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Biogeochemical silicon cycle and carbon sequestration in agricultural ecosystems

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ABSTRACT

Global agricultural ecosystems, the largest biospheric sources of atmospheric carbon dioxide (CO_2), may turn into considerable net carbon (C) sinks through adopting management strategies advised by research. As C sequestration is usually coupled with the silicon (Si) cycle, strategic manipulation of the biogeochemical Si cycle in agricultural ecosystems offers a not yet fully explored possibility to enhance C sequestration. This review summarizes current knowledge of C sequestration coupled with the Si cycle and its management in agricultural ecosystems. Carbon sequestration is coupled with the Si cycle through many processes including dynamics of phytoliths and aggregates, and silicate weathering at different temporal and spatial scales. Cultivation of deep rooting crops, erosion mitigation with buffer strips, fertilization of Si-rich materials are some of the potential management strategies to increase both crop production and C sequestration coupled with the Si cycle. Further questions such as identifying the controlling factors of bioavailable Si pools and C sequestration, and quantifying the cost-efficiency of different management strategies to manipulate the Si cycle with the aim to enhance C sequestration should be investigated.

Contents

Abbreviations: (DSi), dissolved silicon; (BSi), biogenic Si; (LSi), litho-/pedogenic amorphous silica; (PhytOC), phytolith-occluded C; (SRO), Si-rich crop organs; (SOC), soil organic carbon; (SOM), soil organic matter.

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1. Introduction

Agricultural ecosystems cover a global area of 15.33 × 10^8 ha and play a key role in the terrestrial carbon (C) balance (Lal, 2004a,b; Piao et al., 2009; Song et al., 2013a). Although global agricultural ecosystems are the largest biospheric sources of atmospheric CO_2 (Houghton et al., 1999; Smith, 2004), they may turn into considerable net C sinks under strategic management (Lal, 2004a,b; Six et al., 2004; Piao et al., 2009; Song et al., 2013a, 2014; Six and Paustian, 2014).

Silicon (Si), an abundant element of the land surface, is of great concern to ecologists, biogeochemists and agronomists. It is coupled with C in many biogeochemical processes including diatom C pump, dynamics of phytoliths and aggregates, and silicate weathering, and thus may regulate long-term atmospheric CO_2 concentration and climate change (Street-Perrott and Barker, 2008; Li et al., 2011; Song et al., 2012a; Struyf and Conley, 2012). Silicon also contributes to crop resistance to biotic (e.g., pathogens and pests) and abiotic (e.g., nutrient imbalances, heavy metal toxicity, salinity and water stress) stresses (Epstein, 1994; Guntzer et al., 2012a; Vandevenne et al., 2012; Zhu and Gong, 2014).

Silicon is particularly prolific (>10 mg Si g^{-1} of dry weight) in many crops including rice (*Oryza sativa*) (Li et al., 2013), wheat (*Triticum* sp.) (Parr and Sullivan, 2011; Gocke et al., 2013), maize (*Zea mays*) (Song et al., 2014), millet (*Panicum miliaceum*) (Zuo and Lü, 2011) and sugarcane (*Saccharum officinarum*) (Parr et al., 2009). Global cultivation and harvest of crops may export 50–100 kg Si ha^{-1} $year^{-1}$ (Meunier et al., 2008) or 220–820 Tg Si yr^{-1} (1 Tg = 10^{12} g, Matichenkov and Bocharnikova, 2001; Carey and Fulweiler, 2012), while the net river export of Si to the oceans has been estimated as 140 Tg Si yr^{-1} (Tréguer et al., 1995). The agricultural export of Si from crop cultivation and harvest may deplete soils' labile Si pools (Meunier et al., 2008; Clymans et al., 2011; Keller et al., 2012; Vandevenne et al., 2012; Barão et al., 2014). Si management in agricultural ecosystems thus offers a possibility to enhance both crop production and C sequestration (Song et al., 2012a).

Despite the importance of Si for multiple crops and the large contribution of agricultural ecosystems to the global C balance, mechanisms and management of Si – C interactions in agricultural ecosystems have not been well documented (Li et al., 2011; Song et al., 2012a). This is the topic of this review. We first introduced biogeochemical Si cycle in agricultural ecosystems. Then, we briefly reviewed three mechanisms of C sequestration coupled with silicon cycle: (1) phytolith C sequestration, (2) organic C stabilization in agricultural soils, and (3) CO_2 consumption from silicate weathering. At the end of these sections, we discussed feedbacks of C sequestration processes under different topographic conditions.

2. Biogeochemical Si cycle in agricultural ecosystems

Cereals and many other cultivated crops are Si accumulators (Datnoff et al., 2001; Ma and Takahashi, 2002; Hodson et al., 2005). In contrast to less managed terrestrial ecosystems, a significant proportion of the Si accumulated in cultivated crops is harvested and does not directly return to the soil (Desplanques et al., 2006; Clymans et al., 2011; Vandevenne et al., 2012; Barão et al., 2014). For agricultural ecosystems, the main Si sources include atmospheric, groundwater, irrigation and fertilization inputs, while the main Si exports include crop harvest, leaching and erosion losses (Desplanques et al., 2006; Clymans et al., 2011; Vandevenne et al., 2012; Barão et al., 2014). The biogeochemical Si cycle in agricultural ecosystems consists of multiple processes and Si pools (Fig. 1).

2.1. Crop Si uptake and phytolith formation

Crops take up Si mainly in the form of monomeric silicic acid [$Si(OH)_4$ or H_4SiO_4] from soil solutions (Mitani et al., 2005; Ma et al., 2006). Silicon accumulation varies significantly among crop species (Hodson et al., 2005; Liang et al., 2006; Mitani et al., 2009; Cooke and Leishman, 2011) as the density of transporter (e.g., SIT1) differs with crop species (i.e. rice > cucumber > tomato) (Mitani and Ma, 2005; Mitani et al., 2005; Ma and Yamaji, 2006). Silicon is concentrated and polymerized to form silica gel in the shoot of crops owing to transpiration (Ma and Yamaji, 2006). Silica gel is finally deposited as phytoliths in the cell wall, intercellular space, and cell luminas (Ma and Yamaji, 2006). The detailed description of plant Si uptake process can be found in recent reviews such as Cooke and Leishman (2011).

Phytoliths contain about 90% of silica, 1 to 6% of organic carbon, and trace amounts of other components such as aluminum and iron (Bartoli and Wilding, 1980; Bartoli, 1985; Alexandre et al., 1997; Parr and Sullivan, 2005, 2011). About 90% of silica in plants is hosted in phytoliths, thus a plant's phytolith content can be estimated from a plant's silica content (Wang, 1998; Song et al., 2013a, 2014). Phytolith content in crops varies with tissue (Li et al., 2013), age (Ma and Yamaji, 2006), species (Perry et al., 2006; Parr and Sullivan, 2005, 2011; Li et al., 2013) and cultivars (Parr and Sullivan, 2011). Within the same plant, the contents of phytoliths in crop sheath and leaf are much higher than those of grain and stem (Li et al., 2013). More phytoliths accumulate in older tissues than in younger tissues because Si is no longer mobile once it has been polymerized and deposited within plants (Ma and Yamaji, 2006). Rice, wheat, maize, and sugarcane accumulate much more phytoliths (>30 mg g^{-1} phytoliths) than other crops (<10 mg g^{-1}) (Hodson et al., 2005; Perry et al., 2006; Parr et al., 2009; Parr and Sullivan, 2011). Among different wheat (*Triticum* sp.) cultivars, phytolith content also varies from 26.8 mg g^{-1} to 78.5 mg g^{-1} (Parr and Sullivan, 2011).

Rice, maize and wheat are the main crops contributing to the global crop phytolith production because of their large distribution areas and high phytolith production fluxes with 617 ± 132 kg ha^{-1} $year^{-1}$, 404 ± 116 kg ha^{-1} $year^{-1}$ and 342 ± 114 kg ha^{-1} $year^{-1}$, respectively (Carey and Fulweiler, 2012; Rajendiran et al., 2012; Song et al., 2014). The global crop phytolith production rate was estimated by Carey and Fulweiler (2012) to be 29.41 Tmol Si yr^{-1} (1764 Tg SiO_2 $year^{-1}$). This value is much higher than the estimates by Rajendiran et al. (2012) (167 to 286 Tg SiO_2 $year^{-1}$) and Song et al. (2013a) (240 ± 66 Tg SiO_2 $year^{-1}$), and these differences can be explained by the use of different data sources.

2.2. Harvest and return of Si

In less managed terrestrial ecosystems, most plant phytoliths are returned to soil either through plant litter fall or root decomposition (Bartoli, 1983; Alexandre et al., 1997). In contrast, a substantial proportion of phytolith produced in crops is taken from the site during harvest (Meunier et al., 2008).

After crop harvest, some phytolith-Si in crop straw and/or roots may be returned directly (Wickramasinghe and Rowell, 2006; Seyfferth et al., 2013; Ngoc Nguyen et al., 2014) or indirectly as biochar-Si (Houben et al., 2014; Liu et al., 2014) to the site. Some harvested Si will be transformed to human and animal waste Si after food/fodder