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A novel soil amendment for enhancing soil moisture retention and soil carbon in drought-prone soils

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ABSTRACT

Crop yield reductions are common in drought-stressed agroecosystems and are likely to become more frequent with climate change. To combat this, soil amendments are often used to enhance soil moisture retention but typically only lead to marginal improvements. Moreover, even as concern over agricultural water use mounts, a large fraction of food is wasted. Diverting more food waste and byproducts back to agricultural fields could reduce waste issues while ameliorating critical water limitations. We evaluated lactobionate, a lactose derivative and major dairy industry byproduct, as a potential soil amendment for enhancing both soil moisture and soil organic carbon (SOC). Lactobionate (LB) is a hydrophilic compound consisting primarily of cations and simple sugar acids. These combined properties could synergistically modify numerous controls on soil-water balances.

In a laboratory setting, we compared LB stabilized with various cations (K^+, NH_4^+, and Ca^+) across a range of soil types to determine LB effects on soil moisture and SOC retention. All LB amendments increased soil water content relative to unamended soil across a range of soil matric potentials and raised available water content by 37%. Additionally, LB amended soils had on average 70 times more microbial biomass and decreased soil inorganic nitrogen content compared to unamended soils. We found that K^+-LB, the most effective amendment, increased soil water content by 100–600% compared to unamended soils and as much as 87% of the increased SOC following LB additions was retained after 2 months. Our results suggest that tapping into novel sources of organic inputs such as LB may be an effective approach for simultaneously enhancing soil moisture and carbon stocks while increasing the economic and energetic value of food production byproducts.

1. Introduction

Crop water stress resulting from dry soils is common, and a key reason that crops rarely approach their genetic yield potential. At the same time, soil moisture limitations in agroecosystems will be aggravated by climate change-driven increases in drought frequency and magnitude in many regions, and irrigation aquifers are being drawn down at unsustainable rates (Ko et al., 2012; Scanlon et al., 2012). Increased climate variability will further destabilize dryland crop production and drive an overall spatial expansion of dryland agriculture (Quinn et al., 2001; IPCC, 2014; Huang et al., 2016). Water-limited agricultural systems are not only vulnerable to reduced crop yields but are often characterized by low concentrations of soil organic matter (SOM) and carbon (SOC) (O'Brien et al., 2010; Robertson et al., 2017). Given that plant inputs are an important source of SOC, depleted soil C stocks often follow soil water limitations if reductions in crop productivity occur (Plaza-Bonilla et al., 2015). Since SOC is a proximate control on soil moisture, soil water retention may thus be further reduced, exacerbating an already water-limited system (Franzluebbers, 2002; Pimentel et al., 2005).

Soil water retention can often be enhanced through the maintenance of crop residues and the addition of amendments including manure, compost, biochar, or engineered gels (Lotter et al., 2003; Narjary et al., 2012; Omondi et al., 2016; Głąb et al., 2018). However, the supply of organic amendments like manure is concentrated in animal production regions and are expensive to transport (Araji et al., 2001). Moreover, many agricultural systems (especially under dryland production) are limited by the amount of available crop residue biomass and too much manure can have unwanted environmental consequences (Singh et al., 2017; Rosenzweig et al., 2018). Other options are expensive, or have limited effects on soil moisture, making for a poor return on investment to farmers at current water prices (Minasny

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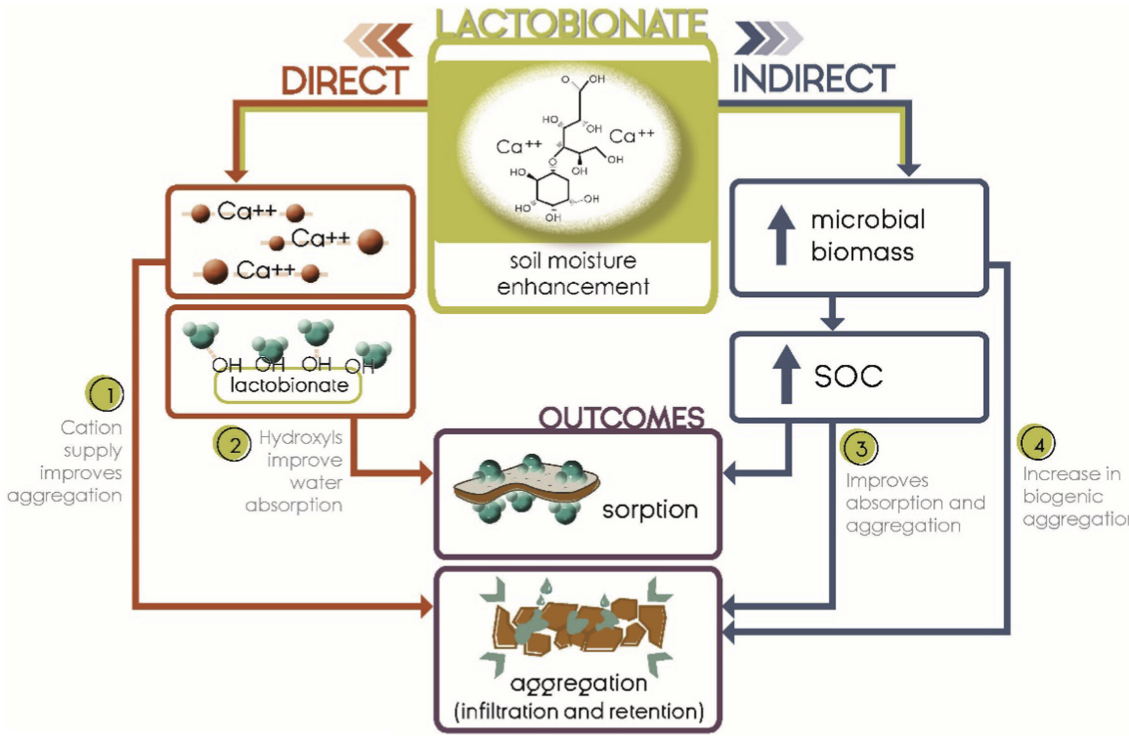

Fig. 1. Depiction of potential direct and indirect impacts of lactobionate on outcomes relevant for soil water content. Lactobionate may directly increase water sorption and aggregation via: 1) cation supply and 2) presence of hydroxyl groups, or indirectly via: 3) increases in soil organic C (SOC) which would support greater aggregation and water sorption, and 4) stimulated microbial activity that could results in higher SOC retention as well as biogenic aggregation through microbial polymeric exudation.

and Mcbratney, 2017). Thus, there is a clear need for new scalable technologies that can enhance soil moisture retention.

The positive effects of amendments on soil moisture are driven partly by subsequent increases in SOC, altering soil structure (e.g., promoting aggregation, modifying pore size), and because of SOC's own water adsorbing capacity (Franzluebbers, 2002; Rawls et al., 2003; Yang et al., 2014; Manns et al., 2016). While higher SOC concentrations typically correspond to improved soil structure, the relationship between SOC and soil water content is highly variable and indeed is not always positive (Rawls et al., 2003; Minasny and Mcbratney, 2017). This may be due to the numerous aspects of soil-water interactions, some of which are independent of SOC. At higher moisture levels, water movement is capillary, driven by pore size and distribution (Or and Tuller, 1999). This regime is likely where SOC will have the greatest impact on soil water (Yang et al., 2014; Karup et al., 2017). In drier soils, soil-water interactions are more a function of sorption and hydration, typically of cations and hydrophilic hydroxyl groups, directly around or within soil particles (Khorshidi et al., 2016). Both these regimes characterizing soil-water interactions can occur simultaneously at intermediate moisture levels (Lu and Likos, 2004; Frydman and Baker, 2009; Khorshidi and Lu, 2017). Novel sources of organic amendments that can capitalize on both soil-water regimes may provide opportunities to increase SOC, while simultaneously enhancing water sorption and particle hydration.

Food waste and food production byproducts are an underutilized resource for novel soil amendments. Even as concerns over agricultural water use mount, we continue to waste a large fraction of the food that is produced. Globally, one third of edible food is lost or wasted, with about 15% lost during food processing (Gunders, 2012; Rutten, 2013). For example, lactose is a major dairy industry byproduct with a global estimated 1.2 M tons produced annually, much of which is wasted (Kowalczyk et al., 2007). The global surplus of lactose has led to the development of value-added lactose derivatives such as lactobionate (LB) but has not yet been evaluated for use in agricultural systems. While diverting food processing byproducts back into agricultural fields may not directly increase calories available for human consumption, it could help close high yield gaps in particularly stressed production systems such as dryland and drought-prone cropping systems.

Here we assess the use of LB as a potential soil amendment for increasing soil moisture. Lactobionate is a unique amendment in that it may modify both capillary and adsorbed water (Fig. 1). Lactobionate is an acidic sugar (gluconic acid and galactose) extracted from whey, which is then stabilized with various cations such as calcium (Ca^{2+}) or potassium (K^{+}). Due to its five hydroxyl groups and one polar carboxyl, it is also a highly hydrophilic molecule that participates in hydrogen bonding, a key mechanism in aggregating soil particles and stabilizing soil C (Gutiérrez et al., 2012). Additionally, the cations associated with LB may be a key property in enhancing both capillary and adsorbed soil water regimes.

In drier soils, the adsorption of water molecules around soil particles is regulated primarily by cation abundance and their hydration (Khorshidi et al., 2016). Soil cations can also directly affect soil structure and aggregation, which are key controls on soil capillary water retention (Guber et al., 2003). The interactions between positively charged cations with negatively charged clay surfaces hold clay particles together, facilitating aggregate formation. For example, it is well known that Ca^{2+} is effective at flocculating clays to help form soil aggregates, improving water infiltration and water movement (Kögel-Knabner et al., 2008; Rowley et al., 2018). As aggregate formation is facilitated by the presence of cations, increased SOC retention may follow. In numerous cases, Ca^{2+} concentrations are strongly related to increases in soil C content, and often more so than clay content in dry soils (Fornara et al., 2011; O'Brien et al., 2015; Rasmussen et al., 2018). Moreover, both monovalent and polyvalent cations facilitate chemical protection of SOC through hydrogen bonding and electrostatic bridging (Rowley et al., 2018), further protecting SOM from microbial breakdown (Whittinghill and Hobbie, 2012). Thus, the hydrophilic property of LB and its associated cations may facilitate water sorption directly to