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Cropland abandonment enhances soil inorganic nitrogen retention and carbon stock in China: A meta-analysis

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Abstract

Transforming cropland into a semi-natural ecosystem is an effective approach to increase soil organic carbon (SOC) and nitrogen sequestration. However, we know little about large-scale response patterns of SOC, soil inorganic nitrogen (SIN), and their interactions over long time of ecosystem restoration. Here, we conducted a meta-analysis to examine changes in SOC, SIN, and their relationship along 50 year's ecosystem development from cropland transformation in China's 'Grain for Green' Programme. Our results showed that SOC and SIN were consistently enhanced by 57% and 35% with transformation, respectively. Similar with SOC, SIN had higher response magnitudes when cropland was restored to forests (47%) than to shrublands (36%) and grasslands (24%). Both SOC and SIN response ratios showed a quadratic relationship with precipitation. Moreover, we found a strong linear relationship (R^2 = 0.36) between SOC and SIN response ratio, with the slope indicating a 0.43% increase in SIN per 1% of increasing SOC. This SIN retention capacity (the slope) significantly increased with restoration time but reduced with precipitation, temperature, and initial SOC. Restored forest had a lower SIN retention capacity than had shrubland and grassland. Overall, this study represents the first to regionally uncover SIN retention mechanism with increasing SOC during ecosystem development. It suggests that ecosystem restoration will contribute more to relieving serious environmental problems (i.e., N leaching and N_2O emission) by enhancing SIN retention in China's Grain for Green Programme.

KEYWORDS

carbon sequestration, ecosystem recovery, land use change, soil nitrogen availability, the 'Grain for Green' Programme

1 | INTRODUCTION

Human agricultural activities have become one of the most influential factors for depleting soil organic carbon (SOC; Lal, 2005; Van der Werf et al., 2009). Conversely, transforming cropland into perennial vegetation is an effective way to restore carbon into soil and reduce CO_2 emission (Deng, Liu, & Shangguan, 2014; Guo & Gifford, 2002; Laganiere, Angers, & Pare, 2010). Meanwhile, changes in soil inorganic N (SIN) availability (the sum of soil NO_3^- and NH_4^+ concentration) during restoration influence ecosystem productivity (Elser et al., 2007; LeBauer & Treseder, 2008) and further impact SOC sequestration. Moreover, changes in SIN are generally related to serious environment problems, such as NO_3^- leaching and N_2O emission (Lu et al., 2011; Shcherbak, Millar, & Robertson, 2014). Although the coupling of SOC and total N is reported during ecosystem development (Li, Niu, & Luo, 2012; Yang, Luo, & Finzi, 2011), the dynamics of SOC, SIN,

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and their interactions remain unclear at large scale when cropland is converted into perennial ecosystems, which limits our ability to predict soil C and N balance under land use change.

During ecosystem restoration from cropland abandonment, SOC is commonly enhanced with time due to more plant litter and root input combined with a decline in microbial decomposition and soil erosion (Figure 1; Deng et al., 2014; Laganiere et al., 2010). However, SIN response is complex, depending on the relative magnitude of N fixation, N loss by leaching or gas emission, plant N uptake, and soil N retention (Figure 1; Niu et al., 2016). Although greater plant growth during restoration may increase N uptake and thus potentially decrease SIN (Elser et al., 2007; LeBauer & Treseder, 2008), less N loss from leaching or gas emission with higher soil N retention may maintain enough SIN with ecosystem development (De Vries et al., 2012; De Vries et al., 2012). This in turn implies that soil N retention is a crucial mechanism to determine SIN change during ecosystem restoration. Generally, cropland has a much lower SOC with increasing soil disturbance and crop harvesting than natural ecosystems (Deng et al., 2014). Agricultural soil disturbance significantly enhances soil erosion and then SIN loss (Lu et al., 2011; Murty, Kirschbaum, McMurtrie, & McGilvray, 2002). Moreover, SOC owns a much greater capacity than does mineral soil for holding water and absorbing cations (Lal, 2004; Miller & Donahue, 1990; Simansky & Pollakova, 2014; Tian & Niu, 2015); thus, an increase in SOC during restoration should substantially increase SIN retention capacity by reducing the leaching of NH_4^+ and NO_3^- and increasing their soil absorption (Lu et al., 2011). These suggest that there should be a coupling relationship between SOC and SIN change during ecosystem restoration, with their slope clearly indicating SIN retention capacity due to SOC holding water and absorbing ions (how much SIN retains per unit SOC change). Despite that some biotic processes controlling soil N retention have been formerly detected (i.e., microbial immobilization and mycorrhizal assimilation; Aber et al., 1998; Niu et al., 2016), this abiotic mechanism of SIN retention by increasing SOC has not been tested yet under the context of land use change.

Following cropland abandonment, the response magnitudes of SOC and SIN and SIN retention capacity may be further regulated by soil property, climate factors, and plant functional group. Low soil N availability normally limits plant growth (Elser et al., 2007), which reduces plant litter input and its turnover into SOC, likely weakening SOC and SIN responses. High initial soil carbon is more prone to be decomposed during cropland conversion (Crowther et al., 2016), perhaps weakening SOC and SIN response magnitude with ecosystem restoration. Increasing temperature enhances plant growth and accelerates litter and root turnover (Dieleman et al., 2012; Knapp et al., 2008; Melillo et al., 2011), with a further influence on promoting biological N fixation and N mineralization (Bai et al., 2013; Herridge, Peoples, & Boddey, 2008). These possibly magnify SOC response and increase SIN retention capacity, which together enlarges SIN response. Increasing precipitation often enhances plant growth and litter transformation into SOC (Z. T. Wu, Dijkstra, Koch, Penuelas, & Hungate, 2011), whereas high precipitation accelerates SIN leaching (Lu et al., 2011). Thus, increasing precipitation is expected to aggravate SOC response but decrease SIN retention capacity, contributing to a less SIN response magnitude than SOC. The presence of N-fixing species should enhance SIN and amplify SIN response (Resh, Binkley, & Parrotta, 2002). Conifers have a higher tissue C:N ratio than have broadleaf species (Yang & Luo, 2011), likely limiting N mineralization and attenuating SIN response. Hence, ecosystems differed with environment factors, and plant functional groups potentially have different

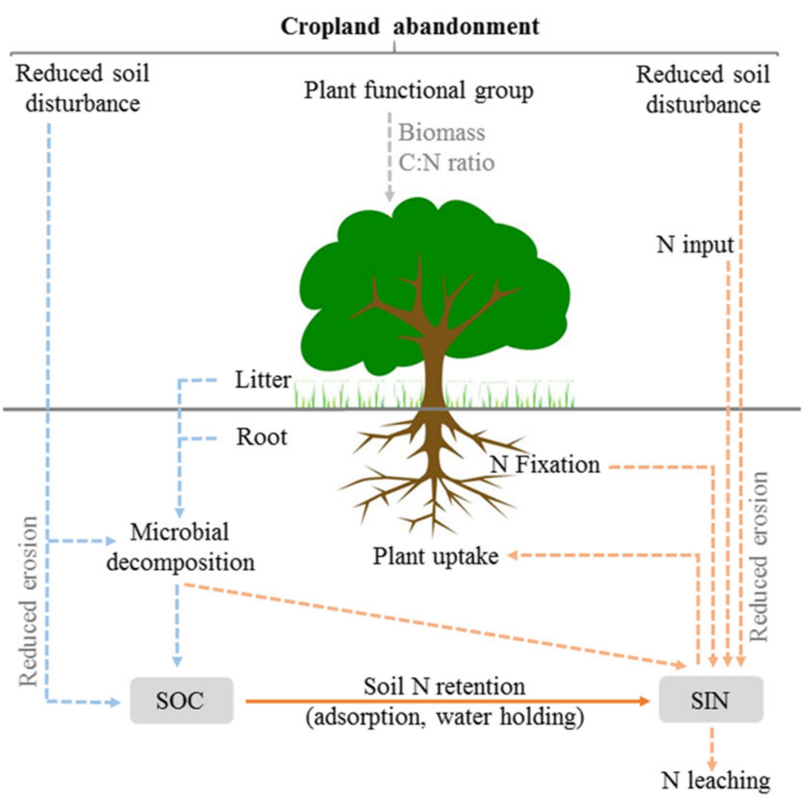

FIGURE 1 Conceptual figure of the processes affecting SOC and SIN response during ecosystem restoration from cropland. SIN: soil inorganic nitrogen; SOC: soil organic carbon [Colour figure can be viewed at wileyonlinelibrary.com]

SOC, SIN response magnitudes, and SIN retention capacity during ecosystem restoration.

In China, long-term intensive agricultural activities have led to severe soil degradation and erosion (Lal, 2002; H. B. Wu, Guo, & Peng, 2003). Thus, from the 1950s, the Chinese Government strived to restore the degraded ecosystems (Fu, Chen, Qiu, Wang, & Meng, 2002). The 'Grain for Green' Programme, one of the largest ecological restoration Programmes in the world, has been implemented to restore cropland into forest, shrubland, or grassland since 1999 (Deng et al., 2014). Under this programme, numerous site-level studies have investigated soil C and N processes during the past 50 years (Deng & Shangguan, 2016; Shi et al., 2016), which provides a good opportunity to synthesize the dynamics of SOC, SIN, and their relationships following cropland abandonment. However, most studies focus on SOC sequestration (Deng et al., 2014; Shi & Han, 2014; Song, Peng, Zhou, Jiang, & Wang, 2014; K. Zhang, Dang, Tan, Cheng, & Zhang, 2010), and less attention is paid to soil N dynamics (Deng & Shangguan, 2016; Zhao et al., 2015). Here, we focus on changes in SOC, SIN, and their interactions. On the basis of the above reasoning, we hypothesize that a strong coupling relationship of SOC and SIN occurs over long period of ecosystem restoration from cropland abandonment. Cropland conversion enhances SOC, SIN, and SIN retention capacity along with restoration time, but their response magnitudes are affected by environmental factors and plant functional groups.

2 | MATERIALS AND METHODS

2.1 | Data preparation

To evaluate the impacts of the Grain for Green program in China on soil C and N dynamics, we searched the publications during 1950–2016 through Web of Science, Google Scholar, and China Knowledge Resource Integrated Database. These publications simultaneously measured SOC and SIN concentrations when cropland was restored into forest, shrubland, or grassland. The literatures were screened according to the following criteria. First, there is a similar condition between cropland and restored sites, such as soil and climate factors. Second, the studies are carried out with paired site, chronosequence, or retrospective design (Deng et al., 2014). Third, soil depth and restoration time are clearly indicated. Fourth, the mean values of examined variables and their sample size are provided. Ultimately, 83 papers were used to establish our dataset generating 295 independent observations (Note S1, Table S1, and Figure S1), with mean annual precipitation ranging from 164 to 3,000 mm and annual temperature from −3°C to 20.5°C. Ecosystem types included forest, shrubland, and grassland, with restoration mode involving natural and artificial recovery and restoration time between 1 and 50 years. Natural recovery allowed ecosystems to develop naturally without any human disturbance, generating plant communities with complex composition. Artificial recovery was that productive plant species were artificially selected and mostly planted in monoculture following cropland abandonment, which resulted in simple species composition communities.

Raw data were collected from either tables or figures in the literature. Data in the figures were acquired using the Engauge Digitizer (Free Software Foundation, Inc., Boston, MA). Due to no significant change in SIN at depth below 20 cm (Figure S2), we focused on examining changes in SOC, SIN, and their relationships at 0- to 20-cm depth. To meet statistical independence, only the measurements of the latest year in each study were considered (L. L. Liu & Greaver, 2010; Lu et al., 2011). Data from different ecosystem types and restoration modes at the same site were regarded as independent observations. For further analysis, the dataset was sorted into various subsets, on the basis of ecosystem type (forest, shrubland vs. grassland; naturally vs. artificially restored ecosystem) and plant functional group (N-fixing species or not; conifer vs. broadleaf species; evergreen vs. deciduous species).

2.2 | Data analysis

Ideally, the calculation for variations in SOC and SIN with land use change is based on equivalent soil mass, not volume due to soil compaction (Barcena et al., 2014; Don, Schumacher, & Freibauer, 2011; Powers, Corre, Twine, & Veldkamp, 2011). Furthermore, the comparison of soil C or N stock across different sites needs to standardize soil depth by the depth functions (Jobbagy & Jackson, 2000; Yang et al., 2011), which possibly induces computed uncertainties over different land uses, ecosystem restoration stages, and so on (Li et al., 2012). Therefore, we analyzed the relative change in percent concentration of SOC and SIN with three strengths. First, relative changes in SOC or SIN concentration are consistent with those in their stock based on equivalent soil mass analysis. Second, the calculation of relative changes greatly increases comparability of results among different soil depths, reducing the uncertainty from depth standardization. Third, we can collect data as much as possible, because many studies provide SOC or SIN concentration but lack the data for bulk density, which are unable to be used for calculating soil C or N stock.

We calculated the relative change in SOC and SIN concentration following cropland conversion as response ratio (RR), $\ln(RR) = \ln(\overline{X}_{treatment}/\overline{X}_{control})$. $\overline{X}_{treatment}$ and $\overline{X}_{control}$ represent the average values of the response variables in restored and cropland plots, respectively. Because about 40% of our data did not have its variance and we tried to include data as much as possible, each observation was weighted by its sample size (Ma & Chen, 2016; Z. T. Wu et al., 2011), $N_{treatment} \times N_{control}/(N_{treatment} + N_{control})$, where $N_{treatment}$ and $N_{control}$ indicate the number of replications for the response variables in restored and cropland plots, respectively. To better handle the independence of observations in each study, a linear mixed effect model was employed to analyze the mean effects [ln(RR)] and their 95% confidence interval of cropland conversion on SOC and SIN at overall level, and these impact with climate factors, soil nutrient, and plant functional groups using the lme4 package (Bates, Maechler, Bolker, & Walker, 2015), with studies as a random effect to explain possible autocorrelation among observations in each study. The predictor variables (i.e., precipitation, temperature, plant functional group, initial SOC, and SIN) were considered as fixed effect. For the continuous predictor variables, we compared linear versus quadratic models based on the Akaike information criterion values (Burnham & Anderson, 2004). Moreover, to evaluate the impacts of environmental factors on the SOC–SIN relationships, we further analyzed the interactive effect of SOC RR and environmental factors on SIN RR. All of the continuous predictor variables were naturally log transformed to meet the assumptions of normality and homogeneity.

3 | RESULTS

3.1 | Changes in SOC and SIN

Overall, our results showed that SOC and SIN were significantly enhanced by 57% and 35% after cropland conversion, respectively (Figure 2), with no significant difference between naturally and artificially restored ecosystems. Significant difference in SOC response was found among different ecosystem types. SOC was increased by 80%, 64%, and 29% when converted to forest, shrubland, and grassland, respectively. SIN also displayed a similar response pattern among forest (47%), shrubland (36%), and grassland (24%). Plant functional groups had no significant impact on SOC response but posed a marginally significant effect on SIN responses, such as N-fixing species present or not (p = 0.082), deciduous versus evergreen tree (p = 0.052), and broadleaf versus conifer tree (p = 0.057).

SOC and SIN consistently elevated with restoration time, with 3.7% and 2.4% increase on average per year for SOC and SIN, respectively (Figure 3). High initial SOC significantly weakened SOC response magnitude, whereas it exerted no influence on SIN response. Temperature and initial SIN did not affect SOC and SIN response. Both SOC and SIN response magnitudes showed a quadratic relationship with precipitation (Figure 4), though the relationship of SIN was not statistically significant (p = 0.105).

3.2 | The coupling relationships of SOC and SIN with changing slopes

Our results revealed a strong linear relationship (R^2 = 0.36) between SOC and SIN RR, with the overall slope equivalent to 0.43 (Figure 5). SOC–SIN slopes did not differ between naturally and artificially restored ecosystems (p = 0.269, Figure 6). Nonetheless, SOC–SIN slopes were significantly higher in restored shrubland and grassland than in forest ecosystems. For plant functional groups, the presence of N-fixing species significantly enhanced SOC–SIN slopes. Nevertheless, their slopes were not affected by tree functional groups, such as deciduous versus evergreen tree (p = 0.200) or broadleaf versus conifer tree (p = 0.214).

SOC–SIN slopes increased with ecosystem restoration time (Figure 7). But they were significantly reduced by increasing precipitation, temperature, and initial SOC. Initial SIN had no significant influence on these slopes.

4 | DISCUSSION

4.1 | Changes in SOC and SIN

Consistent with our expectation and previous studies involved (Deng et al., 2014), we found that SOC increased with restoration time when cropland was converted into forest, shrubland, and grassland. Similar to the important role of afforestation in enhancing SOC sequestration (Deng & Shangguan, 2016; Li et al., 2012), we found that restored forests (80%) had a greater SOC sequestration than had shrublands (64%) and grasslands (29%). Though precipitation does not influence absolute SOC change across China's Grain for Green program (Deng et al., 2014), this study showed a quadratic function of relative SOC

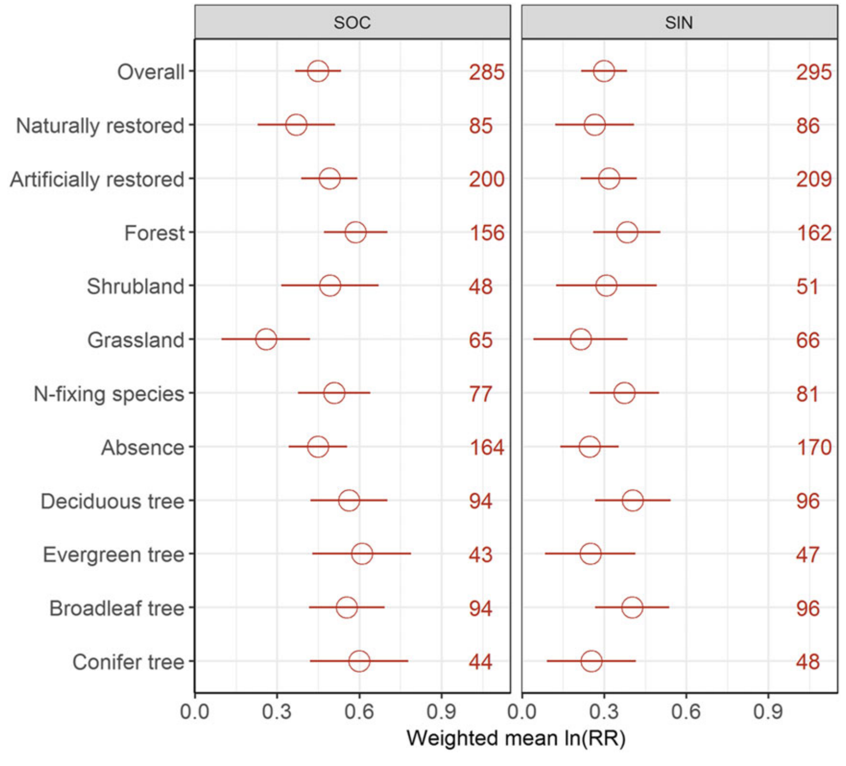

FIGURE 2 Relative changes in SOC (soil organic carbon) and SIN (soil inorganic N) following cropland abandonment at overall and subset levels, such as naturally versus artificially restored ecosystems, forest, shrubland versus grassland, N-fixing species present or not, deciduous versus evergreen tree, and broadleaf versus conifer tree. Circles represent the weighted mean effects with their 95% confidence intervals (CIs). The numbers on the right denote the sample size of the examined variables. If the 95% CI does not cover zero, it shows a significant effect by cropland conversion. RR: response ratio [Colour figure can be viewed at wileyonlinelibrary.com]

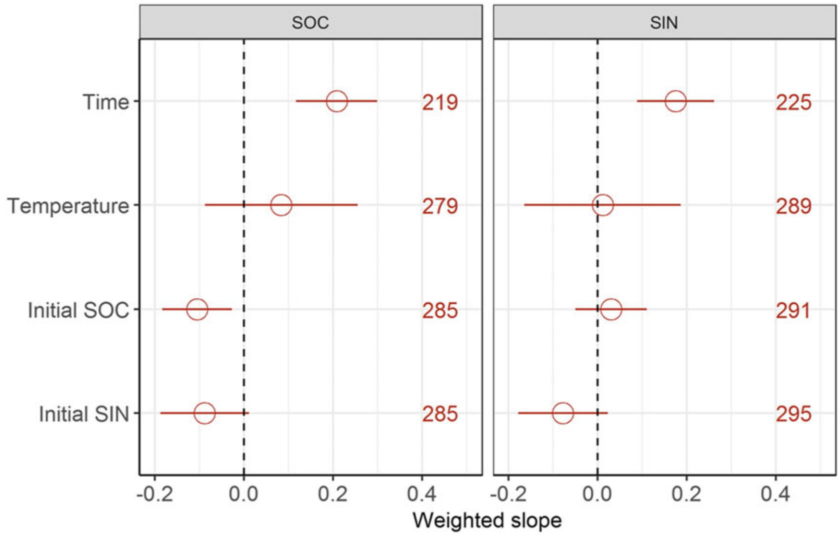

FIGURE 3 Slopes for the relationships of relative changes in SOC (soil organic carbon) or SIN (soil inorganic N) following cropland abandonment with restoration time, temperature, initial SOC and SIN. Circles represent the weighted slopes with their 95% confidence intervals (CIs). The numbers on the right denote the sample size of the examined variables. If the 95% CI does not cover zero, it shows a significant impact by these factors [Colour figure can be viewed at wileyonlinelibrary.com]

change with precipitation. It may be because precipitation below 850 mm mainly promotes plant growth and turning litter and root into SOC sequestration (Z. T. Wu et al., 2011). Nevertheless, precipitation above 850 mm mostly facilitates litter and SOC decomposition (D. Q. Zhang, Hui, Luo, & Zhou, 2008), further attenuating SOC response. In contrast to a previous study that detected a significant impact of tree species on absolute SOC change after cropland abandonment (Deng et al., 2014), we found that plant functional groups, such as N-fixing species present or not, deciduous vs. evergreen tree, and broadleaf vs. conifer tree, did not shift SOC relative changes (Figure 2). It is likely because labile organic matter in litter is gradually degraded with progressive decomposition process (i.e., fragmentation, microbial assimilation, and catabolism) despite species difference in litter quantity and quality (Aerts, 1997; Couteaux, Bottner, & Berg, 1995; Yang & Luo, 2011). It turns out that a very similar proportion of litter (7%) is degraded and formatted into humus regardless of litter types (Schlesinger, 1990; Sollins, Homann, & Caldwell, 1996).

Interestingly, as opposed to our traditional expectation that SIN decreases with active plant growth and increasing soil C:N ratio during

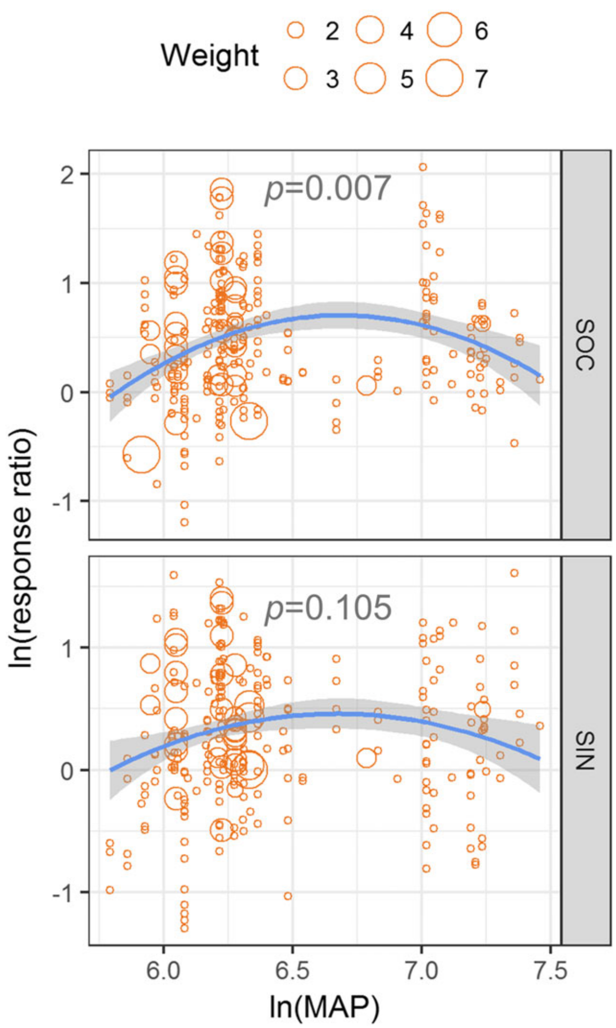

FIGURE 4 Relationships of relative changes in SOC (soil organic carbon) or SIN (soil inorganic N) following cropland abandonment with MAP (Mean Annual Precipitation) [Colour figure can be viewed at wileyonlinelibrary.com]

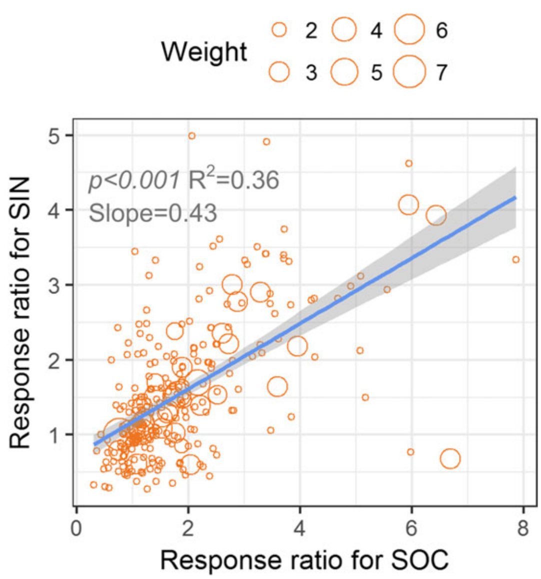

FIGURE 5 Relationships of relative changes in SOC (soil organic carbon) with SIN (soil inorganic N) following cropland abandonment [Colour figure can be viewed at wileyonlinelibrary.com]

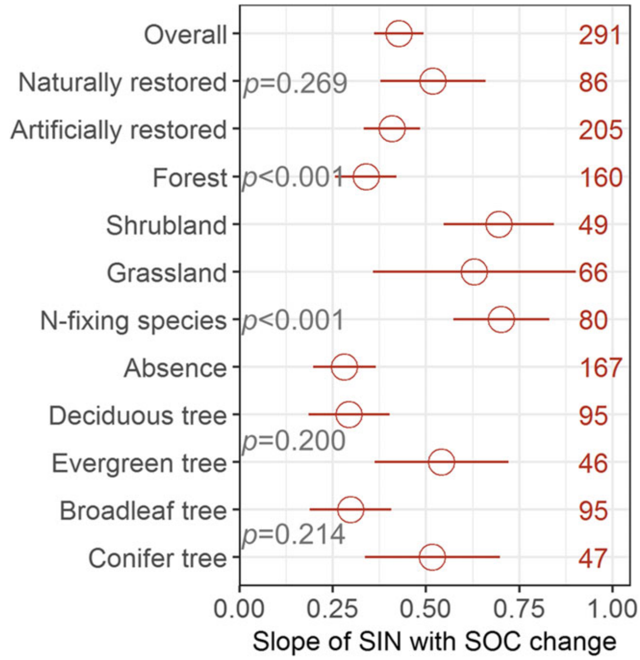

FIGURE 6 Changes in the linear slopes of SOC and SIN response ratio with ecosystem type (naturally vs. artificially restored ecosystem and forest, shrubland vs. grassland) and plant functional group (N-fixing species present or not, deciduous vs. evergreen tree, and broadleaf vs. conifer tree). Circles represent the weighted slopes with their 95% confidence intervals (CIs) at overall and subset levels. The numbers on the right denote the sample size of the examined variables. If the 95% CI does not cover zero, it shows a significant impact by cropland conversion. *p* value indicates the interaction effect of these factors and SOC on SIN change. SOC and SIN denote soil organic carbon and soil inorganic N, respectively [Colour figure can be viewed at wileyonlinelibrary.com]

ecosystem restoration (Cleveland & Liptzin, 2007; Hooker & Compton, 2003; Niu et al., 2016), we found that SIN overall elevated with restoration time following cropland abandonment. This result supports our hypothesis that increasing soil N retention capacity is a dominant driver for SIN changes during restoration (Lu et al., 2011; Niu et al., 2016). Recent studies indicate that when N input is more than 0.8 g m^{-2} yr^{-1}, soil N loss is larger than its retention across 121 forest ecosystems in Europe (Dise, Rothwell, Gauci, Van der Salm, & De Vries, 2009). In China, N deposition increases significantly from 1.32 to 2.11 g m^{-2} yr^{-1} during 1980–2010 (X. J. Liu et al., 2013), which is much greater than the level of 0.8 g N·m^{-2}·yr^{-1} in European forests. These imply that regardless if cropland or restored ecosystems, most of SIN would be potentially leached or lost in gas form under high external N deposition (Niu et al., 2016), which in turn reflects the dominant role of soil N retention in affecting SIN. Moreover, our result is supported by a meta-analysis study, which found that natural ecosystems have a much greater SIN gain than had cropland under N addition experiment (Lu et al., 2011), and also partly supported by a previous result that N stock in trees, litter, and forest floor enhances continuously with forest development (Yang et al., 2011).

More importantly, we found a strong coupling relationship of SIN with SOC change (R^2 = 0.36) during ecosystem restoration at the regional level. Similarly, though a coupled relationship of SOC and total N was previously reported under afforestation, it was mostly due to plant and microbial C:N stoichiometric control (Li et al., 2012; Yang et al., 2011). Our result indicates that increasing SOC is a critical mechanism for SIN retention, especially under high N input. First, it is well known that the water holding capacity of SOC is five times more than that of mineral soil (Lal, 2004; Miller & Donahue, 1990), which largely reduces SIN leaching under high precipitation. Second, the ability of SOC in absorbing ions is 20 times more than that of mineral soil (Miller & Donahue, 1990; Simansky & Pollakova, 2014), further decreasing SIN loss. These together determine the important role of SOC in SIN retention. Similarly, SIN showed a consistent pattern, but less significant, with SOC along precipitation gradient (p = 0.105, Figure 4). This may be caused by the combined effect of SOC and precipitation. Despite the positive effect of increasing SOC on SIN response, more precipitation simultaneously promotes SIN leaching (Lu et al., 2011) and then weakens SOC positive impact, resulting in the less significant pattern for SIN changes. Likewise, the response magnitudes of SIN did not show significant difference among forest, shrubland, and grassland ecosystems, though the SOC magnitudes in grassland were significantly lower than that those in forests (Figure 2). This may be because higher SIN retention capacity in grassland and shrubland, compared with forests, partly compensated their lower increases in SOC (Figure 6).

In addition to SOC retention mechanism, plant functional types also contribute to SIN increase. The presence of N-fixing species tended to increase SIN response magnitude (p = 0.082), which suggests that biological N fixing is a significant source for SIN increase during ecosystem development (Resh et al., 2002). The presence of deciduous (p = 0.052) or broadleaf tree (p = 0.057) also enhanced SIN in comparison with evergreen or conifer tree (Figure 2). This may be because deciduous and broadleaf trees have a lower C:N ratio than have evergreen and conifer tree, respectively (Yang & Luo, 2011), enhancing litter decomposition and then SIN (Cleveland et al., 2014; Silver & Miya, 2001).

4.2 | Changes in SIN retention capacity

Our result showed that the overall slope in the SOC–SIN relationship was 0.43, which indicates a 0.43% increase in SIN retention per 1% increase in SOC. Previous studies on soil N retention capacity mostly focused on the biotic mechanism, such as microbial immobilization, mycorrhizal assimilation, and soil food webs (Aber et al., 1998; De Vries, Bloem, et al., 2012; De Vries, Liiri, et al., 2012; Niu et al., 2016). On the other hand, this study, as one among the first, reveals the abiotic mechanism of SIN retention with increasing SOC under land use change. It suggests that ecosystem restoration from cropland not only enhances SOC sequestration (Shi & Han, 2014; Song et al., 2014) but also reduces SIN loss through increasing SOC. Besides the reduction of CO_2 emission (Deng et al., 2014), this result further reveals the potential role of cropland conversion in decreasing SIN leaching or N_2O emission. This strong SIN retention capacity induced by increasing SOC is largely neglected in previous studies (Niu et al., 2016); we thus suggest that global change C–N model should consider this SOC–SIN coupling relationship, such as land surface model (CABLE, CLM4, EALCO, ISAM, OCN; Zaehle et al., 2014). Moreover,

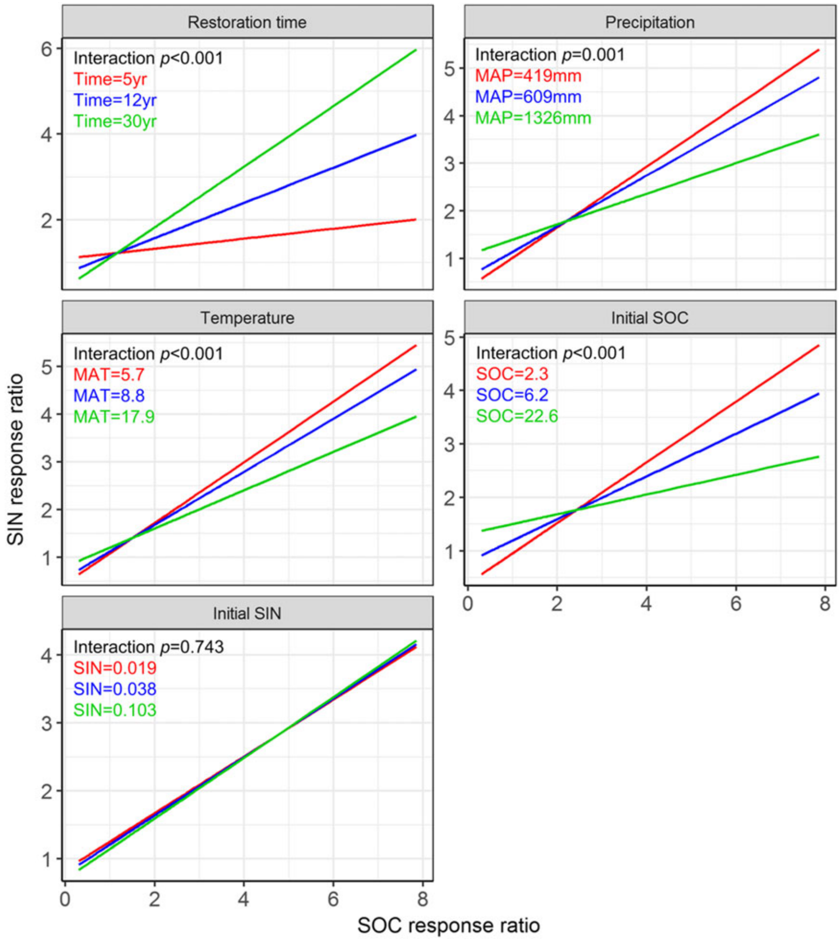

FIGURE 7 Changes in the linear slopes of SOC and SIN response ratio with restoration time, precipitation, temperature, or initial soil nutrient. *p* value indicates the interaction effect of these factors and SOC on SIN change. Based on the 10% fractile, mean, and 90% fractile of the predictor variables, the interaction impact was shown. SOC and SIN denote soil organic carbon and soil inorganic N, respectively [Colour figure can be viewed at wileyonlinelibrary.com]

we found that SIN retention capacity increased continuously with 50 years' restoration time, denoting the important role of long-term restored ecosystems in reducing SIN loss (De Vries, Bloem, et al., 2012; De Vries, Liiri, et al., 2012). Consistent with our expectation, high precipitation and temperature reduced SIN retention capacity, which may be due to the stimulation of SIN leaching by more water under these areas (Lu et al., 2011; Niu et al., 2016).

High initial SOC decreased SIN retention capacity (Figure 7), which in turn indicates that every increase in SOC under low initial SOC is more efficient in retaining SIN (Miller & Donahue, 1990). Initial SIN did not impact SIN retention capacity, which is similar to a previous study that found that SIN can quickly return to ambient level within 2 years after cessation of N addition (O'Sullivan, Horswill, Phoenix, Lee, & Leake, 2011). Soil total N did not affect SIN retention capacity. In accordance with our hypothesis, the presence of N-fixing species enhanced SIN retention capacity, possibly resulting from more biological N fixation retained by increasing SOC (Fisk, Santangelo, & Minick, 2015; Resh et al., 2002). Among different ecosystems, initial SOC was higher in forest (11.55 g kg^{-1}) than in shrubland (10.31 g kg^{-1}) and grassland ecosystems (10.71 g kg^{-1}). Precipitation was higher in forest (738 mm) than in shrubland (552 mm) and grassland ecosystems (647 mm). As our result indicated, together, these lead to a higher SIN retention capacity in shrubland and grassland than in forest ecosystem.

5 | CONCLUSION

This study revealed a ubiquitous increase of SOC and SIN during ecosystem restoration from cropland in China's Grain for Green program. SIN retention capacity was on average a 0.43% increase in SIN per 1% increase of SOC. It indicates that cropland conversion not only is capable of enhancing SOC sequestration but also retains more N by potentially reducing SIN loss in leaching or gas emission. This has important implication that ecosystem restoration may contribute more to alleviating environmental problems than previous studies indicated by suppressing N_2O emission and SIN leaching. Under high precipitation and in forest ecosystem, SIN retention capacity was low, which requires more efforts to reduce SIN loss in these regions (i.e., long ecosystem restoration). Overall, this new mechanism of SIN retention with increasing SOC following cropland abandonment is beneficial to relieve complex environmental problems and sustain SOC sequestration over long time under land use change.

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SUPPORTING INFORMATION

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