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Spatial patterns of nitrogen runoff from Chinese paddy fields

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ABSTRACT

Fertilizer additions (N_{rate}) have increased surface runoff of nitrogen (R_{TN}) from croplands, which is eventually transferred to rivers. This pollution further contributes to ecological degradation and and health risks of drinking waters. Despite this recognition, little is known about the spatial pattern of R_{TN} from croplands and the drivers of its variation. On the basis of 210 site-years of measurements at 41 sites in Chinese paddy fields, we examined the nonlinear response of R_{TN} to N_{rate} and the effects of environmental factors on R_{TN}, R_{TN} per unit nitrogen fertilizer additions (RR), and background N runoff (R^0). The results show that (i) R_{TN}-N_{rate} relationship deviates from linearity and the parameters vary by climate and soil attributes; (ii) Observed variation of R_{TN} is better explained by precipitation and clay content (48%) than N_{rate} and its interaction (17%); (iii) The R_{TN} is 1.09 ± 0.36 Tg N yr^{-1} for Chinese paddy fields in 2008, to which R^0 contributes more than 50%, and the corresponding average RR is $6.8 \pm 1.7\%$ ($1-\sigma$), 30% lower than the linear model. This study therefore suggests that the future policies for agricultural N runoff need to account for local environmental conditions rather than solely attempting to reduce N fertilizer applications.

1. Introduction

Nitrogen (N) export from land to rivers is increasing worldwide, particularly in China and South Asia (Seitzinger et al., 2010). Excess N export from cropland is increasing due to the increasing fertilizer additions (Peterson et al., 2001; Beman et al., 2005; Leip et al., 2011). This pollution further stimulates the growth of phytoplankton biomass (Vahtera et al., 2007), the formation of harmful (often toxic) algal blooms (de Vries et al., 2011; Michalak et al., 2013), and hypoxia conditions (Beman et al., 2005; Sutton et al., 2011; Zhou et al., 2014a). Surface runoff is determined primarily by precipitation and irrigation events, and results in a loss of large pulses of fertilizer additions from cropland (Sorooshian et al., 2008). These pulses transport over watersheds and river channels and eventually flow to coastal oceans. Therefore, representing N exports requires the development of spatial continuity between three processes (Alexander et al., 2000; Harrison et al., 2005; Raymond et al., 2012): the in-stream N flux, N attenuation on landscape, and N runoff from croplands (defined as N loss via surface runoff but not leaching and hereafter referred to as R_{TN}). Recent efforts to monitor the former two processes across heterogeneous watersheds or river channels have met with considerable success (Alexander et al., 2000; Seitzinger et al., 2010; Bouwman et al., 2013; Stålnacke et al., 2015). However, large-scale observation data are scarce for runoff pulses from cropland, resulting in a large uncertainty in spatial patterns of N runoff.

Many control experiments have been conducted in relatively small cropland plots in which soil attributes, climate conditions, and management practices are less variable (Xue et al., 2014; Shi et al., 2010; Kurothe et al., 2014). Few observations of N runoff are available for relatively heterogeneous cropland soils (Yu et al., 2010; Syswerda et al., 2012). Consequently, observation data from

Abbreviations: N_{rate}, Nitrogen (N) fertilizer application rate per unit sowing area; γ_k, coefficient for x_k in R^0 term; R_{TN}, N loss only via surface runoff; *c*, intercept in R^0 term; *RR*, R_{TN} per unit N fertilizer additions; ε, model error; R^0, background N runoff; *U*, urea; ΔRR, change in RR per unit of incremental N_{rate}; *Mix*, mixture of various synthetic fertilizers; RR^0, initial value of RR without the impact of fertilization; *OS*, mixture of urea and manure; x_k, environmental factors (soil attribute climates agricultural management); *Pre*, accumulative precipitation within observation period; α_k, coefficient for x_k in ΔRR term; *TN*, soil total nitrogen; *a*, intercept in ΔRR term pH soil pH value; β_k, coefficient for x_k in RR^0 term SOM soil organic matter; *b*, intercept in RR^0 term; *Clay*, soil clay content.

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similar plots are often pooled to increase the sample size to achieve the necessary statistical power (Malve and Qian, 2006; Huang and Li, 2014). Linear regressions are frequently applied on the combined observations for each type of plots (Ministry of Agriculture (MOA), 2007; Velthof et al., 2009; Liu et al., 2010; Wang et al., 2014a). For example, the first national pollution census program of China (NPCP), which was launched in 2007, provided a collection of empirical runoff models of dissolved nitrogen fit to cross-sectional site data for different geographical regions (see supplementary Table A.1; MOA, 2009; Yu et al., 2010; Wang et al., 2014a).

However, the assumption of homogeneity in the response of R_{TN} to N_{rate} (i.e., $R_{TN} = f(N_{rate}, c)$ where N_{rate} and c stand for N fertilizer application rate per unit sowing area and constant coefficient, respectively) is also rarely realistic. There are two important potential sources of error in developing and applying R_{TN}-N_{rate} models. First, multiple lines of evidence from field trials or meta-analysis indicate that R_{TN}-N_{rate} relationships vary in time and space and that this variance can be partly explained by climate (Sobota et al., 2009; Cao et al., 2014), soil attributes (Quinton et al., 2010; Wang et al., 2014b), and agricultural management drivers (Chien et al., 2009; Kiran et al., 2010), and thus the reported range of R_{TN} per unit nitrogen fertilizer additions (hereafter referred to as RR) exceeds two orders of magnitude across cropland plots. Second, linear model (i.e., $R_{TN} = c_1 \cdot N_{rate} + c_3$) assumed that R_{TN} will respond to N_{rate} as a constant function (Lindgren et al., 2007; MOA, 2009; Velthof et al., 2009; Lu et al., 2013). For example, the Intergovernmental Panel on Climate Change (IPCC Tier 1) guidelines suggests a linear relationship of N losses (including both N leaching and runoff) to N_{rate} for the condition when soil water-holding capacity is exceeded or irrigation occurs (IPCC, 2006). However, such model may be the response function that is applicable only over a limited N_{rate} range, because recent field experiments indicate that the responses of R_{TN} to N_{rate} are quadratic or exponential rather than linear (Liang et al., 2005; Booth and Campbell, 2007; Shi et al., 2010; Zhang et al., 2011; Zhang et al., 2012). Overall, proper application of this R_{TN}-N_{rate} relationship for cropland may require a suitable model form (linear vs. nonlinear) and spatial specificity (constant vs. varying coefficients).

China is the largest rice producer in the world (Li et al., 2015). Here, we use a synthesis of N runoff measurements (including both dissolved and particulate TN) from Chinese paddy fields across diverse environmental conditions, to investigate the nonlinear response of R_{TN} to N_{rate} and the effects of environmental factors (x_k) on RR and background N runoff (R^0). The "best fit" model of the R_{TN}-N_{rate} relationship is identified by comparing the different model forms with and without considering its nonlinearity and variability. We also assess how x_k modulates the spatial variations of R_{TN}, RR, and R^0 and discuss the implications for regional budgets of R_{TN} and N fertilizer reduction.

2. Materials and methods

2.1. Dataset

To train the N runoff model for paddy fields, *in situ* measurements of R_{TN}, N_{rate}, and x_k in each plot were collected from experimental stations across Chinese paddy fields. Water samples

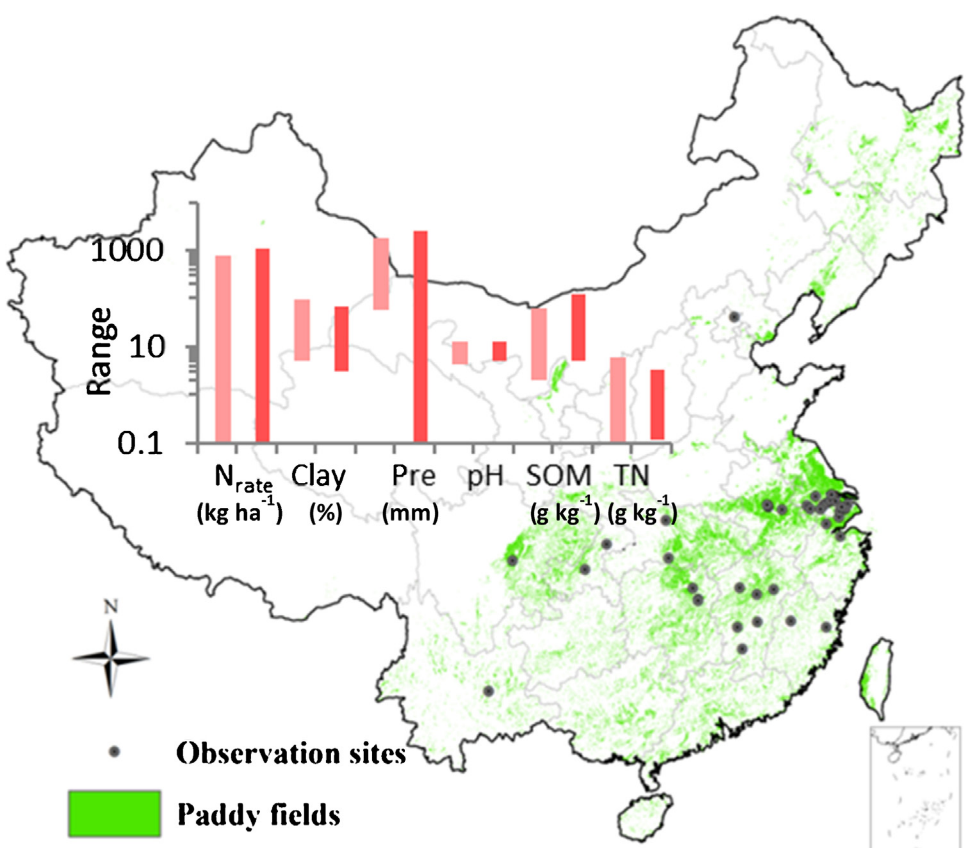

Fig. 1. Location of study sites and data representativeness. The ranges of individual x_k are illustrated as light red bars for observation dataset and dark red bars for whole China's environmental conditions in paddy fields in 2008. x_k includes N_{rate} ($kg\,N\,ha^{-1}$), clay content (Clay, %), precipitation (Pre, mm), soil pH, soil organic matter (SOM, $g\,kg^{-1}$), and soil TN ($g\,kg^{-1}$). Closer ranges of the bars indicate that the observation dataset is more representative of most major rice-production areas. The Y-axis is logarithmic-scaled.