A global meta-analysis shows soil nitrogen pool increases after revegetation of riparian zones

Negar Omidvar^{a*}, Zhihong Xu^a, Thi Thu Nhan Nguyen^b, Babak Salehin^a, Steven Ogbourne^c, Rebecca Ford^a, Shahla Hosseini Bai^{a*}

^a Environmental Futures Research Institute, School of Environment and Science, Griffith University, Nathan, Brisbane, Queensland 4111, Australia

^b Faculty of Environment, Hanoi University of Natural Resources and Environment, Hanoi, Vietnam

^c GeneCology Research Centre, School of Science and Engineering, University of the Sunshine Coast, QLD 4558, Australia

*Corresponding Authors:

Negar Omidvar (Email: negar.omidvar@griffithuni.edu.au)

Shahla Hosseini Bai (Email: s.hosseini-bai@griffith.edu.au)

Abstract

Purpose Sustainable management of riparian zone soils is required to ensure the health of natural ecosystems and maintenance of soil nitrogen (N) pools and soil N cycling. However, the effect of revegetation type and age on soil N pools remains poorly understood.

Materials and methods This study compiled data from published articles to understand the effects of revegetation types and age on soil total N (TN) and soil inorganic N ($\text{NH}_4^+\text{-N}$, and $\text{NO}_3^-\text{-N}$) using a meta-analysis. We extracted 645 observations from 52 published scientific articles.

Results and discussion The revegetation of riparian zones led to a significant increase of soil TN (mean effect size: 11.5%; 95% CI: 3.1% and 20.6%). Woodland increased soil TN significantly by 14.0%, which was associated with the presence of N fixing species and high litter inputs. Soil $\text{NH}_4^+\text{-N}$ concentration significantly increased (mean effect size: 20.1%; 95% CI: 15.1% and 25.4%), whereas a significant decrease in soil $\text{NO}_3^-\text{-N}$ (mean effect size: -21.5%; 95% CI: -15.0% and -27.5%) was observed. Of the revegetation types considered in this paper, $\text{NO}_3^-\text{-N}$ concentration in soil followed the order: grassland < shrubland < woodland, suggesting that woodland might be more efficient in soil $\text{NO}_3^-\text{-N}$ retention than grassland. The high plant N uptake and accelerated $\text{NO}_3^-\text{-N}$ leaching in grassland could be related to the decreased soil $\text{NO}_3^-\text{-N}$ in grassland compared with other revegetation types. Revegetation significantly decreased soil moisture by (mean effect size: -7.9%; 95% CI: -3.3% and -12.2%)

compared with the control, which might be associated with the selection of exotic species as dominant vegetation in the riparian zone. Soil TN increased in revegetation ages between 10 and 40 years following revegetation and was related to increased soil organic carbon inputs within those ages following the establishment.

Conclusions This study provides insight into influence of different vegetation types and age on soil N pools and soil moisture. This study also highlights the importance of revegetation in riparian zones to increase soil TN.

Keywords: Soil N cycling, Riparian zone, Revegetation, Woodland, Shrubland, Grassland

1. Introduction

Riparian zones lie at the interface between aquatic and terrestrial ecosystems, and usually have fertile soil, which plays a crucial role in productivity and biodiversity (Naiman et al. 2010; Jiang et al. 2017). However, soil in riparian zones are highly susceptible to erosion, particularly without vegetation (Naiman et al. 2010). Vegetation in riparian zones provides biodiversity enhancement, water quality improvement, temperature and light control and erosion control (Price and Lovett 1999). Riparian zones are currently subject to vegetation loss and degradation due to human activities, intensification of agricultural practices and global climate change (Njue et al. 2016; Hale et al. 2018). Therefore, sustainable management practices are required to revegetate riparian zones and ensure the health of these “natural” ecosystems.

Riparian zone vegetation plays a key role in improving soil nutrient retention, particularly nitrogen (N) (Karjalainen et al. 2001; Schade et al. 2001; Menyailo et al. 2002; Cheng 2009; Ye et al. 2012). Soil N is an important indicator of soil fertility and potential plant growth (Galloway et al. 2004; Atkinson et al. 2010; Bai et al. 2012; Reverchon et al. 2014; Bai et al. 2017), whereas soil N limitation can result in poor plant growth (Bai et al. 2015). Equally, excess soil N leads to many major environmental impacts such as water quality deterioration, eutrophication in aquatic ecosystems and biodiversity loss (DeSimone et al. 2010; Liu et al. 2011; Jacobs and Harrison 2014; Bai et al. 2015). Revegetation of degraded riparian zones influences soil N cycling and may improve soil N retention (Kreiling et al. 2011; Liu et al. 2011). However, a wide variety of factors including environmental factors, soil characteristics (Bateman and Baggs 2005), revegetation types and plant species (Peterjohn and Correll 1984; Knops et al. 2002; Hefting et al. 2005), revegetation age (Deng et al. 2016), and management practices (Räty et al. 2010; Bottrill et al. 2020; Reverchon et al. 2020) influence N cycling in the revegetated lands. However, an understanding of the effects of revegetation on soil N cycling remains limited.

The effects of revegetation on soil N are governed through several mechanisms (Hefting et al. 2005; Ye et al. 2015). These include soil N transformations (i.e., mineralization and nitrification), which are microbially-mediated processes regulated by soil organic matter (SOM) (Bai et al. 2015; Reverchon et al. 2015), soil moisture and soil pH (Dijkstra et al. 2008; Cheng et al. 2011). Revegetation may alter soil properties including SOM input resulting in changes in soil N transformation and cycling (Bardgett and Wardle 2003; Knoepp and Vose 2007; Kreiling et al. 2011; Do Carmo et al. 2012). Vegetation type may also affect soil N cycling due to differences in the quantities and qualities of SOM inputs through plant root exudation and litter production (Knops et al. 2002; Liu et al. 2011). Many studies have obtained contradictory results on the effects of vegetation type on soil N retention efficiency (Peterjohn and Correll 1984; Knops et al. 2002; Hefting et al. 2005). For example, woodland vegetation has been reported to have a greater N retention efficiency than grassland vegetation (Peterjohn and Correll 1984; Hefting et al. 2005). This was proposed to be due to higher N capacity, higher total biomass and the deep root systems of woodland species (Hefting et al. 2005). Other studies report that grassland species create a greater N retention efficiency than woodland species (Groffman et al. 1991; Kuusemets et al. 2001). Grass strips are considered as sediment traps which are able to deposit a large amount of N from surface flow (Peterjohn and Correll 1984). Therefore, it is important to address contradictory results about which types of revegetation would be more effective in soil N retention. Vegetation age is also reported to impact on soil N availability (An et al. 2009), with some studies reporting an increase (An and Huang 2006; Deng et al. 2016), while others report a decrease (Binkley and Resh 1999; Smal and Olszewska 2008) in soil N content with vegetation age. The decrease in soil TN by revegetation age might be due to the slowing down in the leaf production and root biomass when trees are matured (Vitousek and Reiners 1975; Boggs and Weaver 1994; Dosskey et al. 2010). Using meta-analysis, this study aimed to (a) understand the extent in which revegetation types and age affects soil TN, $\text{NH}_4^+\text{-N}$, $\text{NO}_3^-\text{-N}$, soil moisture and pH (b) explore possible mechanisms underlying alterations of soil N in response to revegetation.

2. Materials and methods

2.1 Study data selection and compilation

Literature was examined by searching the online reference databases of Google Scholar, Griffith University Library, and Science Direct using the specific keywords ('revegetation' OR 'restoration of riparian zone') AND ('soil properties' OR 'nitrogen' OR 'mineral N' OR 'inorganic N') AND ('soil') NOT ('meta-analysis') NOT ('review'). Only publications that met the following criteria were included: 1) the experiment had at least three replicates per treatment; 2) the study was conducted under field conditions with experiments conducted in a laboratory (modelling studies) excluded; 3) the original data could be either extracted from the tables and figures or extracted by digitizing

graphs using the software Plot Digitizer version 2.6.2 (Huwaldt 2012); 4) the standard deviation (SD) of the mean was reported or using the reported standard error (SE) and sample size, SD could be extrapolated; and 5) the experiment included natural vegetation or abandoned lands as the control, and the treatments were categorized as revegetation with grasslands, woodland or shrubland. Relevant publications and studies were identified following application of the PRISMA statement (Moher et al. 2009). The final study dataset included 645 observations from 52 published articles in high quality peer-reviewed sources.

The following basic information was compiled from each published paper: name of author, date and location of study, revegetation age, type and depth of soil, type of land use and type of revegetation (woodland, shrubland and grassland, excluding cropland). Soil pH, moisture, total nitrogen (TN), ammonium (NH₄⁺-N) concentration and nitrate (NO₃⁻-N) concentration were collected as “variables”. Variables were subsequently categorised into the following groups: Revegetation type was classified as woodland, shrubland or grassland. The main dominant species employed for revegetation of riparian zones included in our meta-analysis were black locust *or Robinia pseudoacacia* in woodlands, *Caragana korshinskii* and *Hippophae rhamnoides* in shrublands and *Medicago sativa*, *Artemisia gmelinii*, *Artemisia giralaai* and *Stipa bungeana* in grasslands. Revegetation age was classified as <3 years, 3-10 years, 10-20 years, 20-40 years or >40 years. Soil sampling depth was classified into four groups: 0-10 cm, 10-20 cm, 20-40 cm or > 40 cm (Shi et al. 2013; Xu et al. 2019). If the soil samples were collected within different layers of soil as defined here we used the middle depth to identify the category of the soil (Xu et al. 2019). Soil pH was classified into three groups: very acidic pH < 5, acidic 5 < pH < 6 or neutral pH > 6 (Jeffery et al. 2011). Variable data were then unitised as follows:

The pH, measured using CaCl₂ or KCl, was converted to pH (H₂O) using the following formula (Augusto et al. 2006):

$$pH(H_2O) = 1.65 + 0.86 \times pH(CaCl_2) (r^2 = 0.70; p < 0.001), \quad (1)$$

$$pH(H_2O) = 1.96 + 0.74 \times pH(KCL) (r^2 = 0.57; p < 0.001), \quad (2)$$

We only had four studies reporting N stock (tonne/ha⁻¹) that were converted to g/kg using the soil bulk density (g/cm³) and sampling depth (cm). Missing soil bulk density data were estimated from logarithmic linear function $y = -0.0115x + 1.3792$ (S1, Fig.1), which was established with the soil bulk density and SOC content of the reported published literatures (Shi et al. 2013).

2.2 Statistical analyses

The meta-analysis was conducted using MetaWin Version 2 statistical software (Rosenberg et al. 2000) to determine changes in soil chemical properties after revegetation under different revegetation types. The data extracted was the mean of the control, the mean of the treatment, and the standard deviation (SD) or standard error (SE). Where no SD was reported, the SD was calculated as follows:

$$SD = SE \sqrt{n}, \quad (3)$$

Where SE is the standard error and n is the sample size. Where needed, the corresponding author was contacted to provide more information and clarification.

The effect size was calculated using the natural log-transformed response ratio (RR):

$$\ln RR = \ln \left(\frac{X_T}{X_C} \right), \quad (4)$$

Where X_T is the mean of the treatment and X_C is the mean of the control group.

The following equation was used to calculate the variance (v) in $\ln RR$:

$$v = \frac{SD_T^2}{n_T X_T^2} + \frac{SD_C^2}{n_C X_C^2}, \quad (5)$$

Where SD_T and SD_C are the standard deviations of treatment and control, respectively, and n_T and n_C are the sample sizes of treatment and control, respectively. The effect size of each group was calculated using a categorical random effects model in MetaWin version 2. In this model, the effect size was weighted in inverse proportion to its variance (Adams et al. 1997). Bootstrapping (999 intervals) was used to generate mean effect size for each group with a 95% confidence interval (CI) (Rosenberg et al. 2000). The effect size was converted to % change with the following formula (Cayuela et al. 2013):

$$\% \text{ Change} = (e^{\ln RR} - 1) \times 100, \quad (6)$$

If the 95% CI for a given variable overlapped with zero, the treatment was considered not significantly different from the control ($p > 0.05$) and was considered significantly different if the 95% CIs did not overlap with zero ($p < 0.05$) (Luo et al. 2006).

A significant between-group heterogeneity test (Q_b) of the random effect model was used to test the heterogeneity among categories. Differences among categories were considered significantly heterogeneous when $P < 0.05$

(Borenstein et al. 2011) (Table 1). The funnel plot statistics and fail-safe numbers technique were used to test the effects of publication bias and the robustness of the meta-analysis (Rosenthal and Rosnow 1984; Rothstein et al. 2005) (Table 2). When the funnel plot statistics (Kendall's Tau and Spearman Rank-Order Correlation) were significant ($P < 0.05$), the fail-safe number was applied which were then compared with the tolerance level ($5n + 10$) (n is the number of observations) (Long 2001). Fail-safe numbers greater than the tolerance level shows the reliability in the significance of meta-analysis results (Long 2001) and indicates the dataset has not been affected by publication bias (Deng et al. 2017). In addition to the meta-analysis, a linear regression was performed to examine the relationship between SOC and TN in soil. IBM SPSS Statistics (version 26) was used for the statistical analyses.

3. Results

3.1 Overview of the meta-analysis

Revegetation of riparian zones, independent of revegetation type, age and sampling depths, led to a statistically significant increase in soil TN (mean effect size: 11.5%; 95% CI: 3.1% and 20.6%). Soil $\text{NH}_4^+\text{-N}$ concentration significantly increased (mean effect size: 20.1%; 95% CI: 15.1% and 25.4%) whereas there was a significant decrease in soil $\text{NO}_3^-\text{-N}$ (mean effect size: -21.5%; 95% CI: -15.0% and -27.5%). Revegetation significantly decreased soil moisture by (mean effect size: -7.9%; 95% CI: -3.3% and -12.2%) compared with the control (Fig. 1).

3.2 Influence of revegetation type on soil TN, $\text{NH}_4^+\text{-N}$ and $\text{NO}_3^-\text{-N}$

On average, revegetation resulted in significant increases in soil TN by 10.9% compared with the corresponding control (Fig. 2a). Woodland significantly increased soil TN by 14.0%. No significant differences were observed within different revegetation types (Fig. 2a).

Soil $\text{NH}_4^+\text{-N}$ was significantly increased in all three revegetation types by 20.1% compared with the corresponding control (Fig. 2b). The magnitude of the increase was significantly less in woodland with a 9.8% increase, compared with shrubland (37.1%) and grassland (34.5%) (Fig. 2b).

Soil $\text{NO}_3^-\text{-N}$ was significantly decreased in all three revegetation types by -21.5% compared with the corresponding control (Fig. 2c). Soil $\text{NO}_3^-\text{-N}$ was significantly reduced the least in woodland (-13.9 %), and shrubland (-16.6 %) and the most in grassland (-54 %) compared with the control (Fig. 2c). There was a significant difference between the decrease in $\text{NO}_3^-\text{-N}$ in grassland and that in the other types of revegetation (Fig. 2c).

3.3 Effect of revegetation age on soil TN, $\text{NH}_4^+\text{-N}$ and $\text{NO}_3^-\text{-N}$

No changes in soil TN were observed before 10 years or after 40 years of revegetation compared with the corresponding control, but a significant increase in soil TN occurred between 10 and 40 years of revegetation compared with the control (Fig. 2d). Woodland had a significant effect on the magnitude of soil TN increase between 20 and 40 years following revegetation (Table 3).

No changes in soil $\text{NH}_4^+\text{-N}$, regardless of revegetation type, were detected before 3 years or after 40 years following revegetation compared with the corresponding control (Fig. 2e). However, a significant increase in soil $\text{NH}_4^+\text{-N}$ was detected between 3 and 40 years following revegetation compared with the control (Fig. 2e). Specifically, there was a 35.3% increase between 3 and 10 years, 29.0 % between 10 and 20 years, and 17.1% between 20 and 40 years (Fig. 2e). Grassland had no significant effect on the magnitude of increase (Table 3).

A revegetation age of <20 years significantly decreased soil $\text{NO}_3^-\text{-N}$, increasingly less with 3-10 years following the revegetation. Whereas the revegetation age of >20 years significantly increased soil $\text{NO}_3^-\text{-N}$ (Fig. 2f).

3.4 Effect of soil depth on soil TN, $\text{NH}_4^+\text{-N}$ and $\text{NO}_3^-\text{-N}$

No significant changes in TN were observed in the >20 cm soil depth compared with the control, whilst soil TN was significantly increased by 24.5% and 7.1% in the 0-10 cm and 10-20 cm of soil depths respectively (Fig. 2g). Woodland resulted in a significant increase in soil TN in the 0-10 cm soil depth, while in the 10-20 cm soil depth, all types of revegetation caused a significant increase in soil TN (Table 4)

The effect of revegetation on soil $\text{NH}_4^+\text{-N}$ was positive in all of the observed soil depths, with a significant increase observed in the 0-10 cm (29.9%) and 10-20 cm (18.0%) soil depths regardless of revegetation type (Fig. 2h). Woodland and shrubland vegetation resulted in a significant increase in soil $\text{NH}_4^+\text{-N}$ in the 0-10 cm soil depth, while in the 10-20 cm soil depth in shrubland only, caused a significant increase in soil $\text{NH}_4^+\text{-N}$ (Table 4).

On the other hand, revegetation led to a significant decrease in soil $\text{NO}_3^-\text{-N}$ in the 0-10 cm (-18.1%) and in the 10-20 cm (-46.5%) soil depths regardless of revegetation type (Fig. 2i). Woodland resulted in a significant decrease in soil $\text{NO}_3^-\text{-N}$ in the 0-10 cm soil depth, while in the 10-20 cm soil depth, all types of revegetation caused a significant decrease in soil $\text{NO}_3^-\text{-N}$ (Table 4). Soil $\text{NO}_3^-\text{-N}$ significantly increased in the 20-40 cm (73.9%) and in the >40 cm soil depths (70.1%) (Fig. 2i). Woodland significantly increased soil $\text{NO}_3^-\text{-N}$ in the >40 cm soil depths (Table 4).

3.5 Effect of revegetation on soil moisture and pH

In general, revegetation decreased soil moisture by -7.6% compared with the corresponding control (Fig. 3a). Woodland and grassland had no significant effects on soil moisture and shrubland significantly decreased soil moisture by -10.43% (Fig. 3a).

No changes in soil moisture were detected before 3 years or between 20 and 40 years or after 40 years of revegetation regardless of revegetation type, but soil moisture significantly decreased between 3 and 20 years of revegetation compared with the corresponding control (Fig. 3b). There was a -27.7% decrease between 3 and 10 years and -9.2 % between 10 and 20 years following revegetation (Fig. 3b). All revegetation types were responsible for significant decreases in soil moisture between 3 and 10 years following revegetation (Table 5). No significant changes in soil moisture, regardless of revegetation type, were observed in 0-20 cm soil depth whereas a significant decrease was detected in the >40 cm depth (-25.1%) (Fig. 3c). All types of revegetation caused significant decreases in soil moisture in the >40 cm depth (Table 6).

Revegetation with shrubland or woodland had no significant effect on soil pH but revegetation with grassland significantly increased soil pH by 4.9% compared with the corresponding control (Fig. 3d). Soil pH did not significantly change <3 years or between 10 and 40 years following revegetation, but, a significant increase (9.5 %) was detected between 3 and 10 years and a significant decrease in soil pH (-7.9 %) was detected >40 years (Fig. 3e). Woodland had no significant effect on the magnitude of increase in pH between 3 and 10 years following revegetation, but did significantly affect the magnitude of decrease after >40 years of revegetation (Table 5). No significant differences in soil pH were observed among any of the soil depths assessed (Fig. 3f). A publication bias for the result of soil pH (revegetation types, age and soil depths) were suggested by the fail-safe number (Table 2).

3.6 Relationship between SOC and TN

A linear regression was performed to indicate the relationship between the changes in SOC and TN following revegetation of riparian zone. Subsequently, changes in TN were positive correlated with changes in SOC ($R^2 = 0.69$, $n = 259$, $p < 0.05$). (Fig. 4).

4. Discussion

In general, revegetation of riparian zones led to a significant increase in TN (11.5%), a significant increase in soil $\text{NH}_4^+\text{-N}$ (20.1 %) and a significant decrease in soil $\text{NO}_3^-\text{-N}$ (-21.5 %) concentration regardless of revegetation types compared with the corresponding controls. Soil TN and $\text{NH}_4^+\text{-N}$ did not differ among revegetation types but grassland had lower soil $\text{NO}_3^-\text{-N}$ concentration compared with the woodland and shrubland.

4.1. Changes in soil TN following riparian zone revegetation

Our study showed that revegetation significantly increased soil TN. The quality and quantity of litterfall inputs and vegetation cover types are linked to soil TN and SOC (Vitousek et al. 1994; Vigulu et al. 2019). Increased SOM inputs to the soil result in stimulation of microbial biomass and activity, which in turn increased soil N pools (Liu et al. 2019). In our study, increases in soil TN after revegetation was also supported by the positive relationship observed between soil TN and SOC ($R^2 = 0.69$, $n = 259$, $p < 0.05$). We also found that woodland significantly increased TN compared with the control, which was not the case for grasslands and shrublands. Shade provided by the vegetation can facilitate litter decomposition compared with unshaded areas (Ofori-Frimpong et al. 2007). In our study, woody species might have provided optimal shade leading to accelerated litter decomposition which would explain increased soil N pools. Litter quality also drives N return to soil (Seneviratne 2000; Vigulu et al. 2019). Litter in communities with N fixing species usually has soil with high N concentrations (low C: N ratio) due to their ability to fix N (Xu et al. 2014; Jin et al. 2016). The dominant species in woodlands in our study was *R. pseudoacacia* which is an exotic species and is commonly used as artificial woodland plantation in riparian restoration. Planting *R. pseudoacacia* in revegetation is popular due to high growth rate, capacity of symbiotic rhizobium bacteria to fix N and improve N availability in soil (Xu et al. 2014; Jin et al. 2016; Liang et al. 2018). Previous studies have demonstrated that *R. pseudoacacia* has a high rate of biological N fixation (Boring et al. 1984; Danso et al. 1995) and their leaves are also rich in N (Cierjacks et al. 2013; De Marco et al. 2013). Hence legume litters increase soil N when decomposing compared with non-legume species (Seneviratne 2000). Our study highlighted the importance of revegetation type to increase soil TN in riparian zones.

Our study showed that soil TN significantly increased between 10 and 40 years following revegetation establishment. Soil TN may decrease at initial stages of revegetation due to high N uptake from soil to support plant growth and low N input (Mao et al. 2010; Li et al. 2012; Liu et al. 2018). Our studies did not show a significant decrease in TN during > 10 years following revegetation. However, a high within data variation in soil TN was observed in our study for those data were related to > 10 years following revegetation. SOC and TN input to the soil through plant litter production and root residues increases when plants growth and biomass accumulations are

slowed down over time (Hooker and Compton 2003; Xu et al. 2014). Soil enzyme activity also increases by revegetation age, which in turn increases soil N retention (Wang et al. 2012). Increases in plant biomass by revegetation age may also lead to increased root density, which in turn increases soil enzyme activity (Wang et al. 2012) and dead roots are an additional source of N inputs to the soil. Hence, increased TN between 10 and 40 years of revegetation might be attributed to increased belowground and aboveground biomass, increased litter accumulation on the floor and subsequent increased litter decomposition (Xu et al. 2014). Additionally, species composition can also be one of the main driving factors to increase soil TN as revegetation ages. For example, N fixation in legume species such as *R. pseudoacacia* increases soil N pools over the revegetation age increase (Wang et al. 2012). A study has reported that a plantation of *R. pseudoacacia* at ages between 30 and 38 years has more soil TN content compared with that of ages between 10 and 15 years (Liu et al. 2018). Our study showed that revegetation age more than 40 years did not significantly increase soil total N. The dominant species in woodlands in our study was *R. pseudoacacia* which is an exotic species and is commonly used as artificial woodland plantation in riparian restoration. The *R. pseudoacacia* plantations take almost 25-30 years to reach maturity, and then experience a decline in both density and canopy cover (Wang et al. 2012; Kou et al. 2016). Decreased plant density and canopy cover have been associated with decreased soil N due to decreased organic matter inputs (Burger et al. 2010; Kou et al. 2016; Xu et al. 2020). We believe that species composition is a potential factor accounting for a lack of significant change in revegetation after 40 years. Additionally, there was also a high within-data variation and a limited number of studies for the above 40 years category, meaning caution should be made when interpreting the related results.

4.2. Changes in soil NO_3^- -N following the riparian zone revegetation

Our results suggested that woodland might be more efficient in soil NO_3^- -N retention than grassland. Soil NO_3^- -N can be controlled by both nitrification and denitrification (Bateman and bags 2005). Denitrification is driven by increased soil moisture (Liu et al. 2011; Xiong et al. 2017). Higher soil moisture can reduce oxygen diffusion, hence provides a favourable environment for denitrification (Xiong et al. 2017). We observed a decreased in soil moisture and hence denitrification could not explain decreased NO_3^- -N in our study. Soil pH can control soil N nitrification (Paul and Clark 1989; Curtin et al. 1998). We found an increase of pH in grassland. Increased soil pH stimulates microbial nitrification (Li et al. 2014). The SOC dissolubility increases in high soil pH, and thus promotes the activity of nitrobacteria in soil, thereby increasing nitrification (Curtin et al. 1998). However, nitrifying bacteria are more active in pH 7 to 8.5 (Allison and Prosser 1993). The average pH in the observed grassland was 7.3. Our study showed a 4.9% increase in soil pH in grassland (average 0.2 unit increases in pH), but our conclusion from pH

should be carefully considered to avoid over interpretation because our pH results suffered from a publication bias. In our study, decrease in NO_3^- -N was accompanied by increase of NH_4^+ -N in grasslands, which suggested the substrate was not limited for nitrification. Thus, we could suggest that the pH increases may not be biologically significant to stimulate nitrification.

Other factors can also affect NO_3^- -N concentrations (Dhondt et al. 2004; Sahrawat 2008). For example, rapid plant growth and high N uptake by plants lead to decreased NO_3^- -N accumulation in soil of grassland compared with woodland and shrubland (Jackson et al. 1989). However, the grasslands have lower above-ground biomass and shallower root systems than woodland and shrubland. Shallow rooted plants are less efficient at controlling soil NO_3^- -N leaching than those of deep rooted plants (Neilen et al. 2017). We also observed an increased NO_3^- -N concentration in deeper layers of the soil in woodlands, which was not the case in grasslands (95.9 vs. -16.5%, respectively). The high concentration of NO_3^- -N in the soil profile of woodlands could suggest a NO_3^- -N retention by woodlands. Therefore, a combination of high N uptake and accelerated NO_3^- -N leaching in grasslands could have been two of the main driving factors for NO_3^- -N decreases in grasslands.

4.3 Changes in soil moisture following riparian zone revegetation

In the present study, revegetation significantly decreased soil moisture by -7.9% compared with the corresponding controls, regardless of revegetation type or age. Our finding is consistent with those that reported a decrease in soil moisture following revegetation (Deng et al. 2016; Liang et al. 2018). Different vegetation types affect soil moisture differently due to different water consumption characteristics (Xiao et al. 2014). Species compositions with various root distribution have been associated with soil moisture alteration (Deng et al. 2016) and the rate of evaporation (Wang et al. 2001; Xiao et al. 2014). Shrubland significantly decreased soil moisture compared with the corresponding control. In our meta-analysis study, the dominant species employed for revegetation of riparian zone included black locust or *R. pseudoacacia* in woodlands, *C. korshinskii* and *H. rhamnoides* in shrublands, and *M. sativa* in grasslands. The exotic shrub species such as *C. korshinskii* and *H. rhamnoides* consume more water to sustain their growth (Chen et al. 2008). The dominance of exotic species can, therefore, have implications for soil moisture retention of the revegetated lands.

Additionally, we observed a significant soil moisture deficit in deeper layers of soil (>40 cm). Species composition can also be one of the main driving factors to control soil moisture in the soil profile. For example, *R. pseudoacacia* has shown a decline in soil moisture in various soil layers (Xiao et al. 2014). In contrast, both *C. korshinskii* and *H. rhamnoides* species have resulted in severe soil moisture deficit at deep layers of soil (Wang et al. 2009; Jia et al. 2017). The species *C. korshinskii*, *H. rhamnoides* and *R. pseudoacacia* have deep and well-developed root systems,

which have the potential to obtain water from deeper levels of soil (Gao et al. 2018). These exotic and newly introduced species usually have high transpiration demand, which is a main cause for soil moisture depletion (Yuan & Xu 2004). Soil moisture is a limiting factor of riparian zone development and revegetation success (Li et al. 2013). Decreased soil moisture after revegetation can lead to revegetation failure particularly in dry and low rainfall lands (Ren et al. 2018), and the cost of repeat revegetation efforts can be significant (Follstad Shah et al. 2007). Therefore, species selection in revegetation systems is important to maintain soil moisture at optimum levels in riparian zones.

5. Conclusions

Examining the influence of riparian zone revegetation with different revegetation types and age on soil N dynamics provides essential information for decision makers to revegetate riparian zones. This meta-analysis indicated that riparian zone revegetation significantly increased soil TN (11.0%), particularly in topsoil layers and woodlands. However, revegetation significantly decreased soil moisture by -7.6% compared with the corresponding control. Decreased soil moisture was associated with the selection of exotic species as dominant vegetation in riparian zone revegetation. Our study highlighted the importance of revegetating riparian zones to increase soil N retention. This quantitative literature review may provide insight into influence of different vegetation types and age on soil N pools. We expect that this information will help decision-makers select suitable vegetation types in riparian restoration projects in the future.

Acknowledgements

We would like to acknowledge the authors whose published data were used for this meta-analysis. The authors thank Griffith University, University of the Sunshine Coast and Mary River Catchment Coordinating Committee for their help with this study. NO would like to acknowledge Griffith University and the Environmental Future research Institute for granting her a merit PhD scholarship to undertake this study. NO also thanks Dr Ruby Michael for her insightful paper writing workshop and guidance.

Reference

- Adams DC, Gurevitch J, Rosenberg MS (1997) Resampling tests for meta-analysis of ecological data. *Ecology* 78:1277–1283
- Allison SM, Prosser JI (1993) Ammonia oxidation at low pH by attached populations of nitrifying bacteria. *Soil Biol Biochem* 25:935–941

- An SS, Huang YM, Zheng FL (2009) Evaluation of soil microbial indices along a revegetation chronosequence in grassland soils on the Loess Plateau, Northwest China. *Appl Soil Ecol* 41:286–292
- An S, Huang Y (2006) Rapid changes of soil properties following *Caragana korshinski* plantations in the hilly-gully Loess Plateau. *Front For China* 1:394–399
- Atkinson CJ, Fitzgerald JD, Hipps NA (2010) Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: a review. *Plant Soil* 337:1–18
- Augusto L, Badeau V, Arrouays D, Trichet P, Flot JL, Jolivet C, Merzeau ED (2006) Caractérisation physico-chimique des sols à l'échelle d'une région naturelle à partir d'une compilation de données exemple des sols du massif forestier landais. *Etude et Gestio des Sols* 13:7–22
- Bai SH, Blumfield TJ, Xu Z, Chen C, Wild C (2012) Soil organic matter dynamics and nitrogen availability in response to site preparation and management during revegetation in tropical Central Queensland, Australia. *J Soils Sediments* 12:386–395
- Bai SH, Xu Z, Blumfield TJ, Reverchon F (2015) Human footprints in urban forests: implication of nitrogen deposition for nitrogen and carbon storage. *J Soils Sediments* 15:1927–1936
- Bai SH, Trueman SJ, Nevenimo T, Hannet G, Bapiwai P, Poienou M, Wallace HM (2017) Effects of shade-tree species and spacing on soil and leaf nutrient concentrations in cocoa plantations at 8 years after establishment. *Agric Ecosyst Environ* 246:134–143
- Bardgett RD, Wardle DA (2003) Herbivore-mediated linkages between aboveground and belowground communities. *Ecology* 84:2258–2268
- Bateman EJ, Baggs EM (2005) Contributions of nitrification and denitrification to N₂O emissions from soils at different water-filled pore space. *Biol Fertil Soils* 41:379–388
- Boggs K, Weaver T (1994) Changes in vegetation and nutrient pools during riparian succession. *Wetlands* 14:98109
- Boring LR, Swank WT (1984) Symbiotic nitrogen fixation in regenerating black locust (*Robinia pseudoacacia* L.) stands. *For Sci* 30:528–537
- Borenstein M, Hedges LV, Higgins JP, Rothstein HR (2011) Introduction to meta-analysis. *JWS*

- Bottrill D, Ogbourne SM, Citerne N, Smith T, Farrar MB, Hu HW, Omidvar N, Wang J, Burton J, Kämper W, Bai SH (2020) Short-term application of mulch, roundup and organic herbicides did not affect soil microbial biomass or bacterial and fungal diversity. *Chemosphere* 244:125436
- Binkley D, Resh SC (1999) Rapid changes in soils following Eucalyptus afforestation in Hawaii. *Soil Sci Soc Am J* 63:222–225
- Burger B, Reich P, Cavagnaro TR (2010) Trajectories of change: riparian vegetation and soil conditions following livestock removal and replanting. *Austral Ecol* 35: 980-987
- Cayuela ML, Zwieten LV, Singh BP, Jeffery S, Roig A, Sánchez-Monedero MA (2013) Biochar's role in mitigating soil nitrous oxide emissions: a review and metaanalysis. *Agric Ecosyst Environ* 191:5-16
- Chen H, Shao M, Li Y (2008) Soil desiccation in the Loess Plateau of China. *Geoderma* 143:91–100
- Cheng WX (2009) Rhizosphere priming effect: its functional relationships with microbial turnover, evapotranspiration, and C–N budgets. *Soil Biol Biochem* 41:1795–180
- Cheng X, Luo Y, Su B, Wan S, Hui D, Zhang Q (2011) Plant carbon substrate supply regulated soil nitrogen dynamics in a tallgrass prairie in the Great Plains, USA: results of a clipping and shading experiment. *J Plant Ecol* 4:228–235
- Cierjacks A, Kowarik I, Joshi J, Hempel S, Ristow M, Von der Lippe M, Weber E (2013) Biological flora of the British Isles: *Robinia pseudoacacia*. *Ecology* 101:1623–1640
- Curtin D, Campbell CA, Jalil A (1998) Effects of acidity on mineralization: pH-dependence of organic matter mineralization in weakly acidic soils. *Soil Biol Biochem* 30:57–64
- Danso SKA, Zapata F, Awonaike KO (1995) Measurement of biological N₂ fixation in field-grown *Robinia pseudoacacia* L. *Soil Biol Biochem* 27:415–419
- De Marco A, Arena C, Giordano M, De Santo AV (2013) Impact of the invasive tree black locust on soil properties of Mediterranean stone pine-holm oak forests. *Plant Soil* 372:473–486
- Deng Q, Hui D, Dennis S, Reddy KC (2017) Responses of terrestrial ecosystem phosphorus cycling to nitrogen addition: A meta-analysis. *Glob Ecol Biogeogr* 26:713–728

- Deng L, Yan W, Zhang Y, Shangguan Z (2016) Severe depletion of soil moisture following land-use changes for ecological restoration: evidence from northern China. *For Ecol Manag* 366:1–10
- DeSimone J, Macrae ML, Bourbonniere RA (2010) Spatial variability in surface N₂O fluxes across a riparian zone and relationships with soil environmental conditions and nutrient supply. *Agric Ecosyst Environ* 138:1–9
- Dhondt K, Boeckx P, Hofman G, Van Cleemput O (2004) Temporal and spatial patterns of denitrification enzyme activity and nitrous oxide fluxes in three adjacent vegetated riparian buffer zones. *Biol Fertil Soils* 40:243–251
- Dijkstra FA, Pendall E, Mosier AR, King JY, Milchunas DG, Morgan JA (2008) Long-term enhancement of N availability and plant growth under elevated CO₂ in a semi-arid grassland. *Funct Ecol* 22:975–982
- Do Carmo JB, De Sousa Neto ER, Duarte-Neto PJ, Ometto JPHB, Martinelli LA (2012) Conversion of the coastal Atlantic forest to pasture: Consequences for the nitrogen cycle and soil greenhouse gas emissions. *Agric Ecosyst Environ* 148:37–43
- Dosskey MG, Vidon P, Gurwick NP, Allan CJ, Duval TP, Lowrance R (2010) The role of riparian vegetation in protecting and improving chemical water quality in streams 1. *JAWRA J Am Water Resour Assoc* 46:261–277
- Follstad Shah JJ, Dahm CN, Gloss SP, Bernhardt, ES (2007) River and riparian restoration in the Southwest: results of the National River Restoration Science Synthesis Project. *Restor Ecol* 15: 550-562
- Galloway JN, Dentener FJ, Capone DG, Boyer EW, Howarth RW, Seitzinger SP, Karl DM (2004) Nitrogen cycles: past, present, and future. *Biogeochemistry* 70:153–226
- Gao X, Li H, Zhao X, Ma W, Wu P (2018) Identifying a suitable revegetation technique for soil restoration on water-limited and degraded land: Considering both deep soil moisture deficit and soil organic carbon sequestration. *Geoderma* 319:61–69
- Groffman PM, Axelrod EA, Lemunyon JL, Sullivan WM (1991) Denitrification in grass and forest vegetated filter strips. *J Environ Qual* 20:671–674
- Hale R, Reich P, Daniel T, Lake PS, Cavagnaro TR (2018) Assessing changes in structural vegetation and soil properties following riparian restoration. *Agric Ecosyst Environ* 252:22–29

- Hefting MM, Clement JC, Bienkowski P, Dowrick D, Guenat C, Butturini A, Verhoeven JT (2005) The role of vegetation and litter in the nitrogen dynamics of riparian buffer zones in Europe. *Ecol Eng* 24:465–482
- Hooker TD, Compton JE (2003) Forest ecosystem carbon and nitrogen accumulation during the first century after agricultural abandonment. *Ecol Appl* 13:299–313
- Huwaldt JA, Steinhorst S (2015) Plot Digitizer, version 2.6. 8
- Jackson LE, Schimel JP, Firestone MK (1989) Short-term partitioning of ammonium and nitrate between plants and microbes in an annual grassland. *Soil Biol Biochem* 21:409–415
- Jacobs AE, Harrison JA (2014) Effects of floating vegetation on denitrification, nitrogen retention, and greenhouse gas production in wetland microcosms. *Biogeochemistry* 119:51–66
- Jeffery S, Verheijen FG, Van der Velde M, Bastos AC (2011) A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. *Agric Ecosys Environ* 144:175–187
- Jia X, Zhu Y, Luo Y (2017) Soil moisture decline due to afforestation across the Loess Plateau, China. *J Hydrol* 546:113–122
- Jiang Q, Xu Z, Hao Y, Dong H (2017) Dynamics of soil labile carbon and nitrogen pools in riparian zone of Wyaralong Dam in Southeast Queensland, Australia. *J Soils Sediments* 17:1030–1044
- Jin Z, Li X, Wang Y, Wang Y, Wang K, Cui B (2016) Comparing watershed black locust afforestation and natural revegetation impacts on soil nitrogen on the Loess Plateau of China. *Sci Rep* 6:25048
- Karjalainen H, Stefansdottir G, Tuominen L, Kairesalo T (2001) Do submersed plants enhance microbial activity in sediment?. *Aquat Bot* 69:1–13
- Kou M, Garcia-Fayos P, Hu S, Jiao J (2016) The effect of *Robinia pseudoacacia* afforestation on soil and vegetation properties in the Loess Plateau (China): A chronosequence approach. *For Ecol Manag* 375:146–158
- Knoepp JD, Vose JM (2007) Regulation of nitrogen mineralization and nitrification in Southern Appalachian ecosystems: separating the relative importance of biotic vs. abiotic controls. *Pedobiologia* 51:89–97
- Knops JMH, Bradley KL, Wedin DA (2002) Mechanisms of plant species impacts on ecosystem nitrogen cycling. *Ecol Lett* 5:454–466

- Kreiling RM, Richardson WB, Cavanaugh JC, Bartsch LA (2011) Summer nitrate uptake and denitrification in an upper Mississippi River backwater lake: the role of rooted aquatic vegetation. *Biogeochemistry* 104:309–324
- Kuusemets V, Mander Ü, Lohmus K, Ivask M (2001) Nitrogen and phosphorus variation in shallow groundwater and assimilation in plants in complex riparian buffer zones. *Water Sci Technol* 44:615–622
- Li D, Niu S, Luo Y (2012) Global patterns of the dynamics of soil carbon and nitrogen stocks following afforestation: a meta-analysis. *New Phytol* 195:172–181
- Li H, Shen W, Zou C, Jiang J, Fu L, She G (2013) Spatio-temporal variability of soil moisture and its effect on vegetation in a decertified aeolian riparian ecotone on the Tibetan Plateau, China. *J Hydrol* 479: 215-225
- Li M, Zhou X, Zhang Q, Cheng X (2014) Consequences of afforestation for soil nitrogen dynamics in central China. *Agric Ecosyst Environ* 183:40–46
- Liang H, Xue Y, Li Z, Wang S, Wu X, Gao G, Fu B (2018) Soil moisture decline following the plantation of *Robinia pseudoacacia* forests: Evidence from the Loess Plateau. *For Ecol Manag* 412:62–69
- Liu D, Huang Y, Sun H, An S (2018) The restoration age of *Robinia pseudoacacia* plantation impacts soil microbial biomass and microbial community structure in the Loess Plateau. *Catena* 165:192-200
- Liu R, Zhou X, Wang J, Shao J, Fu Y, Liang C, Yan E, Chen X, Wang X, Bai SH (2019) Differential magnitude of rhizosphere effects on soil aggregation at three stages of subtropical secondary forest successions. *Plant Soil* 436:365–380
- Liu WZ, Liu GH, Zhang QF (2011) Influence of vegetation characteristics on soil denitrification in shoreline wetlands of the Danjiangkou Reservoir in China. *Clean-Soil Air Water* 39:109–115
- Liu X, Zhang W, Wu M, Ye Y, Wang K, Li D (2018) Changes in soil nitrogen stocks following vegetation restoration in a typical karst catchment. *Land Degrad Dev* 30:60–72
- Long J (2001) An Introduction to and Generalization of the "Fail-Safe N.". Paper presented at the Annual Meeting of the Southwest Educational Research Association, New Orleans, LA ED449210
- Luo Y, Hui D, Zhang D (2006) Elevated CO₂ stimulates net accumulations of carbon and nitrogen in land ecosystems: a meta-analysis. *Ecology* 87:53–63

- Mao R, Zeng DH, Hu YL, Li LJ, Yang D (2010) Soil organic carbon and nitrogen stocks in an age-sequence of poplar stands planted on marginal agricultural land in Northeast China. *Plant Soil* 332:277–287
- Menyailo O, Hungate BA, Zech W (2002) The effect of single tree species on soil microbial activities related to C and N cycling in the Siberian artificial afforestation experiment. *Plant Soil* 242:183–196
- Moher D, Liberati A, Tetzlaff J, Altman DG (2009) Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *Ann Intern Med* 151:264–269
- Naiman RJ, Decamps H, McClain ME (2010) *Riparia: ecology, conservation, and management of streamside communities*. Elsevier
- Neilen AD, Chen CR, Parker BM, Faggotter SJ, Burford MA (2017) Differences in nitrate and phosphorus export between wooded and grassed riparian zones from farmland to receiving waterways under varying rainfall conditions. *Sci Total Environ* 598:188–197
- Njue N, Koech E, Hitimana J, Sirmah P (2016) Influence of land use activities on riparian vegetation, soil and water quality: An indicator of biodiversity loss, South West Mau Forest, Kenya. *Open J For* 6:373–385
- Ofori-Frimpong K, Asase A, Mason J, Danku L (2007) Shaded versus unshaded cocoa: implications on litter fall, decomposition, soil fertility and cocoa pod development. In symposium on multistrata agroforestry systems with perennial crops, CATIE Turrialba, Costa Rica (Vol. 1721)
- Paul EA, Clark FE (1989) *Soil Microbiology and Biochemistry*, Academic. Press, San Diego
- Peterjohn WT, Correll DL (1984) Nutrient dynamics in an agricultural watershed: observations on the role of a riparian forest. *Ecology* 65:1466–1475
- Price P, Lovett S (1999) *Riparian Land Management Technical Guidelines Vol 1: a Principles of sound management*
b. Review of legislation
- Räty M, Uusi-Kämpä J, Yli-Halla M, Rasa K, Pietola L (2010) Phosphorus and nitrogen cycles in the vegetation of differently managed buffer zones. *Nutr Cycl Agroecosys* 86:121–13
- Ren Z, Li Z, Liu X, Li P, Cheng S, Xu G (2018) Comparing watershed afforestation and natural revegetation impacts on soil moisture in the semiarid Loess Plateau of China. *Sci Rep* 8: 1-10

- Reverchon F , Abdullah KM, Bai SH, Villafán E, Blumfield TJ, Patel B, Xu Z (2020) Biological nitrogen fixation by two *Acacia* species and associated root-nodule bacteria in a suburban Australian forest subjected to prescribed burning. *J Soils Sediments* 20:122–132
- Reverchon F, Bai SH, Liu X, Blumfield TJ (2015) Tree plantation systems influence nitrogen retention and the abundance of nitrogen functional genes in the Solomon Islands. *Front Microbiol* 6:1439
- Reverchon F, Flicker RC, Yang H, Yan G, Xu Z, Chen C, Zhang D (2014) Changes in $\delta^{15}\text{N}$ in a soil–plant system under different biochar feedstocks and application rates. *Biol Fertil Soils* 50:275–283
- Rosenberg MS, Adams DC, Gurevitch J (2000) MetaWin (version 2). Retrieved from. <http://www.metawinsoft.com/>
- Rosenthal R, Rosnow RL 1984 *Essentials of Behavioral Research: Methods and Data Analysis*. McGraw-Hill Higher Education
- Rothstein HR, Sutton AJ, Borenstein M (2005) Publication bias in meta-analysis: Prevention, assessment and adjustments. *JWS* 1–7
- Sahrawat KL (2008) Factors affecting nitrification in soils. *Commun Soil Sci Plant Anal* 39:1436–1446
- Schade JD, Fisher SG, Grimm NB, Seddon JA (2001) The influence of a riparian shrub on nitrogen cycling in a sonoran desert stream. *Ecology* 82:3363–3376
- Seneviratne G (2000) Litter quality and nitrogen release in tropical agriculture: a synthesis. *Biol Fertil Soils* 31:60–64
- Shi S, Zhang W, Zhang P, Yu Y, Ding F (2013) A synthesis of change in deep soil organic carbon stores with afforestation of agricultural soils. *Forest Ecol Manag* 296: 53–63
- Smal H, Olszewska M (2008) The effect of afforestation with Scots pine (*Pinus silvestris* L.) of sandy post-arable soils on their selected properties. II. Reaction, carbon, nitrogen and phosphorus. *Plant Soil* 305:171–187
- Vigulu V, Blumfield TJ, Reverchon F, Bai SH, Xu Z (2019) Nitrogen and carbon cycling associated with litterfall production in monoculture teak and mixed species teak and flueggea stands. *J Soils Sediments* 19:1672–1684

- Vitousek PM, Turner DR, Parton WJ, Sanford RL (1994) Litter decomposition on the Mauna Loa environmental matrix, Hawai'i: patterns, mechanisms, and models. *Ecology* 75:418–429
- Vitousek PM, Reiners WA (1975) Ecosystem Succession and Nutrient Retention: A Hypothesis. *BioScience* 25:376–381
- Wang J, Fu B, Qiu Y, Chen L, Wang Z (2001) Geostatistical analysis of soil moisture variability on Da Nangou catchment of the loess plateau, China. *Environ Geol* 41:113–120
- Wang Z, Liu B, Liu G, Zhang Y (2009) Soil water depletion depth by planted vegetation on the Loess Plateau. *Sci China Earth Sci* 52:835–842
- Wang B, Liu G, Xue S (2012) Effect of black locust (*Robinia pseudoacacia*) on soil chemical and microbiological properties in the eroded hilly area of China's Loess Plateau. *Environ Earth Sci* 65:597–607
- Xiao L, Xue S, Liu GB, Zhang C (2014) Soil moisture variability under different land uses in the Zhifanggou catchment of the Loess Plateau, China. *Arid Land Res Manag* 28:274–290
- Xiong Z, Guo L, Zhang Q, Liu G, Liu W (2017) Edaphic conditions regulate denitrification directly and indirectly by altering denitrifier abundance in wetlands along the Han River, China. *Environ Sci Technol* 51:5483–5491
- Xu M, Gao D, Fu S, Lu X, Wu S, Han X, Yang G, Feng Y (2020) Long-term effects of vegetation and soil on the microbial communities following afforestation of farmland with *Robinia pseudoacacia* plantations. *Geoderma* 367:114263
- Xu M, Zhang J, Liu GB, Yamanaka N (2014) Soil properties in natural grassland, *Caragana korshinskii* planted shrubland, and *Robinia pseudoacacia* planted forest in gullies on the hilly Loess Plateau, China. *Catena* 119:116–124
- Xu S, Liu X, Li X, Tian C (2019) Soil organic carbon changes following wetland cultivation: A global meta-analysis. *Geoderma* 347:49–58
- Ye C, Cheng X, Liu W, Zhang Q (2015) Revegetation impacts soil nitrogen dynamics in the water level fluctuation zone of the Three Gorges Reservoir, China. *Sci Total Environ* 517:76–85

- Ye C, Cheng X, Zhang Y, Wang Z, Zhang Q (2012) Soil nitrogen dynamics following short-term revegetation in the water level fluctuation zone of the Three Gorges Reservoir, China. *Ecol Eng* 38:37–44
- Yuan HY, Xu XM (2004) Soil water dynamics of plantations in sub-arid gully and hilly regions of the Loess Plateau. *J Northeast For Univ* 19:5–8

Figure Captions:

Fig. 1 Overall mean effect size of revegetation regardless of revegetation types, age and soil sampling depth on changes of soil TN, $\text{NH}_4^+\text{-N}$, $\text{NO}_3^-\text{-N}$ and moisture. Error bars represent 95% confidence intervals. The sample size (n) for each variable is shown next to the each class. The effect was considered significant if the 95% CI of the effect size did not cover zero

Fig. 2 Mean effect size of revegetation types on changes of soil (a) TN; (b) $\text{NH}_4^+\text{-N}$; and (c) $\text{NO}_3^-\text{-N}$, the mean effect size of revegetation age on changes of soil (d) TN; (e) $\text{NH}_4^+\text{-N}$; and (f) $\text{NO}_3^-\text{-N}$; and the mean effect size of soil depth on changes of soil (g) TN; (h) $\text{NH}_4^+\text{-N}$; and (i) $\text{NO}_3^-\text{-N}$. Error bars represent 95% confidence intervals. The sample size (n) for each variable is shown next to the each class. The dotted line indicates the mean effect size. The effect was considered significant if the 95% CI of the effect size did not cover zero

Fig. 3 The mean effect size of revegetation types on changes of (a) soil moisture; and (d) soil pH, the mean effect size of revegetation age on changes of (b) soil moisture and (e) soil pH; and the mean effect size of soil depth on changes of (c) soil moisture; and (f) soil pH. Error bars represent 95% confidence intervals. The sample size (n) for each variable is shown next to the each class. The dotted line indicates the mean effect size. The effect was considered significant if the 95% CI of the effect size did not cover zero

Fig. 4 Relationship between soil organic carbon (SOC) and total nitrogen (TN)

Fig. 2

Fig. 3

Supplementary material

A global meta-analysis shows soil nitrogen pool increases after revegetation of riparian zones

Negar Omidvar^{a*}, Zhihong Xu^a, Thi Thu Nhan Nguyen^b, Babak Salehin^a, Steven Ogbourne^c, Rebecca Ford^a, Shahla Hosseini Bai^{a*}

^a Environmental Futures Research Institute, School of Environment and Science, Griffith University, Nathan, Brisbane, Queensland 4111, Australia

^b Faculty of Environment, Hanoi University of Natural Resources and Environment, Hanoi, Vietnam

^c GeneCology Research Centre, School of Science and Engineering, University of the Sunshine Coast, QLD 4558, Australia

*Corresponding Authors:

Negar Omidvar (Email: negar.omidvar@griffithuni.edu.au)

Shahla Hosseini Bai (Email: s.hosseini-bai@griffith.edu.au)

Supplementary Fig. 1 Empirical functions for estimating soil bulk density (BD) based on the data from studies reporting soil organic carbon (SOC) and soil BD