A simple approach to assess N load capacity of rice paddy fields in the southern Taihu Lake watershed


ABSTRACT

High nitrogen (N) leaching from irrigated agricultural soils is the result of N input exceeding soil N load capacity (NLC). A simple approach was developed in this research to assess the NLC of paddy soils in the southern Taihu Lake watershed. Paddy soils were classified into four types (Submergenic, Illuvium, Gleyed, and Percogenic) and 28 soil samples representing all four types were collected from across the region. The NLC values of the paddy soils were assessed using a split-line model and the spatial variability of the NLC among various rice paddy soils in the region was also evaluated with Kriging analysis. Results showed the NLC of paddy soils were both soil type and background N content related. The critical N sorption values (NLC plus soil N background) of the Gleyed, Illuvium, Submergenic, and Percogenic paddy soil samples varied from 283.1 to 315.6 mg kg\(^{-1}\), 203.0 to 270.2 mg kg\(^{-1}\), 240.6 to 254.4 mg kg\(^{-1}\), and 177.4 to 186.2 mg kg\(^{-1}\), respectively. However, on average the NLC of paddy soils in the region was 80.3 mg kg\(^{-1}\), and the corresponding environmental N load threshold was around 110 kg N ha\(^{-1}\). Geo-statistic results showed that the NLCs were unevenly distributed throughout the rice paddy dominated areas of the southern Taihu Lake watershed. The NLC assessment approach and spatial distribution information provided helpful guidance to set an environmental N threshold for best N management and hence reduce degradation of water for the whole rice ecosystem.

Key words | China, N application, N load capacity, rice fields, Taihu Lake watershed

INTRODUCTION

Nitrogen (N) is the most limiting nutrient in rice paddy fields, but use of excessive N fertilizer accelerates N leaching. Under these conditions, extra N becomes a contaminant rather than a nutrient and rice paddy soils receiving extra N can switch from being a N sink to a N source (Zhu & Chen 2002; Liang et al. 2007). Many reports have attributed the eutrophication of adjacent surface waters to the N export from agricultural soils where there is a N imbalance, i.e., N fertilization exceeding the soil N load capacity (NLC) (Penuelas et al. 2009; Peng et al. 2011). The NLC of paddy soils is largely dependent on the different soil types involved (Dontsova et al. 2005; Ji et al. 2011). Therefore, it is necessary to investigate the NLC across different rice paddy soils, which may highlight how high N fertilizer application rates can be optimized for particular conditions.

One strategy to determine the NLC is to use a split-line model to find a change point of two linear relationships between added N and N concentration in the soil solution. The split-line model has been successfully employed to develop an environmental threshold of soil phosphorus (P), helping to target remedial P management options of agricultural fields within watersheds (Sharpley et al. 2001; Vadas et al. 2005; Wang et al. 2012). Sharpley et al. (2001) developed a split-line model to find the change point between P loss of surface runoff and soil Mehlich-3 P concentration and subsequently concluded that 200 mg P/kg soil could be identified as the soil P threshold for a watershed in south central Pennsylvania. Vadas et al. (2005) investigated data from eight published articles and found a clear relationship between soil P sorption saturation and filterable reactive P in surface runoff, highlighting that
considered as one of the most important measures to China has been a major rice-producing region for several decades, including both soil nutrient management and dissolved nutrient concentrations in various waters such as surface runoff, leachate, and soil solution, with a greater slope observed above the change points than below them. Thus, this approach can be theoretically extended to assess the environmental threshold for N absorbed by soils such as NH$_4^+$.N or NO$_3^-$.N. Since NO$_3^-$.N in the soil has high mobility and low absorption, the size of soil NLC mainly depends on the NH$_4^+$.N, particularly in flooded and anaerobic paddy systems. We assumed that there was a split linear relationship between N added into the soils and water extracted NH$_4^+$.N, and the change point established in the split lines could provide guidance for sound N fertilizer application in the rice systems.

Furthermore, a spatial analysis can be utilized to scale up the NLC data from tested points to a wide region, which can provide information on whether non-sampled fields in the region exceed their environmental thresholds or not. The ArcGIS-based Kriging method has been one of the most important tools in soil fertility or quality assessments for several decades, including both soil nutrient management and soil pollutant load capacity analysis. For instance, Smith et al. (1995) constructed a soil quality assessment index using multiple-variable Kriging to assess the soil quality under standard conditions. Schepers et al. (2000) studied the spatial heterogeneity of soil P distribution and proposed corresponding improvement measures and a management strategy for fertilization. Schnabel et al. (2004) used log-normal anisotropic Kriging interpolation to estimate environmental thresholds of soil pollutants with less data. Simasuwannarong et al. (2012) investigated the spatial distributions of six soil heavy metals and assessed their health risk using the Kriging method. However, few studies to date have evaluated the spatial characteristics of NLC of regional soils.

At present, agricultural soils in most grain-producing regions of China have a high N status due to continuously high N inputs. On average, the N application rate in China has reached 345 kg N ha$^{-1}$ in paddy systems (Zhu & Zhang 2005). The Taihu Lake region in Southeastern China has been a major rice-producing region for several centuries. However, in recent years, Lake Taihu has been a hyper-eutrophic lake, and reducing N input has been considered as one of the most important measures to control long-term eutrophication and cyanobacterial blooms (Paerl et al. 2011). In fact, many researchers have concluded that excessive N fertilizer in paddy systems is the main contributor of N flowing into the lake. Rice paddies occupy the largest area in the cultivated systems of the region (Xing & Zhu 2000; Zhu & Chen 2002; Roelcke et al. 2004).

In this research, the southern Taihu Lake watershed was selected as a geographical unit. The southern Taihu Lake watershed has an area of 11,600 km$^2$ and is located in northeastern Zhejiang Province, China and has supported rice cultivation for more than 700 years. The average N application rate of this region is close to 300 kg N ha$^{-1}$ while recovery of applied fertilizer N is less than 20% (Wang et al. 2007) and N loss accounted for 5.6–8.3% of applied N (Tian et al. 2007). Therefore, suitable N fertilizer management is urgently needed for this region.

According to the analysis by Zhu (1985), paddy soils can be sub-classified into four types – Submergenic, Percogenic, Gleyed, and Illuvium – based on their different physicochemical variables. We hypothesized that all four paddy soil types can be identified in this region. The objective of this research was to evaluate the NLC among various rice paddy soils on a regional scale. This will provide information for optimal N management practice and help mitigate agricultural nonpoint source pollution.

**MATERIALS AND METHODS**

**Main schedule of regional NLC assessment**

The assessment process of NLC of paddy soils in the southern Taihu Lake watershed is divided into three steps (Figure 1): (1) identification of the distribution of various paddy soils in the ArcGIS interface to establish the distribution layer after rasterization and vectorization; (2) taking representative soil samples in the region, and determining NLCs for the soil samples using a split-line model; (3) spatial interpolation of the sampling coverage areas, rasterizing and vectorizing the results, then multiplying spatial output by the distribution layer from the first step to obtain regional NLCs of paddy soils.

**Geostatistical analysis of paddy soils in the southern Taihu Lake watershed**

Paddy soil distribution in the southern Taihu Lake watershed was geo-statistically analyzed by ArcGIS using...
Landsat TM image and land-use map (1:250,000). In order to further classify paddy soil types, a soil-type map (1:250,000), a topographic map (1:250,000), basic geographic data (boundary lines, water systems, 1:250,000) were employed. The paddy soils were then classified into four types: Submergenic paddy, Illuvium paddy, Gleyed paddy, and Percogenic paddy (Zhu 1985). Characteristics of these four paddy soil types are shown in Table 1.

Soil sampling and NLC analyses

Soil samples were taken from 28 rice paddy fields in the southern Taihu Lake watershed from June to July 2011, before rice planting. These sampling fields represented different paddy soils distributed at Hangzhou, Jiaxing, Yuhang, Wuxing, Deqing, Changxing and Nanxun, respectively, with a distance of around 10–15 km between each field (Figure 2). The latitude and longitude of each sampling site was recorded for geographic information system (GIS) analysis.

Soil samples were sifted using a 2 mm sieve after air-drying and milling. Ten subsamples of 5 g each were weighed and put into 50 mL centrifuge tubes, then adding (NH₄)₂SO₄ solution (200 mg N L⁻¹) and deionized water into tubes to give a series of (NH₄)₂SO₄ concentrations of 0, 12.5, 25, 37.5, 50, 62.5, 75, 100, 150, and 200 mg N L⁻¹, respectively. The final volume was 40 mL for each test tube. After a quick vortex, tubes were stored at room temperature for 3 days to allow the soil to become saturated with N. The supernatant in each tube was removed by pipette, and NH₄⁺-N concentrations in the supernatant and soil extract (2 mol L⁻¹ KCl) were determined using a continuous-flow analyzer (Mulvaney 1996).

The relationship between NH₄⁺-N concentrations in the supernatant and N added was established to accomplish the piecewise linear regression. The change point was determined using a split-line model that describes two linear relationships whose slopes were significantly different from each other (at \( P < 0.05 \)) on either side of a threshold (Sharpley et al. 2001). According to the x-axis value at the change point, the NLC can be identified. The \( r^2 \) values for all regression lines were greater than 0.80 to maximize the accuracy of the change point calculation. In addition, critical N sorption was equal to NLC plus NH₄⁺-N content of the soil background.

Spatial Kriging prediction of NLC on a regional scale

In order to understand spatial characteristics of the NLC in the whole rice paddy covered area, the NLC values from 28 rice fields of the southern Taihu Lake watershed were interpolated by the Kriging method. As a spatial analysis process, normal QQ plot and semivariogram/covariance cloud graphs were drawn to check whether the data follows a normal distribution, anisotropic trend, and spatial correlation. The predicted surface was extrapolated to cover the paddy boundary in the whole region.

RESULTS AND DISCUSSION

Distribution and classification of paddy soil in the region

Rice paddies were the main land use in the southern Taihu Lake watershed, covering 55.2% of the area (64.2 × 10⁴ ha)
(Figure 2). As expected, four main paddy soils, i.e., Gleyed, Illuvium, Percogenic, and Submergenic paddies, were all identified in the region (Figure 2). The Gleyed paddy soil in the region was around $32.9 \times 10^4$ ha, occupying 51.3% of the whole paddy area. The Illuvium paddy soil had a smaller area than the Gleyed paddy soil but also covered $22.7 \times 10^4$ ha. The sum of the above two paddy soils was 86.7% of the total paddy area. Percogenic and Submergenic paddy soils covered just 7.7% and 5.6% of the paddy area, respectively (Figure 3).

NLC of the soil samples

Figure 4 depicts examples of the relationship between N addition and NH$_4$-N concentration in supernatant solution and the individual NLC for each paddy soil type, i.e., the x-axis values at the change points. Based on the critical N sorption values shown in Figure 5, NLC values could be identified as 107.1, 58.7, 80, and 92 mg kg$^{-1}$ at sites 26, 20, 3, and 7 (Table 2), respectively, representing the Gleyed, Illuvium, Submergenic, and Percogenic paddy soils. Moreover, the NH$_4$-N concentrations in the supernatant increased slowly for all of these soils with the increase of N below the change point, then rapidly above the change point, indicating that high N leaching potential will be provoked if N addition exceeds the NLC. The slope value in the later regression line (after NLC has been reached) was similar for each soil, with values around 0.12 to 0.13. However, it was quite different in the initial regression line between the soils, especially between the Gleyed (0.06) and Percogenic (0.02) paddy soils, mainly due to the difference in soil texture (Table 1).

The NLC in individual paddies was also influenced by soil background N content. Because each site had a different background N due to the long-term site-specific N management, the NLCs might be different from each other even if they were classified as the same soil type (Table 2). Notably, the NLC values could not always be calculated by the split-sorption values shown in Figure 5, NLC values could be x-axis values at the change points. Based on the critical N and the individual NLC for each paddy soil type, i.e., the critical sorption values of NH$_4$-$\text{N}$ in all paddy soil samples. The critical sorption values of NH$_4$-$\text{N}$ in the Gleyed, Illuvium, Submergenic, and Percogenic paddy soil samples varied from 283.1 to 315.6 mg kg$^{-1}$, 203.0 to 270.2 mg kg$^{-1}$, 240.6 to 254.4 mg kg$^{-1}$, and 177.4 to 186.2 mg kg$^{-1}$, respectively. These results further suggest that the critical sorption exhibited small ranges within the same soil type but was significantly different between most soil types ($P = 0.01$). On average, the Gleyed paddy soil had the highest value (303.8 mg kg$^{-1}$) of critical N sorption, and the Percogenic had the least (177.8 mg kg$^{-1}$). There was no significant difference in the critical N sorption between the Illuvium and Submergenic paddy soils (Table 5, $P < 0.01$). The higher NH$_4$-$\text{N}$ adsorption ability of Gleyed paddy soil capacity. In rice paddy fields where significant N losses by volatilization and hydrologic factors (e.g., runoff, leaching, lateral seepage) were identified, the NLC results might be overestimated by our approach.

However, this approach could still be considered as a worthy reference to set an environmental N threshold for best N management. For instance, there were two Gleyed paddy soil sites (sites 5 and 6) having NLC values higher than $180$ mg kg$^{-1}$ (Table 2) with investigated soil bulk density and fertilization effect depth of 1.4 g cm$^{-3}$ and 10 cm, respectively. Based on this information, the environmental N threshold, meaning the amount of N that can be added to soil before it is leached, at these two sites could be set at 250 kg N ha$^{-1}$. Fundamentally, this N rate refers to a single N fertilization event. According to the farmer’s N management practice at these two sites, the N fertilization rate in a single event never exceeded 200 kg N ha$^{-1}$. Thus, fortunately, N leaching losses from these two sites is unlikely to be a serious environmental hazard. However, once N fertilizer is added, we cannot ensure that 200 kg N ha$^{-1}$ will be used in a specific rice growing stage or a season. So there is the risk of the left-over N causing problems in the next N fertilizer event and/or the following season. Furthermore, for most sampling sites (75% of total samples), the NLC values were less than 100 mg kg$^{-1}$ and the corresponding environmental N threshold was only 140 kg N ha$^{-1}$. Moreover, the NLC at site 17 was negative, reflecting that this site was excessively rich in N. Those sites with relatively low NLCs should be identified as the hotspots where best N management practice is urgently needed for both mitigating N leaching and maintaining crop productivity.

Theoretically, there is a similar value of critical N sorption (NLC plus soil N background) at the same soil type. Table 2 shows the background, load capacity, and critical sorption values of NH$_4$-$\text{N}$ in all paddy soil samples. The critical sorption values of NH$_4$-$\text{N}$ in the Gleyed, Illuvium, Submergenic, and Percogenic paddy soil samples varied from 283.1 to 315.6 mg kg$^{-1}$, 203.0 to 270.2 mg kg$^{-1}$, 240.6 to 254.4 mg kg$^{-1}$, and 177.4 to 186.2 mg kg$^{-1}$, respectively. These results further suggest that the critical sorption exhibited small ranges within the same soil type but was significantly different between most soil types ($P = 0.01$). On average, the Gleyed paddy soil had the highest value (303.8 mg kg$^{-1}$) of critical N sorption, and the Percogenic had the least (177.8 mg kg$^{-1}$). There was no significant difference in the critical N sorption between the Illuvium and Submergenic paddy soils (Figure 5, $P < 0.01$). The higher NH$_4$-$\text{N}$ adsorption ability of Gleyed paddy soil
Figure 2 | Distribution of rice paddy soils in the southern Taihu Lake watershed and soil sampling sites.
possibly attributed to its clay soil texture with high viscosity and cation exchange capacity (Table 1). This result was supported by Jiang (2004), who found the critical sorption capacities of NH$_4^+$-N across various soils ranged from 200 to 900 mg kg$^{-1}$, and the higher the soil clay content, the stronger the N absorption ability.
Spatial distribution of NLC of paddy soils in the southern Taihu Lake watershed

Normal QQ plot (a) and semivariogram/covariance cloud (b) in Figure 6 show that the NLC data of soil samples had a good normal distribution and space correlation, indicating that the Kriging method could be used with high prediction accuracy rate (Johnston et al. 2003).

Through extrapolation of surface prediction combined with border restriction of paddy soil distribution, the regional NLC of paddy soils was obtained (Figure 7). It showed that the NLCs were unevenly distributed throughout the rice paddy dominated area of the region. As a whole, the eastern part of the region had high NLC values with a range of 150 to 250 mg kg\(^{-1}\), mainly due to the predominance of the Gleyed paddy soil type (Figure 2). Meanwhile, in the mid-eastern part, the NLCs decreased to 100 to 150 mg kg\(^{-1}\), possibly because the dominant soil type was the Illuvium. The middle of the region exhibited NLCs of 50 to 100 mg kg\(^{-1}\) or less, mainly due to the high background N in the soils under long-term high N input. In the western part, where low soil background N was observed (Table 2), the NLC was similar to the high values observed in the eastern counties. However, there were still many ‘white hotspots’ with NLC less than zero unevenly scattered over the region, to which more attention should be paid since they were over-fertilizing and had higher N leaching risk. On average, the geo-statistical result also showed that the NLC of paddy soils in the region was

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80.3 mg kg\(^{-1}\), and the corresponding environmental N load threshold was around 110 kg N ha\(^{-1}\).

**Implication for best N management**

Our results showed that different paddy soil types had different NLC values. In fact, the NLC depended on two aspects. First, it depended on soil texture as soils with higher clay content may absorb more NH\(_4\)+ N. For sandy or silt soils with low clay content, soil N sorption ability could also be improved by modifying soil properties, such as by addition of chemical/biological materials (Dontsova et al. 2005; Jiang et al. 2010; Busscher et al. 2011). Liu et al. (2008) suggested that N sorption increases by 10 to 20% when soil is treated by combined fertilization (NPK or NPK + organic matter) as compared to chemical N fertilizer alone. Moreover, they confirmed that continuous long-term application of chemical N fertilizer alone had negative effects on N adsorption.

Secondly, the NLC relied on how much residual N was left in the soil as background N before rice planting. Accordingly, N inputs in each split fertilization should be more accurately matched to crop N requirements to change soil N rich status and prevent further N losses. One technology that utilized this approach was site-specific nutrient management (SSNM). Field experiments from rice growing regions of China, India, and Bangladesh have indicated that SSNM is an effective tool to reduce fertilizer application rates (Witt et al. 1999; Wang et al. 2001; Dobermann et al. 2003). SSNM practices were designed to take into account indigenous nutrient supply, local weather conditions, reasonable grain yield targets and corresponding nutrient demands for specific rice cropping seasons as well as socioeconomic factors (Wang et al. 2007). When compared to conventional farming practices, average grain yields, economic benefits, and N use efficiency could increase with SSNM by 7–25%, 11%, and 12%, respectively (Wang et al. 2003). In this
research, the NLC assessment approach helped set an environmental threshold of N load for each split N fertilization when the SSNM practice was implemented. Using the spatial distribution information of regional NLC, the N use efficiency can be improved and degradation of water can be reduced in the whole rice ecosystem.

CONCLUSIONS

A simple approach was developed in this research to assess the NLC of paddy soils in the southern Taihu Lake watershed using a split-line model and spatial Kriging analysis. Paddy soils were classified into four types (Submergenic, Illuvium, Gleyed, and Percogenic) according to their different properties. For most collected paddy soil samples, the NLC values could be identified from the x-axis values at the change point of two split lines. Generally, the Gleyed paddy soil with high clay content had higher NLC values than other paddy soils. Moreover, the NLC also depended on the soil background N content resulting from continuously long-term excessive N application. Our NLC assessment approach provided a worthy reference for best N management, and it set an environmental N threshold to each N split fertilization in rice paddy soils. The NLC data of the collected soil samples was also scaled up to the whole rice paddy system in the southern Taihu Lake watershed. The spatial distribution results of regional NLC provided important information on how to increase N use efficiency and prevent degradation of water for this rice paddy dominated region. Further research should use more accurate digital maps and add more sampling sites to improve our results, which would provide more helpful guidance on how to adopt alternative N fertilizations such as combined fertilization instead of urea alone to modify soil properties and increase its NLC value.

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