Journal of Environmental Management 345 (2023) 118904

Contents lists available at ScienceDirect

Journal of Environmental Management

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

Research article

Effects of conservation tillage on soil enzyme activities of global cultivated land: A meta-analysis

Linsheng Wen [a,b], Yun Peng [f], Yunrui Zhou [a,b], Guo Cai [a,b], Yuying Lin [b,c,d,e,*], Baoyin Li [a,b,**]

[a] State Key Laboratory for Subtropical Mountain Ecology of the Ministry of Science and Technology and Fujian Province, Fujian Normal University, Fuzhou, 350117, China
[b] School of Geographical Sciences, School of Carbon Neutrality Future Technology, Fujian Normal University, Fuzhou, 350117, China
[c] Postdoctoral Research Station of Ecology, Fujian Normal University, Fuzhou, 350117, China
[d] School of Culture, Tourism and Public Administration, Fujian Normal University, Fuzhou, 350117, China
[e] The Higher Educational Key Laboratory for Smart Tourism of Fujian Province, Fuzhou, 350007, China
[f] Yuanzhou District Forestry Bureau, Yichun City, Jiangxi Province, 336000, China

A R T I C L E I N F O

Handling Editor: Raf Dewil

Keywords:
Agricultural management
Conservation tillage
Meta-analysis
Soil enzyme
Straw returning
Tillage measure

A B S T R A C T

The negative impacts of conventional agriculture and the imperative to adopt conservation tillage garnered significant attention. However, the effects of conservation tillage on soil enzyme activities still lack comprehensive cognition. Here, we collected 14,308 pairwise observations from 369 publications worldwide to systematically evaluate the effects of different conservation tillage practices (reduced tillage (T), reduced tillage with straw return (TS), reduced tillage with straw mulch return (TSO), no-tillage (NT), no-tillage with straw return (NTS), and no-tillage with straw mulch return (NTSO)) on the activities of 35 enzymes in soil. The results showed that: (1) the effect of conservation tillage on soil enzyme activity varied by enzyme type, except for peroxidase (−12.34%), which showed an overall significant positive effect (10.28–89.76%); (2) the NTS and TS demonstrated strong potential to improve soil enzyme activities by increasing a wide variety of soil enzyme activities (12–15) and efficacy (9.76–75.56%) than other conservation tillage (8.60–68.68%); (3) in addition, the effect of conservation tillage on soil enzyme activity was regulated by soil depth, crop type, years of conservation tillage, climate (mean annual precipitation and temperature), and soil physicochemical properties (e.g., pH, bulk density, electrical conductivity, organic matter, ammonium nitrogen, total phosphorus, available phosphorus, total potassium, available potassium, etc.). Overall, our quantitative analysis clearly suggests that conservation tillage is an effective measure for improving soil enzyme activity on global croplands, where combination of reduced tillage or no-till with straw return are considered to have great potential and promise. The results contribute to better comprehend the effects of conservation tillage on soil activity and provide a valuable insight for agricultural management.

1. Introduction

Cultivated land plays an important role in agricultural development by ensuring food security and economic crop production (Greenland et al., 1997). However, over-cultivation and poor tillage systems have led to the threat of cropland degradation worldwide (Hossain et al., 2020; Nkonya et al., 2016). To address this issue and enhance quality and productivity of cropland, conservation tillage has been adopted on over 155 million hectares of cropland worldwide, focusing on crop residue return, crop rotation and minimum tillage (Kassam et al., 2014; Pittelkow et al., 2015). Conservation tillage could increase carbon and nitrogen fixation of cropland by increasing straw residues or reducing tillage (Blanco-Canqui and Ruis, 2018; Dong et al., 2021; Sithole et al., 2016), which directly or indirectly affects soil physicochemical properties, microbial quantity and quality, while regulating the soil environment through soil enzymes involved in or mediating soil biochemical reactions (Bertiller et al., 2009; Bielińska and Mocek-Płóciniak, 2012; Mina et al., 2008). However, a global perspective on the response of soil

* Corresponding author. School of Geographical Sciences, School of Carbon Neutrality Future Technology, Fujian Normal University, Fuzhou, 350117, China.
** Corresponding author. State Key Laboratory for Subtropical Mountain Ecology of the Ministry of Science and Technology and Fujian Province, Fujian Normal University, Fuzhou, 350117, China.
E-mail addresses: linyuying2019@fjnu.edu.cn (Y. Lin), liby@fjnu.edu.cn (B. Li).

https://doi.org/10.1016/j.jenvman.2023.118904
Received 16 May 2023; Received in revised form 5 August 2023; Accepted 27 August 2023
Available online 31 August 2023

enzyme activity to conservation tillage is still lacking, and we have not yet obtained clear insights.

Previous research has shown that soil enzyme activity can be used to explain tillage-induced changes in soil properties, revealing the key role of microorganisms in soil biochemical processes (Acosta-Martínez et al., 2007; Gispert et al., 2013), and the level of their activity could effectively reflect soil biological activity, soil quality, and sensitivity to tillage practices (He et al., 2021; Zheng et al., 2022a). No-till and straw return are common conservation tillage practices that have been reported to increase soil enzyme activity (He et al., 2021; Zuber and Villamil, 2016). This can be attributed to (a) the stability provided by reduced soil disturbance associated with no-till and straw incorporation, resulting in a more stable pool of extracellular enzymes in the soil biochemical environment (Mangalassery et al., 2015), and (b) the continuous and sufficient energy supply to microorganisms, which promotes increased enzyme secretion (Balota et al., 2003). Until now, little is known about whether the same effects on different enzymes occur with the same conservation tillage practices. Mina et al. (2008) indicated that no-till in the Indian Himalayas significantly increased the activities of dehydrogenase and alkaline phosphatase but decreased cellulase compared to conventional tillage, similar studies have also occurred elsewhere (Melero et al., 2008). This suggests that the response of soil enzyme activity to different conservation tillage methods may be influenced by the type of enzyme. In particular, randomized local experiments may yield divergent results, but a comprehensive meta-analysis could provide deeper insights into the interaction between different conservation tillage methods and soil enzymes.

Soil enzyme activity is dramatically correlated with nutrient accumulation in soils (Aponte et al., 2020; De Mastro et al., 2022; Sherene, 2017). For instance, plant organic residues can be degraded by cellulase and cellobiohydrolase, and invertase, β-1,4-glucosidase and β-1,4-xylosidase can convert micromolecular carbohydrates into monosaccharides that contribute to the C cycle in soil (Curtright and Tiemann, 2021; De Mastro et al., 2022; Zhang et al., 2015); N-related enzymes, such as urease and protease, convert urea and proteins, respectively, while polypeptides can be degraded by β-1,4-N-acetylglucosaminidase and leucine aminopeptidase (Chen et al., 2023; Ekenler and Tabatabai, 2004; Meng et al., 2020); also, phosphatases hydrolyze complex organophosphorus compounds, sulfatase and arylsulfatase are associated with the S cycle (Gispert et al., 2013; Margalef et al., 2017), and there are also some studies showing a relationship between soil metal ions and soil enzyme activities (Cesur et al., 2022; Cetin et al., 2022a, 2022b). Thus, the type of soil enzymes has to do with nutrient accumulation in the soil, but few studies have comprehensively investigated the differences in the effects on different soil enzymes under conservation tillage.

Furthermore, soil enzyme activity in conservation tillage is also influenced by factors such as soil depth (He et al., 2021), crop type (Roldán et al., 2007), and years of conservation tillage (Melero et al., 2008). Melero et al. (2008) indicated that the activities of dehydrogenase, β-glucosidase, alkaline phosphatase, and arylsulphatase were higher under direct drilling in semi-arid Mediterranean conditions than under conventional tillage, especially in the topsoil (0–5 cm). Roldán et al. (2007) observed differences in microbial biomass and enzyme activity between beans and maize in Mexico. In addition, other moderator variables such as different climates, pH, soil moisture, and initial soil properties were also closely important for soil enzyme activity (Roldán et al., 2007; Zuber and Villamil, 2016). However, it is not clear how diverse moderator variables modulate the effect of different conservation tillage on soil enzyme activity, and it is critical to understand the underlying logic.

Although the relationship between conservation tillage and soil enzymes has been experimentally demonstrated in previous studies and definitive conclusions have been drawn for local agricultural management (He et al., 2021; Melero et al., 2008; Mina et al., 2008), synthetic analyses at the a global scale are still scarce. To fill the gap in quantitative research on the effects of different conservation tillage on the activity of different soil enzymes and explore their driving factors on global croplands, we conducted a meta-analysis of 14,308 paired observations (including 6 conservation tillage and 35 soil enzymes) extracted from 369 publications. We use meta-analysis of synthetic data because the method is useful for integrating a variety of data and it provides a systematic and statistically rigorous way to compare studies with methodological and experimental differences (Koricheva et al., 2013). The objectives of this study were (1) to quantify the effects of conservation tillage (T、TS、TSO、NT、NTS、NTSO) on various soil enzyme activities; (2) to evaluate the role and relative importance of various regulatory variables in the response of soil enzyme activities to conservation tillage.

2. Materials and methods

2.1. Data collection and compilation

Data collection for this study was conducted through collecting peer-reviewed articles, book chapters and academic papers published in the *China National Knowledge Infrastructure* (*CNKI*) and *Web of Science* before October 20, 2022. The search terms used were (“soil biochemical environment” OR “soil enzyme” OR “soil enzyme activity” OR phosphatase OR catalase OR urease OR proteinase OR glucosidase OR invertase OR dehydrogenase) AND (“tillage treatment” OR “tillage system” OR “tillage management” OR “conservation till” OR “conservation practice” OR no-tillage OR “no till” OR “zero till” OR “reduced tillage” OR “strip till” OR “mulch till” OR “ridge till” OR “shallow till” OR “vertical till” OR “tillage treatment” OR “tillage system” OR “tillage management” OR “minimum tillage” OR “minim till” OR “straw return” OR “crop residue return” OR “residue management” OR “mulching treatment” OR “mulching measure”). We then obtained 29,951 publications, first searching the titles to screen out a total of 7832 articles on agroecosystems only, then selecting 3632 articles on agricultural tillage treatments based on abstract information, and finally compiling the database by searching the full text and applying the following criteria: (1) the object of the publications must be crops, fruits and vegetables under agricultural cultivation, forest or compound management under forest were excluded; (2) at least one conservation tillage and one conventional tillage must be included in the study to form a control; (3) there should be at least one soil enzyme among the soil variables studied; (4) the data were reported directly in the paper or the mean, standard deviation or standard error and sample size of the variables can be estimated; (5) we refer to Yue et al. (2023) and consider strip tillage, drilling tillage, vertical tillage, shallow tillage and minimum tillage as reduced conservation tillage (T), except for no-tillage (NT), and “straw return” and “straw mulch return” were recorded as “S" and “SO”, respectively, till then the six types of conservation tillage (T, TS, TSO, NT, NTS, NTSO) were obtained. A flow illustrating the data collection steps are shown in Fig. S1. After collection and compilation, the database yielded 14,308 paired observations from 369 publications for subsequent data analysis (Fig. S2, Appendix S1).

In order to evaluate the potential mechanisms of influence of regulatory variables on soil enzyme activity in response to conservation tillage, latitude, elevation, mean annual precipitation (MAP), mean annual temperature (MAT), potential evapotranspiration (PET), and initial soil physicochemical properties were also included in the database for recording. Data were collected directly from the text, tables or appendices, or extracted indirectly from the images by using the GetData graphic digitizer (version 2.26; http://www.getdata-graph-digitizer.com).

2.2. Data analyses

The natural logarithmic response ratio (lnRR) was applied to quantify the effect size of various conservation tillage on soil enzyme activities. The formula used to calculate the lnRR for each pair of observations was (Hedges et al., 1999):

$$lnRR = \ln\left(\overline{X_t X_c}\right) \tag{1}$$

where $\overline{X_t}$ and $\overline{X_c}$ are the mean responses to the soil enzyme activities of the treatment plot and the control plot, respectively. We then conducted a normality test (Fig. S3) and variance estimation for the effect of conservation tillage on soil enzyme activity. The estimate of variance match with each lnRR was:

$$v = \frac{s_t^2}{n_t \overline{X}_t^2} + \frac{s_c^2}{n_c \overline{X}_c^2} \tag{2}$$

where n_t and n_c were the size of sample, as well as s_t and s_c were the standard deviation (SD) of the response to conservation and conventional tillage, respectively. Subsequently, the inverse of each lnRR variance was taken its weight (w):

$$w = 1 / v \tag{3}$$

Here, we applied the intercept-only linear mixed-effects models of the *lme4* package (Bates et al., 2014) to estimate the weighted average effect size (lnRR_{++}) of each conservation tillage on soil enzyme activity. The principle was to fit lnRR_{++} as the response variable and fit the main research identifier as the random effect factor, which sufficiently considering the potential non-independence of observations extracted from individual research. Then, meta-regressions were conducted to evaluate the effects of multiple moderator variables on soil enzyme activity in response to conservation tillage based on linear mixed-effects model, with the moderator variables as categorical or continuous fixed-effect factors in the process. And each moderating variable was evaluated separately. For the observations with different soil depth, the calculation of overall lnRR_{++} first included and then soil depth was used as a moderating metric to evaluate how it can regulate the effect of soil enzyme response to conservation tillage. All our data model fits and statistical analyses were performed in R (version 4.1.1) (R Core Team, 2021).

3. Results

3.1. Overall effects of conservation tillage

The effects of different conservation tillage on soil enzyme activities varied enzyme type (Figs. 1 and 2, S4). Overall, conservation tillage had a significant effect on soil enzyme activities ($P < 0.05$), with conservation tillage having a significant positive effect (10.28–89.76%) on the activities of 28 enzymes such as CATAL, UREAS and INCER, while it had a significant negative effect on PEROX (−12.34%) (Fig. 1).

3.2. Impacts of moderator variables on soil enzyme activity in response to conservation tillage

Different conservation tillage treatments had various effects on enzyme activity, as TS had positive effects on 15 soil enzymes (CATAL, UREAS, INVER, ALKAL, ACIDP, DEHYD, CELLU, NEUPH, PROTE, βGLUC, ARYLS, βXYLO, βACET, LEUCI, GLOMA) (10.21–68.23%), followed by NTS (9.76–75.56%) and NT (9.91–41.13%), which could also had a promoting effect on 12 soil enzymes, respectively (Fig. 2, S4). Moreover, six conservation tillage treatments (T, TS, TSO, NT, NTS, NTSO) significantly increased the activity of CATAL, INVER, and ALKAL (8.60–28.78%) (Fig. 2a, c, d), but the effect values of INVER and ALKAL were significantly different in response to different conservation tillage ($P < 0.05$), and similar for UREAS, ACIDP, CELLU, NEUPH, FLUOR, GLOMA, and OXIDO (Fig. 2b, e, i, p, S4i, m).

The effect of soil enzyme activity in response to conservation tillage was influenced by soil depth, crop type and conservation tillage years (Fig. 3, S5, S6). Specifically, conservation tillage had a positive effect (8.71–28.81%) on the activities of CATAL, UREAS, and INVER in the shallow (0–20 cm), medium (20–40 cm), and deep (>40 cm) soil layers (Fig. 3a), but conservation tillage had a positive effect on the activities of PROTE, ACIDP, αGLUC, DEHYD, CELLU, βGLUC, βXYLO, βACET, LEUCI and ARYLS (2.56–47.93%) in the shallow soil only, as well as the positive effect on the activities of ALKAL and NEUTR (11.14–32.48%) in the surface and middle layers of the soil ($P < 0.05$) (Fig. 3). In addition, the activities of UREAS, ALKAL, PEROX, βACET and SULFA showed significantly different effect values in response to conservation tillage under different crop types (Fig. S5), and the activity of PEROX was inhibited (−42.22%) by conservation tillage in wheat cultivation (Fig. S5). Moreover, the significant increase in soil enzyme activity (14.53–79.88%) were mainly concentrated in the medium (1–5 year) term conservation tillage; and there were significant differences in CATAL, UREAS, INVER, POLYP, βACET and GLOMA between the long (>5 year), medium and short term (0–1 year) duration of conservation tillage (Fig. S6).

In addition, the geographical characteristics, climatic elements and initial physicochemical properties of the soil were also important metrics on moderating the response of soil enzymes to conservation tillage, and their impacts varied by enzyme type (Table 1). Specifically, MAP, MAT, pH ammonium nitrogen (NH_4) and total phosphorus (TP) could positively or negatively affect the activity of soil enzyme in response to conservation tillage ($P < 0.05$), such as the effect of MAT on CATAL and UREAS. Besides, soil bulk density (SBD), electrical conductivity (EC) restraint the activity of ALKAL, DEHYD, βGLUC and INVER; but elevation and SOM could significantly promote effects on the activities of UREAS, NEUPH and PROTE, respectively, and similarly acting moderator variables include available phosphorus (AP), total potassium (TK), and available potassium (AK) (Table 1).

4. Discussion

4.1. Effect of conservation tillage on soil enzyme activity

The results of our global meta-analysis indicate that the effect of different conservation tillage treatments on soil enzyme activity varies according to enzyme type (Fig. 1). This was not entirely consistent with the previous conclusion that conservation tillage is a good measure to increase soil enzyme activity (He et al., 2021; Roldán et al., 2005). This study also showed that conservation tillage significantly increased the activity of most soil enzymes, but there were still some soil enzymes that did not respond to conservation tillage or even had a negative effect. Previous studies have shown that conservation tillage was focused on increasing straw residues and reducing soil disturbance (Kassam et al., 2014; Pittelkow et al., 2015), which provided a high-quality detritusphere and rhizosphere to promote enzyme secretion by microorganisms (Wang et al., 2023), while organic matter stabilized and protected enzymes by complexing with humus (Saha et al., 2008). In addition, the magnitude of the difference in the effect of conservation tillage on enzyme activity varies with the type of enzyme (Chen et al., 2019), and enzyme activity can be enhanced to some extent when substrate conditions are of high quality, just as conservation tillage promotes organic matter accumulation and eventually triggers an increase in the activity of β-glucosidase and urease, which are involved in the decomposition of soil organic matter (Mangalassery et al., 2015). However, altering the soil microenvironment through conservation tillage can inhibit soil enzyme activity and may not be optimal. In other studies, the activities of soil enzymes were found to be not significantly different from those of conventional tillage after the introduction of conservation tillage (Melero et al., 2008; Tian et al., 2020), and even the activities of β-glucosidase and cellulase were lower in conservation tillage than in conventional tillage (Mina et al., 2008). This reflects the effects of conservation tillage on the activity of soil enzyme regulated by other

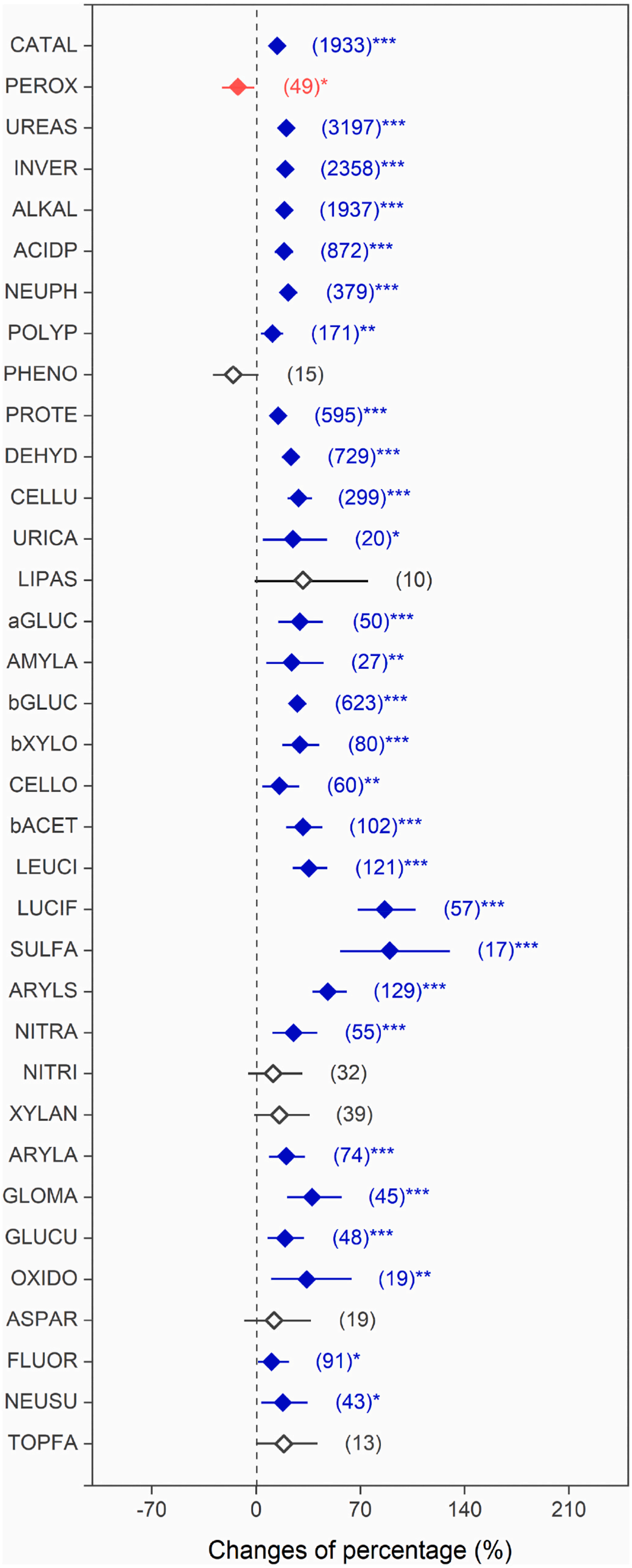

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Fig. 1. Overall mean changes of percentages for the 35 soil enzymes included in the meta-analysis: catalase (CATAL), peroxidase (PEROX), urease (UREAS), invertase (INVER), alkaline phosphatase (ALKAL), acid phosphatase (ACIDP), neutral phosphatase (NEUPH), polyphenol oxidase (POLYP), phenol oxidase (PHENO), proteinase (PROTE), dehydrogenase (DEHYD), cellulase (CELLU), uricase (URICA), lipase (LIPAS), α-glucosidase (αGLUC), amylase (AMYLA), β-1,4-glucosidase (βGLUC), β-1,4-xylosidase (βXYLO), cellobiosidase (CELLO), β-1,4-N-acetyl-glucosaminidase (βACET), leucine aminopeptidase (LEUCI), luciferase (LUCIF), sulfatase (SULFA), arylsulfatase (ARYLS), nitrate reductase (NITRA), nitrite reductase (NITRI), xylanase (XYLAN), arylamidase (ARYLA), glomalin (GLOMA), glucuronidase (GLUCU), oxidoreductase (OXIDO), asparaginase (ASPAR), fluorescein diacetate (FLUOR), neutral sugar (NEUSU), total phospholipid fatty acids (TOPFA), respectively. Red symbols (value less than zero line) indicate significant negative effects in soil enzymes with conserving tillage cultivation and blue symbol (value more than zero line) represents significant positive effects increase in soil enzymes due to conserving tillage compared to conventional tillage. ***$P < 0.001$, **$P < 0.01$, *$P < 0.05$.

elements (e.g., pH, MAT, years of conservation tillage) (Table 1, Fig. S6).

Different conservation tillage practices had different effects on soil enzyme activity (Fig. 2, S4), which could be attributed to the different effects of conservation tillage on the soil microenvironment. The result of straw return is biased toward increasing SOM, while no-till maintains low soil disturbance and high continuity, both of which have been shown to increase enzyme activity (Dong et al., 2021; Chen et al., 2019; Li et al., 2018), but the changes in microenvironment may result in different states of enzyme activity (Piazza et al., 2020; Saha et al., 2008). Recent studies suggest that the TS provides a detritusphere that is similar but not identical to the subsurface rhizosphere (Wang et al., 2023). In addition, the TSO and TS (or NTSO and NTS) resulted in microbial aggregation and homogenization of the soil surface, respectively, which would lead to differences in soil enzyme activities among different tillage methods (Wang et al., 2023; Zheng et al., 2018; Zhu et al., 2022). Combining T or NT with straw return did not absolutely result in an exponential increase in enzyme activity (Acosta-Martinez and Tabatabai, 2001), but the effects of the TS and NTS on soil enzyme activity were higher than those of T and NT (Fig. 2, S4), suggesting that straw return has great potential when combined with other conservation tillage practices.

4.2. *Impacts of moderator variables on soil enzyme activity in response to conservation tillage*

Our results also suggest that the effect of conservation tillage on soil enzyme activity was moderated by variables such as soil depth, crop type, years of conservation tillage, climate, geographic characteristics and initial soil properties (Fig. 3, S5, S6, Table 1). The positive effect of conservation tillage on enzyme activity was mainly concentrated in the topsoil, which might due to the topsoil microenvironment being more susceptible to conservation tillage (de la Horra et al., 2003; He et al., 2021; Luo et al., 2011). Interestingly, we also found positive effects of conservation tillage on CATAL, UREAS, and INVER activities in the surface, middle, and lower layers of the soil ($P < 0.05$), and the effect values increased with depth (Fig. 3). This suggests that although conservation tillage usually leads to the accumulation of SOM in the topsoil (Piazza et al., 2020), the effects of rhizospheric microbial hot zone and nutrient leaching on enzyme activities should not be underestimated (Liang et al., 2007; Wang et al., 2023).

Crop type also showed a significant role in moderating the response of soil enzyme activity under conservation tillage (Fig. S5). This could be a synergistic effect of crop type combining multiple moderator variables, as well as the prevalence of differences in soil microbial communities under different crop types (Thomson et al., 2015). And the differences in root density, root secretions, and plant nutrient utilization strategies (Ai et al., 2023; Yue et al., 2023), which would ultimately lead to the regulation of soil enzyme activity by crop type. In addition, the type of

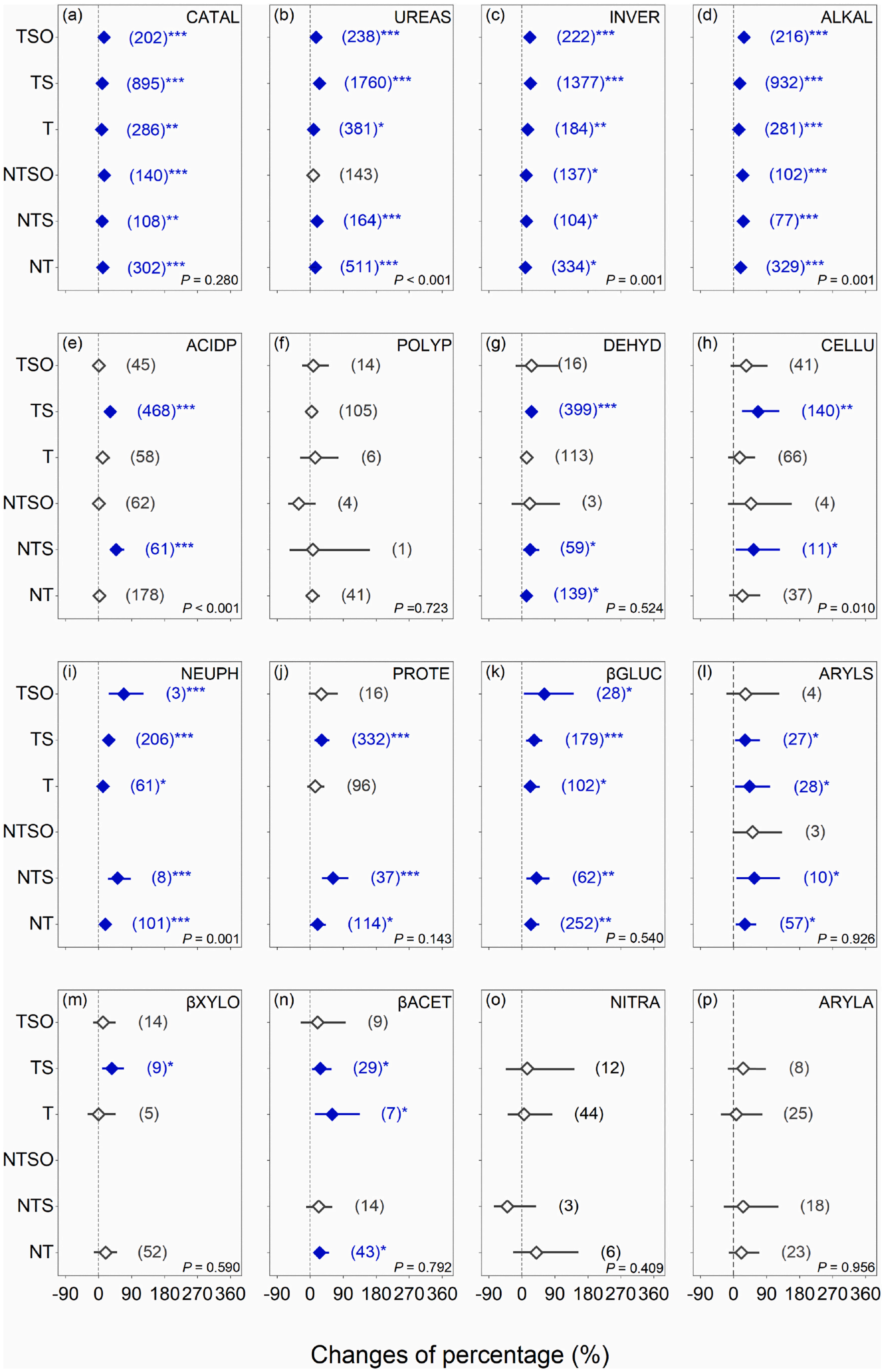

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Fig. 2. The effects of different conserving tillage implementation on various soil enzyme activity were estimated by database. The 95% confidence intervals and estimated value of fixed effects of different conserving tillage on soil enzyme activity from linear mixed-effects models were represented by horizontal lines and diamonds, respectively. The numbers in parentheses represent the count of observations and colored diamonds indicates significant effects of different soil enzyme activity while the statistically non-significant results were represented by grey symbols, respectively. (a) ~ (p): CATAL, catalase; UREAS, urease; INVER, invertase; ALKAL, alkaline phosphatase; ACIDP, acid phosphatase; POLYP, polyphenol oxidase; DEHYD, dehydrogenase; CELLU, cellulase; NEUPH, neutral phosphatase; PROTE, proteinase; βGLUC, β-1,4-glucosidase; ARYLS, arylsulfatase; βXYLO, β-1,4-xylosidase; βACET, β-1,4-N-acetyl-glucosaminidase; NITRA, nitrate reductase; ARYLA, arylamidase. ***$P < 0.001$, **$P < 0.01$, *$P < 0.05$.

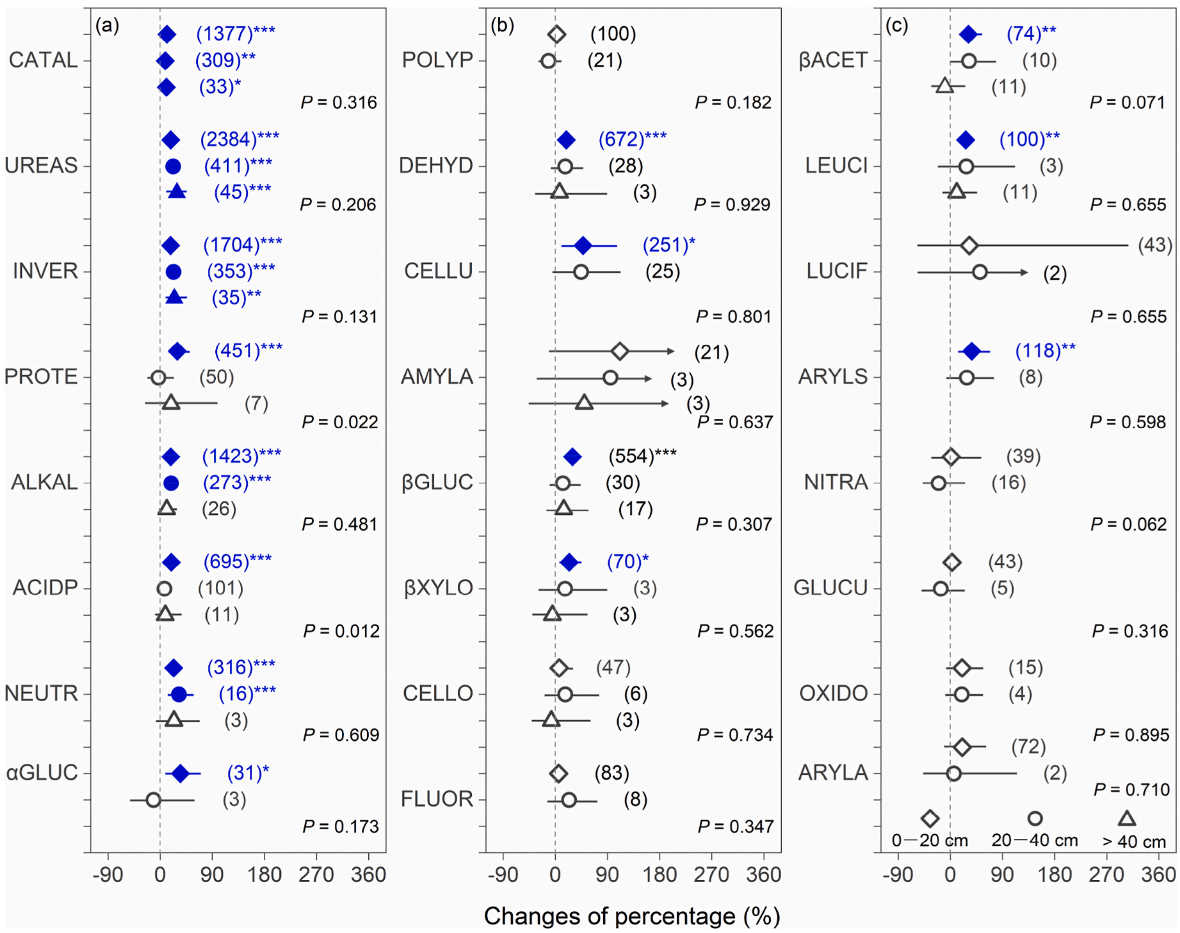

Fig. 3. Effects of soil depth on the responses of catalase (CATAL), urease (UREAS), invertase (INVER), proteinase (PROTE), alkaline phosphatase (ALKAL), acid phosphatase (ACIDP), neutral phosphatase (NEUPH), α-glucosidase (αGLUC), polyphenol oxidase (POLYP), dehydrogenase (DEHYD), cellulase (CELLU), amylase (AMYLA), β-1,4-glucosidase (βGLUC), β-1,4-xylosidase (βXYLO), cellobiosidase (CELLO), fluorescein diacetate (FLUOR), β-1,4-N-acetyl-glucosaminidase (βACET), leucine aminopeptidase (LEUCI), luciferase (LUCIF), arylsulfatase (ARYLS), nitrate reductase (NITRA), glucuronidase (GLUCU), oxidoreductase (OXIDO) and arylamidase (ARYLA) to conservation tillage. The 95% confidence intervals and estimated value of fixed effects of invertebrate variables on soil enzyme activity from linear mixed-effects models are represented by horizontal lines and diamonds, respectively. The numbers in parentheses represent the count of observations and p-values for differences among soil depth are shown, and blue solid diamonds, rounds, triangles indicate significant positive effects while the statistically non-significant results were represented by empty symbols. ***$P < 0.001$, **$P < 0.01$, *$P < 0.05$.

cultivated land (e.g., paddy and dryland) may affect enzyme activity through SBD, aggregates, compaction, and water-filled void (Gao et al., 2019; Piazza et al., 2020). We also found that the significant effect of conservation tillage on enzyme activity was mainly observed in the years with medium and long conservation tillage (Fig. S6) (Melero et al., 2008), this may be attributed to the fact that conservation tillage significantly alters the soil microbial community, for example, long-term conservation tillage increases the abundance of fungi (Zhang et al., 2022), resulting in the formation of stable fungal and bacterial networks (Zheng et al., 2022b); moreover, the recently reported synergistic effect of long-term conservation tillage on enzyme activity by global warming is also worth pondering (Wang et al., 2022). In contrast to the mechanism by which long-term conservation tillage promotes enzyme activity, short-term conservation tillage promotes enzyme activity that may be associated with the "priming effect" of soil C accumulation (Guo et al., 2021), i.e., the increase in SOM stimulated the activity of microorganisms in the short term and promoted the secretion of enzymes. It is worth noting that the promotional effect of conservation tillage on soil enzymes was highest in the medium term, and whether this is a single-peak curve pattern over time still needs to be supported by continuously monitored data.

In addition to soil depth, crop type, and the years of conservation tillage, the geographical characteristics, climate, pH, and initial soil properties (bulk and nutrients) were also important moderating variables for driving soil enzyme activity in response to conservation tillage (Table 1). There may be an interaction between the moderating effects of latitude, elevation, and climate, as they ultimately act to influence the moisture and temperature of the soil environment, which in turn has an

Table 1
The linear mixed effect model was used to analyze the effects of main variables on the response of soil enzyme activity to conservation tillage implementation.

Soil enzyme	Latitude	Elevation	MAP	MAT	PET	pH	SBD	SOM	TN	AN	NH_4	TP	AP	TK	AK	EC
CATAL	−0.003	0.001	0.001	**0.004**	0.001	−0.010	0.193	0.005	−0.156	3.711	111.32	**0.669**	0.159	−0.005	0.009	0.001
PEROX	−0.006	0.001	0.001	0.003		**−0.652**		0.571	−20.350	131.691			−145.97		−87.324	
UREAS	**−0.003**	**0.001**	−0.001	−0.003	0.001	0.032	−0.172	−0.016	−0.599	−4.952	**−366.26**	0.418	−0.214	0.003	−0.007	−0.002
INVER	−0.001	0.001	0.001	−0.002	0.001	−0.054	−0.093	0.038	−1.054	18.898	**267.91**	−0.410	−0.251	−0.002	−0.017	**−0.002**
ALKAL	−0.001	0.001	−0.001	0.001	0.001	0.036	**−0.346**	0.001	−0.039	−10.479	139.14	0.367	−0.066	−0.003	−0.002	−0.001
ACIDP	−0.001	0.001	−0.001	0.004		**0.102**	0.277	−0.028	0.013	−6.099	−158.41	**−2.128**	−29.07	0.003	8.609	−0.002
NEUPH	−0.003	**0.001**	−0.001	0.004	0.002	0.008	−0.534	−0.004	−0.656	2.314	−27.460	0.616	0.501	0.059	**27.453**	−0.002
POLYP	0.005	0.001	−0.001	−0.003	−0.001	0.040		−0.004	−0.395	6.941	−122.04	0.127	6.068	−0.034	−0.726	0.001
PHENO	0.049	−0.001	−0.002	**−0.090**		0.188	−12.037	−0.202	−6.482				353.83		178.69	
PROTE	−0.003	0.001	0.001	0.002	−0.001	0.039	−0.435	**0.078**	−0.961	−27.745		**1.242**	16.523	**1.405**	**11.425**	−0.003
DEHYD	−0.001	0.001	0.001	0.001	−0.002	0.023	**−1.796**	0.040	−0.162	6.418		−1.055	**3.261**	−0.006	8.462	−0.001
CELLU	−0.002	−0.001	0.001	0.030		−0.330	−1.067	0.073	−0.754	74.658		−5.470	−0.641	−0.136	−0.035	
αGLUC	**0.014**	−0.001	−0.001	−0.024	0.001	0.032		−0.300	23.731				188.92		148.82	
βGLUC	0.002	0.001	−0.001	−0.008	−0.002	0.052	**−1.095**	−0.028	−0.729	4.060	1363.9	−10.805	−2.603	−0.328	−3.977	−0.002
βXYLO	0.007	−0.001	0.001	**0.042**		0.044	0.090	−0.542	−5.588	−0.904			−46.805		**113.81**	
CELLO	0.007	0.001	−0.001	−0.013	−0.002	−0.044		−0.080	−13.245				3.975		0.115	
βACET	−0.005	0.001	**0.001**	0.011	−0.009	0.075	−5.662	−0.094	−1.201	−39.081		21.788	127.53		47.602	
LUCIF	0.044	0.019	−0.002	−0.171		1.028		0.618	10.087		1080.2	32.520	**423.23**	1.502	33.300	
SULFA	0.005	0.002	−0.002	−0.118		**0.261**		0.023	−1.243	−7.980			−77.129		−51.569	
ARYLS	−0.007	−0.001	**−0.002**	−0.030		0.008	−0.205	0.173	3.684			28.599	102.89	0.431	67.739	
NITRA	**0.046**		−0.002	−0.022				0.217	1.982			−11.677			−25.206	
POTEN	0.002	−0.001	0.001	0.015		0.054		−0.070	**14.190**							
TOPFA	0.006		**−0.001**	−0.007		0.290		−0.493	−16.200				41.922		27.796	

Estimates (i.e., the slop of the model) of soil enzyme are exhibited, and the bold numbers indicate statistical significance (***$P < 0.001$, **$P < 0.01$, *$P < 0.05$).
MAP mean annual precipitation (mm); MAT mean annual temperature (°C); PET potential evapotranspiration (mm); SBD soil bulk density (g/cm^3); SOM soil organic matter (%); TN total nitrogen (%); AN available nitrogen (%); NH_4 ammonium nitrogen (%); TP total phosphorus (%); AP available phosphorus (%); TK total potassium (%); AK available potassium (%); EC electric conductivity (μs/cm).

effect on soil microorganism and enzyme activity (Bahram et al., 2018; Mod et al., 2021; Zhou et al., 2020; Zuber and Villamil, 2016). MAT, pH positively or negatively influenced the effect value of soil enzyme activity in response to conservation tillage ($P < 0.05$), which is similar to the convex curve relationship between temperature, pH and microorganisms (Bahram et al., 2018), and the same pattern holds for soil enzyme activity due to the close association of microorganisms with soil enzyme activity. However, due to the specificity of soil enzymes, they may have different optimal pH and temperature values when they are most efficiently on their own substrates (Gispert et al., 2013; Mod et al., 2021). Although soil properties, particularly SBD and EC, were thought to moderate the effects of conservation tillage on soil enzymes, their effects were inconsistent. For example, SBD has been linked to SOM decomposition and anaerobic conditions (Jin et al., 2009; Yue et al., 2023), thus it could indirectly regulate soil enzyme activity under conservation tillage; similarly, EC mediated salinity effects could lead to a decrease in soil enzyme activity as ES increase (Frankenberger Jr. and Bingham, 1982). Soil nutrients regulate enzyme activity in response to conservation tillage primarily through SOM, NH_4, TP, AP and AK. Soil enzymes are involved in the soil elemental cycle, so enzyme activity is closely linked to nutrients. A recent synthetic report on litter removal indicated that soil enzyme activity in terrestrial ecosystems is strongly influenced by carbon and nitrogen (Ai et al., 2023).

Conservation tillage overall increased soil enzyme activity while increasing surface organic matter (Lv et al., 2023). This phenomenon was reasonable and it was also influenced by the duration of conservation tillage (Fig. S6) (Melero et al., 2008). Although the increase in enzyme activity would promote SOM conversion and decomposition, the input of SOM provided by the increased plant residues from straw would be much greater than the amount of SOM consumed by microbial decomposition, consistent with the view that conservation tillage increases carbon sequestration and reduces carbon emissions (Huang et al., 2018; Yue et al., 2023). We also found that soil enzyme activity was more sensitive in wheat and less sensitive in rice under conservation tillage conditions, suggesting that in addition to regulation of soil enzymes by plant secretions and nutrient strategies, the negative correlation between soil moisture conditions and soil enzyme activity may be key to this phenomenon (Nugroho et al., 2023; Schmidt et al., 2016). This can be supported by the modulation of soil enzyme activity response to conservation tillage by MAP (Table 1), in addition to crop irrigation, which can also modulate soil enzyme activity through moisture (Muhammad et al., 2022).

4.3. *Uncertainty analysis*

Although our study compiled 14,308 paired observations across global cropland to quantify the effects of conservation tillage on soil enzyme activity, there are still some limitations to our synthesis. For example, although cropland data from Asia, Europe, and North America were collected in our database, there was limited data from other croplands around the world, which hinder to evaluate the effect of conservation tillage on soil enzyme activity under different climatic zones, and the lack of sampling sites at high latitudes limits our study to a global context with various climatic conditions. In addition, the lack of data on heavy metal ions in soil and s soil moisture in evaluating moderator variables is one of the limitations of this study because these variables are also important factors affecting enzyme activity (Aksoy et al., 2023; Bozdogan Sert et al., 2019; Cetin, 2013; Pekkan et al., 2021). Therefore, we encourage future studies to include heavy metal ions and soil moisture in the study of the effect of conservation tillage on soil enzyme activity as well.

5. Conclusions

The comprehensive meta-analysis found that conservation tillage has a positive effect on the activity of several soil enzymes, with effects varying enzyme type and influenced by other moderating variables. Our results also suggest that the combination of various conservation practices (e.g., no-till, straw return) might not absolutely lead to an exponential increase in enzyme activity, but the combination of straw return and other conservation practices still has great potential. In addition, the effect of conservation tillage on soil enzyme activity is concentrated in the topsoil and is moderated by crop type, years of conservation tillage, climate, and soil properties, with elevation, MAT, MAP, SBD, pH, and AK being crucial factors affecting a variety of enzyme activities. The results of this study can help to better comprehend the effects of conservation tillage on soil activity and provide useful guidance for agricultural management.

CRediT authorship contribution statement

Linsheng Wen: Conceptualization, Methodology, Software, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Yun Peng:** Conceptualization, Methodology, Software, Investigation. **Yunrui Zhou:** Visualization, Investigation. **Guo Cai:** Visualization, Investigation. **Yuying Lin:** Formal analysis, Writing – review & editing. **Baoyin Li:** Formal analysis, Supervision, Project administration, Funding acquisition, Writing – review & editing.

Declaration of competing interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled "Effects of conservation tillage on soil enzyme activities of global cultivated land: A meta-analysis".

Data availability

Data will be made available on request.

Acknowledgments

The research was supported by the Natural Science Foundation of Fujian Province (2023J01514), the National Natural Science Foundation of China (Grant No. 41901221 and 31971643), the Science and Technology Project of Fujian Provincial of Water Resources Department (Grant No. SC-290), and the Science and Technology Project of Fujian Forestry Bureau (Grant No. SC-259). Finally, we would like to thank the anonymous reviewers and the editors for their helpful comments that improved the manuscript substantially.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2023.118904.

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