., 2016). Due to the different potential functions provided by fungi and bacteria in ecosystem processes, the relatively coarse metric of the ratio of fungi to bacteria in soil is often related to its C sequestration potential (Strickland and Rousk, 2010), and others (Malik et al., 2016) suggest that fungi play a central role in SOC accrual (Fig. 1). Still, the functional importance of the fungi:bacteria ratio remains a point of controversy due to the wide range of functional diversity across both groups, and several lines of evidence have disputed the relationship between fungal dominance and C stabilization (Rousk and Frey, 2015).

Cropping system intensity also influences soil moisture and the availability of C substrates (Farahani et al., 1998b; Sherrod et al., 2003), both of which are strong determinants of microbial community dynamics (Drenovsky et al., 2004). For example, increasing the availability of C substrates by reducing the duration of fallow periods can increase populations of arbuscular mycorrhizal fungi (Thompson, 1987; Harinikumar and Bagyaraj, 1988). Additionally, cropping system intensification is often achieved by growing a greater diversity of crops, and previous studies have linked crop diversity to higher fungi:bacteria ratios and microbial biomass (Lange et al., 2014; McDaniel et al., 2014). However, Acosta-Martinez et al. (2007) found that cropping system intensity increased microbial biomass, but not always fungal biomass, and Stromberger et al. (2007) observed few differences between the microbial community structures of different dryland crop rotations. Further investigation into the effects of no-till crop rotations on microbial communities is needed to understand the potential role of microbes as mediators of C stabilization in dryland agroecosystems.

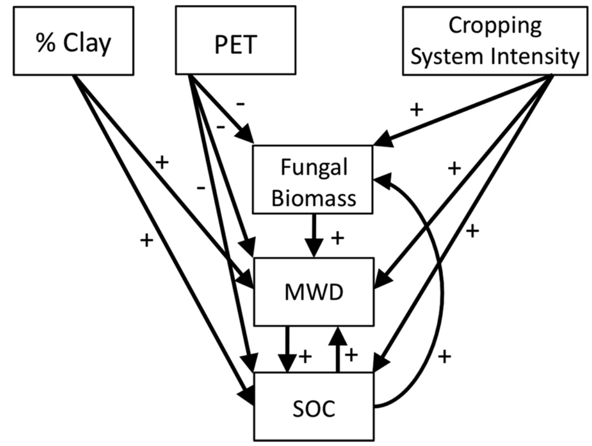

Fig. 1. Hypothesized relationship between cropping system intensity and the mechanistic drivers of SOC accrual as affected by climate, soil texture, and management. Plus and minus signs denote positive and negative relationships, respectively. MWD = Mean weight diameter of water-stable aggregates, PET = Potential evapotranspiration, SOC = Soil organic carbon.

The effects of cropping system intensity on microbial communities and aggregation as drivers of C sequestration may change based on environmental factors like soil clay content and climate (Acosta-Martinez et al., 2003; Sherrod et al., 2003; Peterson and Westfall, 2004). As SOC accrual associated with cropping system intensity has primarily been observed in controlled experimental systems, and mainly considered in combination with reduced tillage (e.g. Norton et al., 2012), further exploration is needed into the extent that cropping system intensification impacts the mechanisms of SOC stabilization independent of tillage and across a range of environmental and management factors.

We conducted a study on dryland, no-till farms and long-term experiment stations in the semi-arid Great Plains, USA that captured a wide range of crop rotations, soil textures, PET rates, and management histories. This allowed us to quantify the potential for cropping system intensification to enhance SOC storage and aggregation relative to traditional crop-fallow systems and to evaluate the relative effects of management, texture, and climate on SOC levels. We hypothesized that increased cropping system intensity would be associated with greater SOC, fungal biomass, and aggregation, and that these trends would be robust across a range of environmental and management contexts (Fig. 1).

2. Materials and methods

2.1. Cropping systems

Wheat-fallow (WF) is one of the most common dryland cropping systems in the semi-arid Great Plains (Hansen et al., 2012). This system consists of growing winter wheat (*Triticum aestivum*) from September to