Chemosphere 145 (2016) 450–456

Contents lists available at ScienceDirect

Chemosphere

journal homepage: www.elsevier.com/locate/chemosphere

Simulation of silicon leaching from flooded rice paddy soils in the Red River Delta, Vietnam

Minh N. Nguyen [a, *], Stefan Dultz [b], Flynn Picardal [c], Anh T.K. Bui [d], Quang V. Pham [a], Than T.N. Dam [a], Cu X. Nguyen [a], Nghia T. Nguyen [e], Hoa T. Bui [e]

[a] Department of Pedology and Soil Environment, Faculty of Environmental Science, VNU University of Science, Vietnam National University, 334–Nguyen Trai, Thanh Xuan, Hanoi, Viet Nam

[b] Leibniz Universität Hannover, Herrenhäuser Straße 2, 30419 Hannover, Germany

[c] School of Public and Environmental Affairs, Indiana University, MSBII, Room 418 N. Walnut Grove Ave, Bloomington, IN 47405-2204, USA

[d] Institute of Environmental Technology, Vietnam Academy of Science and Technology, 18-Hoang Quoc Viet, Hanoi, Viet Nam

[e] Department of Nuclear Physics, Faculty of Physics, VNU University of Science, Vietnam National University, 334–Nguyen Trai, Thanh Xuan, Hanoi, Viet Nam

HIGHLIGHTS

- Vertical transport results in a potential loss of upto 10 ton Si ha^{-1} from paddy soils with two, annual rice-cropping cycles.
- This loss by leaching is about one order-of-magnitude higher than potential rice uptake.
- Our experiments suggest that a strong deficiency of Si might occur near the end of the flooding period.
- A "peak application" of Si during the deficiency stage may be necessary to insure sufficient Si transfer to rice plants.

ARTICLE INFO

Article history:
Received 10 April 2015
Received in revised form
10 November 2015
Accepted 26 November 2015
Available online xxx

Handling Editor: X. Cao

Keywords:
Silicon
Leaching
Paddy soil
Red River Delta
Hydrus-1D

1. Introduction

The importance of silicon (Si) to crops such as rice, sugarcane, and corn has been a subject of recent interest (Guntzer et al., 2012a; Haynes, 2014). The deposition of Si into inter- and intracellular spaces throughout plants' leaves and stems forms silicified structures termed phytoliths. These Si phytoliths contribute increased mechanical strength and resistance to drought (Chen et al., 2011), resistance to pests and fungi (Ma and Yamaji, 2006; Meena et al., 2014; Tripathi et al., 2014), and enhanced photosynthesis (Kato and Owa, 1997). Researchers have highlighted the need to provide crops with supplemental Si in order to moderate yield losses in dryland areas where plant-available soil Si is as low as 10 mg L^{-1} (Berthelsen et al., 2001) and in wetlands where Si can fall to 19 mg L^{-1} (Korndörfer et al., 2001). A challenge to these efforts in wetland areas is identifying "critical" Si levels (the point below which response to Si fertilizer is expected), as the rate and degree to which runoffs affect Si levels through leaching and transport are not well understood (Struyf and Conley, 2008). Calibration of Si loss due to vertical transport is therefore a key factor in improving crop production through Si management.

In rice-cultivation paddies, on-site burning of rice straw after harvesting is the primary method of returning nutrients to the soil. Through this process, the inedible crop matter serves as a Si source (Keller et al., 2012; Seyfferth et al., 2013; Nguyen et al., 2014). However, this plant matter can also be utilized for a range of purposes such as animal fodder or cooking fuel. Where this practice occurs, decreasing phytogenic Si pools in agricultural soils has become a concern (Struyf et al., 2010; Vandevenne et al., 2011; Keller et al., 2012). The flooding of paddy soils, while essential for rice growth, promotes the transport of dissolved compounds through leaching. Given that rice is an Si-accumulator, the need to understand Si cycling in paddy soils is therefore critical to decision making concerning management practices, yet no study to date has

* Corresponding author.
E-mail address: minhnn@vnu.edu.vn (M.N. Nguyen).

http://dx.doi.org/10.1016/j.chemosphere.2015.11.104

quantified Si loss under typical flooding conditions.

Soil-solution Si is understood to derive from dissolution of primary and secondary minerals. In recent years, phytoliths have also been recognized as an important short-term source of Si in soil solution (Fraysse et al., 2006, 2009; Nguyen et al., 2014). Waterlogging conditions may enhance desilification of the phytolith by promoting nucleophilic attack of water molecules that cause breakage of siloxane bonds (≡Si–O–Si≡) (Dove and Crerar, 1990). Released Si in the form of uncharged monomeric silicic acid (H_4SiO_4) can be immobilized by adsorption onto the surfaces of Al and Fe oxides, while the remaining Si in the soil solution can be subject to leaching (Haynes, 2014). However, there have been knowledge gaps in identification of leaching rates and factors that control the behavior and transport of Si, issues that are tightly linked to diminution of Si pool in paddies. This study attempts to quantify Si transport in a 100-cm-deep, flooded rice paddy soil, and to provide an overview of Si fluxes under the leaching conditions of a rice-based cropping system that is of importance for sustainable management of paddy farming.

Models such as HYDRUS, GLEAMS-PADDY, RICEWQ, and VADOFT were developed and have been used to study nutrient management and describe water balances under flooded conditions. Hydrus-1D (Šimůnek et al., 1998) is widely used to simulate solute transport in soils (Seuntjens et al., 2001; Nguyen et al., 2009a; Li et al., 2015). The Hydrus-1D model allows for the description of a water layer at the soil surface, making it suitable for modeling solute transport in paddy fields. In this study, the Hydrus-1D model was applied to describe Si leaching in a paddy soil of the Red River Delta (RRD), the primary region for rice cropping in northern Vietnam. Samples were collected from seven field sites in order to capture variability in soil properties that can affect predictions of Si loss. Sorption coefficients derived from batch experiments represent partitioning of Si between the solid and liquid phases. Data on agricultural rice cropping practices was also collected to develop a conceptual model for Si budget changes in the paddy soil throughout the process of cultivation. From the study results, we developed suggestions for optimizing Si fertilization e.g. by ash application, to ensure sufficient Si transfer for rice production.

2. Materials

2.1. Study site

The study site is in the Thanh Tri district of Hanoi (105°48′55″ E, 20°54′27″ N), exemplifying typical RRD conditions for rice cultivation. The study site covers an area of ca. 80 ha and is located in a lower plain that has been formed from fluvial deposits of the Red River. A dike system was constructed in the 1990s to prevent river water from intrusion into the paddies. The site has been continuously used for rice cultivation for at least 750 years. Site soils are Eutric Fluvisols, and each of the sampled locations have similar geological/pedogenical histories, topography, anthropogenic influences, and climate (tropical wet, hot, and with an average annual rainfall of more than 1600 mm) (see Fig. 1).

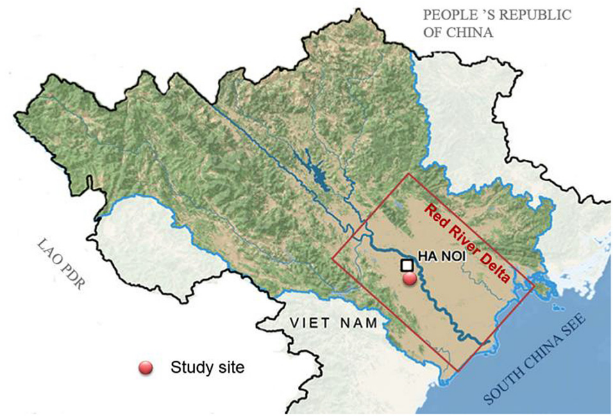

Fig. 1. The study site in the Red River Delta, south of Hanoi. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.2. Water regime and crop and field condition

As is typical of rice cultivation in the RRD, the studied area relies on two-annual rice cropping cycles and a yield of ca. 12 ton ha^{-1} $year^{-1}$. The spring season begins near the middle of January and ends toward the close of April, and the summer season lasts from the beginning of June to the middle of September. The cropping time corresponds to the flooding period lasting from January to August, during which the water table may change from 2 to 10 cm in depth, keeping the soils saturated. Following the spring harvest, the field is kept flooded and almost all rice straw is directly incorporated into the soils. At the end of the summer season, when the paddy fields become dry (and soils are unsaturated), the rice straw from the second harvest is usually burned on site, with products spread on the fields. The field is typically left fallow twice each year, first in May and again from October to December.

2.3. Soil sampling and properties

Soil samples were taken from seven different paddy fields at the beginning of the dry season (October, 2014). In each field, the soil samples were collected from four layers (0–25, 25–50, 50–75, and 75–100 cm in depth). The samples from each layer were air-dried and passed through a 2-mm sieve.

Soil pH values were determined using 0.2 M KCl (w/v = 1:2.5) and ranged from 6.6 to 7.4. These values are close to neutral pH and typical for the Eutric Fluvisols of the RRD. The organic matter contents were quantified using the Walkley and Black wet-oxidation method (Nelson and Sommers, 1996), and varied from 0.62 to 1.03% carbon (C), which is also typical for the often-flooded and reduced paddy soils in Northern Vietnam. Higher C levels observed at the top layer could be a result of irrigation using domestic wastewater with a high organic matter content discharged from Hanoi city (Duc et al., 2007). Analysis of soil texture by the pipette method revealed silt loam as the soil texture of the 25–50 cm layer, and silty clay loam as the texture of the other three layers. Lower clay content in the second layer could be due to the area's long history of flooding, with the top layer experiencing clay illuviation, and clay additions from irrigation water. XRD analysis of the clay fraction (Bruker AXS D5005, Germany) via oriented samples on glass slides revealed soil clay mineralogy dominated by illite and kaolinite. This analysis mirrors previous findings on mineralogical properties of a paddy soil in the Red River Delta (Nguyen et al., 2009b) at a study site approximately 80 km farther south.

Chemical composition (listed in Table 1) was examined using the Particle Induced X-Ray Emission (PIXE) method and a tandem accelerator proton beam (5SDH-2 Pelletron accelerator system, National Electrostatics Corporation, USA, installed at the VNU University of Science, Vietnam National University). The soil samples were dried at 103 °C and positioned in the vacuum chamber using an electromechanical system and a camera for visualization. The pressure inside the PIXE chamber was 10^{-6} Torr throughout the experiments. The X-rays induced by the proton beam were measured using a silicon drift detector with an energy resolution of