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Forest transformation effects on the soil water-holding capacity depend on the forest characteristics and soil properties: A case study in the subtropical regions of southeast China

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Abstract: Forest transformation commonly occurs in subtropical areas due to extensive human disturbance. However, we know little about how forest transformation may affect the soil water-holding capacity. Here, we evaluated the effects of forest transformation from natural forests to secondary forests, *Castanopsis carlesii* plantations, and *Cunninghamia lanceolata* plantations on the soil water-holding capacity, including the soil water content (*SWC*), maximum water holding rate (R_t), capillary holding rate (R_c), and non-capillary water holding rate (R_n), and assessed the influences of soil properties and stand characteristics on the forest transformation effects. The results showed that (*i*) the soil water-holding capacity in secondary forests increased significantly (*SWC*: 27.3%; R_t: 50.9%; R_c: 36.9%; R_n: 14.0%), but decreased in the *Cunninghamia lanceolata* plantations (*SWC*: 24.6%; R_t: 47.0%; R_c: 34.0%; R_n: 13.0%), compared to the nature forests (*SWC*: 26.0%; R_t: 48.3%; R_c: 34.9%; R_n: 13.4%); (*ii*) the soil water-holding capacity was positively correlated with the soil porosity, soil total nitrogen concentration, stand density, but negatively influenced by the soil bulk density and diameter at breast height (*DBH*); and (*iii*) the stand density, *DBH* and litterfall amount were the major factors regulating the soil water-holding capacity after the forest transformation. Overall, these results indicated that the soil water-holding capacity would be strongly altered by the forest transformation, but it depends on the soil properties before the transformation and the characteristics of the transformed forests. Our findings will help to better understand the functions of forests in water source conservation under the pressures of human disturbances and environmental changes.

Keywords: *Castanopsis carlesii*; *Cunninghamia lanceolata*; soil water relationship; stand characteristics; subtropical forests

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Soil serves as the primary entity for water conservation in forests and the vital water source for downstream aquatic ecosystems (Tanaka et al. 2021), and its water-holding capacity impacts the productivity of the forest directly. The soil water-holding capacity may be easily affected by various environmental factors, including changes in the climate (Feng, Liu 2015), soil properties (Phillips et al. 2019), and stand characteristics (Archer et al. 2015). Forest transformation, which refers to the process where one type of forest ecosystem is converted into another type due to natural or anthropogenic impacts (Zischg et al. 2021), can induce changes in the forest environment and would thus have the potential to influence the soil water-holding capacity substantially. However, few studies have focused on how the forest transformation may affect the soil water-holding capacity, especially in subtropical regions where intensive forest transformation commonly occurs (Luo et al. 2019).

Forest transformation can affect the forest environment from various aspects, and thus directly or indirectly impact the soil water-holding capacity. For example, following forest transformation, changes in the forest litterfall amount and litter quality would directly regulate the amount of water retained in the litter layer (Tan et al. 2024). The litter quality and quantity can also indirectly regulate the soil water-holding capacity by affecting the infiltration and evaporation of the forest floor (Sharafatmandrad et al. 2010; Wang et al. 2020). Also, different forest types usually have divergent canopy structures, which can significantly affect the rainfall partitioning and thus the amount of water reaching the soils (Yue et al. 2021). In addition, root systems will change substantially following the forest transformation, and thus would affect the soil properties such as the bulk density, soil porosity, and the concentrations of soil organic matter that are closely related to the water-holding capacity (Yu et al. 2018; Yang et al. 2023).

Subtropical forests play a significant role in water and soil conservation (Zhou et al. 2012; Zhang et al. 2022). However, with intensive disturbances from anthropogenic activities, many of the natural subtropical forests have been transformed into secondary forests or tree plantations. To explore the responses of the soil water-holding capacity following forest transformation in subtropical areas, we carried out a year-long experiment from March 2022 to February 2023 to evaluate how the transformation of natural forests to broadleaved secondary forests, *Castanopsis carlesii* plantations, and *Cunninghamia lanceolata* plantations may affect the soil water content, maximum water holding rate, capillary holding rate, and non-capillary water holding rate in the subtropic region of southeast China. We hypothesised that (*i*) the soil water-holding capacity would significantly increase in the secondary forests and *Castanopsis carlesii* plantations, but decrease in the coniferous *Cunninghamia lanceolata* plantations following the forest transformation; and (*ii*) the changes in the soil properties and forest characteristics induced by the forest transformation were the major drivers of the forest transformation effects on the soil water-holding capacity.

MATERIAL AND METHODS

Study area. The study area is situated in the subtropical forests of the Sanming Research Station for Forest Ecosystem and Global Change, Fujian Normal University, Sanming, Fujian Province (26°19'N, 117°36'E), with an average elevation of around 300 m a.s.l. The climate is humid subtropical (Köppen classification), with a long-term (between 1981 and 2010) mean annual temperature of 19.3 °C and a mean annual precipitation of 1610 mm (Yang et al. 2024). During the study period, the rainfall events mainly occurred in May and June, with minimal rainfall amount occurring in July and August (Figure 1).

The study area hosts the most extensive evergreen broadleaved forests in China, dominated by *Castanopsis carlesii* and *Castanopsis kawahamii*. Since 1958, a large proportion of the original natural forests (i.e. primary forests) have been transformed into *Castanopsis carlesii* and *Cunninghamia lanceolata* plantations, while some of the deforested areas developed as secondary forests through natural succession, dominated by *Castanopsis carlesii*. The soil was classified as a Ferric Acrisol with a sandy clay texture developed from biotite granite according to the World Reference Base (WRB) classification system (Jiang et al. 2019). The site conditions, including the soil type, terrain, elevation, slope, and climate, were the same before the transformation. However, the stand characteristics of the four types of forests, such as the stand density and litterfall amount, greatly differed. De-

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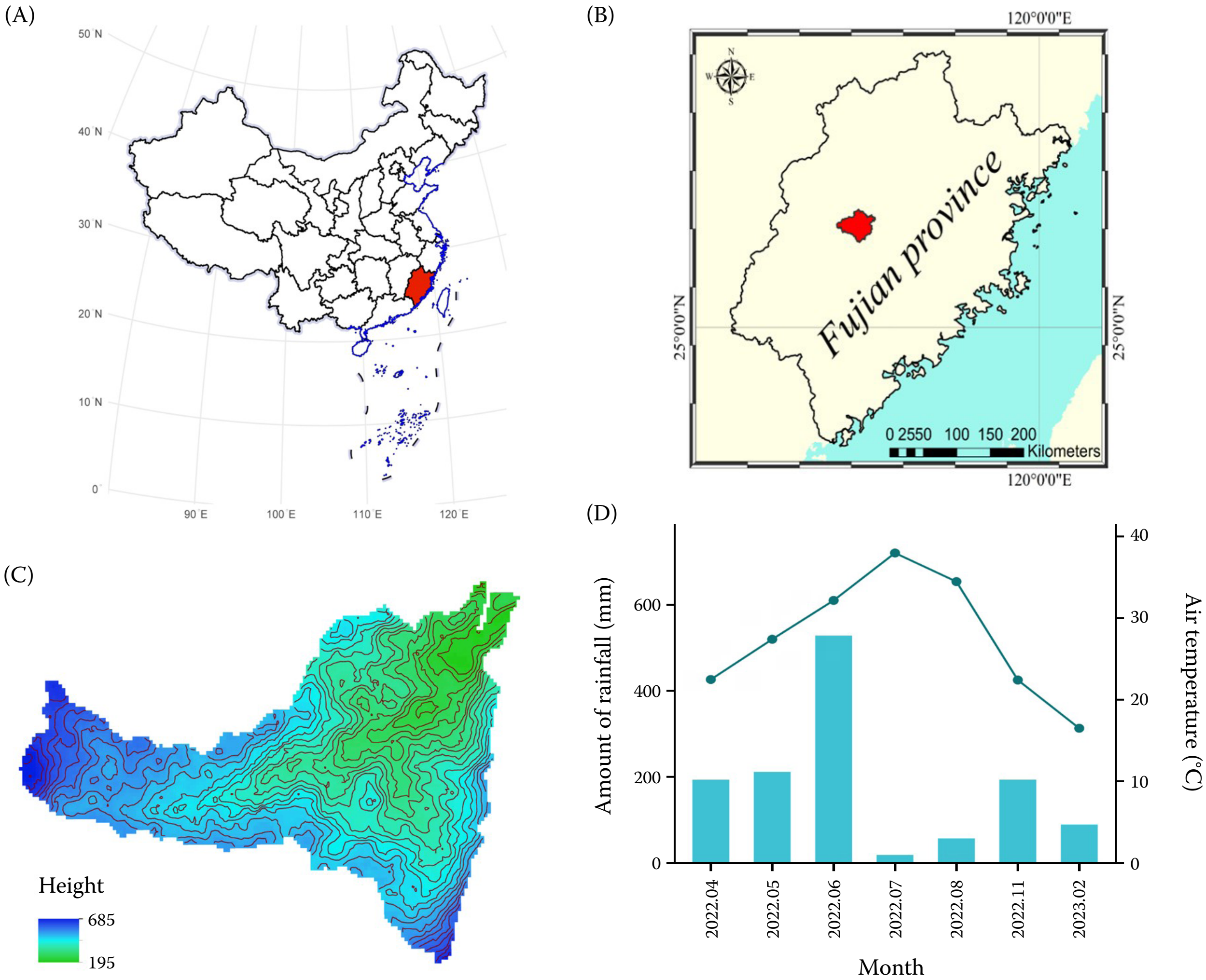

Figure 1. (A) The map of China and the position of Fujian province, (B) the location of the study area and (C) its topography and (D) climate during research period

tailed information on these variables was described in a previous study (Xu et al. 2023).

Experimental design. Soil samples were collected monthly during the rainy season (April–August 2022) and bimonthly during the dry season (September 2022 – February 2023), resulting in seven sampling events in total. While considering the topography, soil samples were taken from sites with similar slopes (between 31.7° and 33°) under the canopy. After excavating a soil profile approximately 0.5 m away from the tree base to a depth of 40 cm, sampling rings (7.98 cm in diameter, 2 cm in height) were inserted at 0–20 cm and 20–40 cm depths in independent plots. Three replicates of soil samples were collected for each forest type.

The soil water content and bulk density were determined after drying the samples to a constant weight at 105 °C. The maximum water holding capacity was calculated by immersing the samples in water for 12 h, followed by weighing. The capillary water holding capacity was measured after drying the samples in sand for 48 h and weighing them. The non-capillary water holding capacity was determined after drying the samples at 105 °C to a constant weight and reweighing. The maximum water-holding capacity, capillary water-holding capacity and non-capillary water-holding capacity were static measures (volume of water per volume of soil). In contrast, the maximum water-holding rate, capillary water-holding rate, and non-capillary water-holding rate were gravimetric measures (mass of water per mass of soil), derived from the porosity and bulk density. The soil particle composition of homogenised samples (sieved

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< 2 mm) was analysed using a laser particle size analyser (MasterSize 2000, United Kingdom). The soil organic carbon (*SOC*) and total nitrogen (*TN*) concentrations were quantified using an automatic elemental analyser (Elemental Analyser Vario EL III, Germany).

Calculation and statistical analysis. The maximum water holding rate, capillary holding rate, and non-capillary water holding rate of soil were calculated using the following Equations (1–3):

$$R_t = \frac{P_t}{b} \times 100\% \quad (1)$$

$$R_c = \frac{P_c}{b} \times 100\% \quad (2)$$

$$R_n = \frac{P_n}{b} \times 100\% \quad (3)$$

where:

R_t – maximum water holding rate (%) of the soil;
R_n – non-capillary water holding rate (%) of the soil;
R_c – capillary holding rate (%) of the soil;
P_t – soil total porosity (%);
P_c – capillary porosity (%);
P_n – non-capillary porosity (%);
b – soil bulk density ($g \cdot cm^{-3}$).

Before the statistical analysis, the normality and homogeneity of the data were assessed ($P > 0.05$). A one-way analysis of variance (ANOVA) was used to test the differences in the soil's physical and chemical properties, soil water content, maximum water holding capacity, capillary holding capacity, and non-capillary water holding capacity across forest types ($P < 0.05$). A post hoc analysis was conducted using the least significant difference (LSD) method where applicable ($P < 0.05$). Pearson's correlation analysis examined the relationships between the environmental factors and soil water-holding capacity variables, while a principal component analysis (PCA) was used to assess the relative importance of the environmental factors. Linear mixed-effects models were used to quantify the relationships between the soil water holding capacity and environmental factors. All the data analyses were performed using R (Version 4.3.3; R Core Team 2020), and the following packages were utilised: 'nortest', 'agricolae', 'FactoMineR', 'factoextra', and 'lmerTest'.

RESULTS

Overall, following the forest transformation, the annual mean soil water-holding capacity generally increased in the secondary forests and *Castanopsis carlesii* plantations, but decreased in the *Cunninghamia lanceolata* plantations compared with natural forests (Figure 2). However, variations in the *SWC*, R_t, R_c, R_n and among the different forest types changed during the different sampling months. Likewise, significant differences in the soil properties were also observed among the different forest types, including the bulk density (*BD*), texture, and chemical properties such as the soil pH, organic carbon (*SOC*), and total nitrogen (*TN*) concentrations (Table 1). However, the soil capillary and non-capillary porosities showed minimal variation between the stands. Compared to natural forests, the *BD* and pH increased in the secondary forests and *Castanopsis carlesii* plantations, but decreased in the *Cunninghamia lanceolata* plantations. The soil clay and silt contents exhibited an increasing trend after the forest transformation, whereas the soil sand content showed an opposite trend. In addition, the *SOC* concentration decreased in the *Castanopsis carlesii* plantations, but increased in the secondary forests and *Cunninghamia lanceolata* plantations following the forest transformation, while the *TN* concentration increased in the secondary forests, but decreased in both the *Castanopsis carlesii* and *Cunninghamia lanceolata* plantations.

Strong correlations between the soil water-holding capacity, soil properties, and stand characteristics were observed (Figure 3). Specifically, the soil clay and silt contents exhibited negative correlations with the stand characteristics, whereas the soil sand content and *BD* showed positive correlations. The soil chemical properties, including the soil pH, *SOC*, and *TN* concentrations, were also closely related to the stand characteristics. Additionally, the stand characteristics, particularly the stand age and diameter at breast height (*DBH*), negatively correlated with the soil water-holding capacity.

The principal component analysis (PCA) of the stand characteristics influencing the soil properties and soil water-holding capacity revealed that the first axis (Dim1) accounted for 39.9%, 36.6%, 54.8%, 46.9%, 36.0%, and 41.3% of the variances in the stand age, *DBH*, canopy density, litterfall amount, tree species, and stand density, respectively, while

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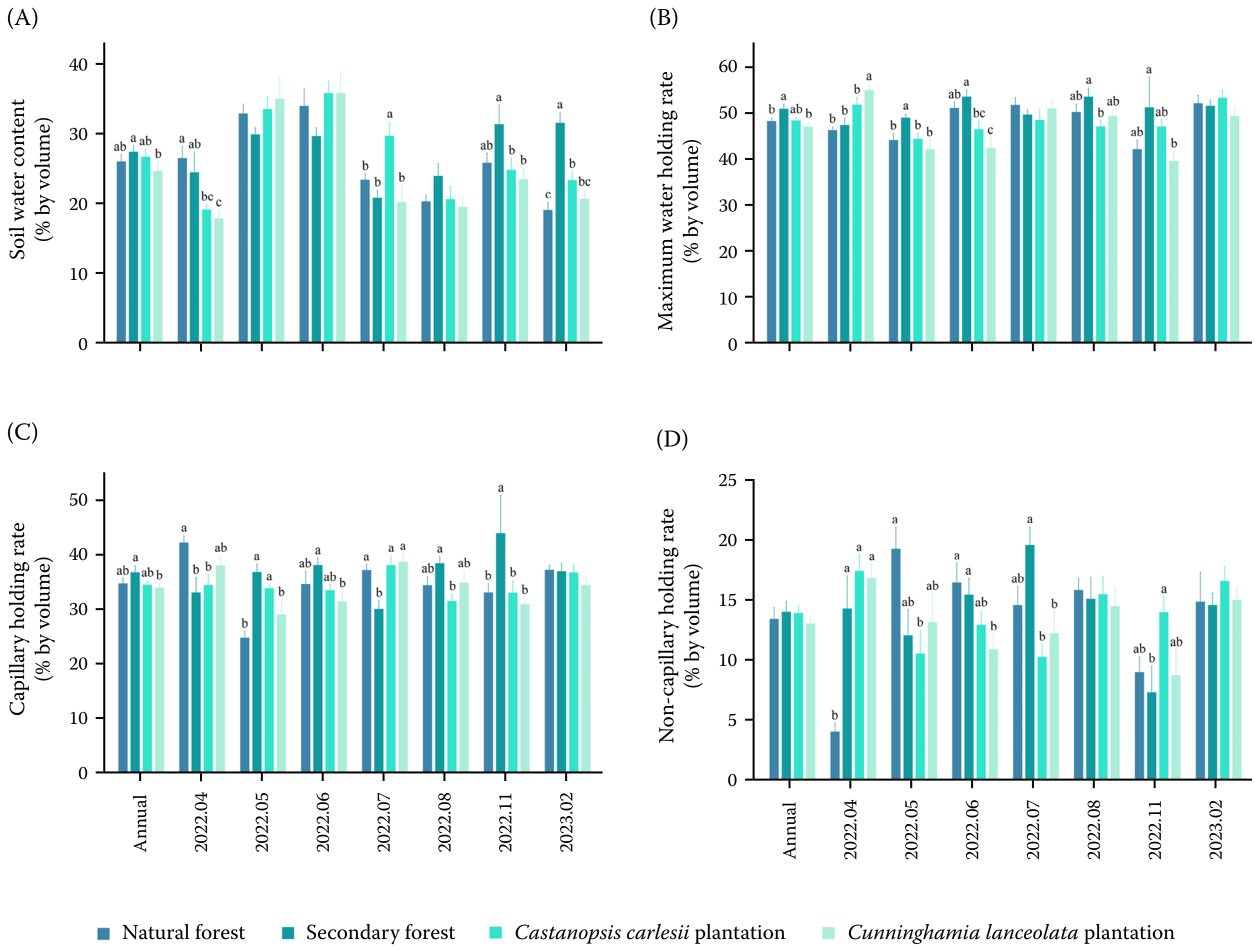

Figure 2. (A) Characteristics of in-soil water content, (B) maximum water holding rate, (C) capillary holding rate, and (D) non-capillary water holding rate among different forest types

[a–c]significant differences ($P < 0.05$) between forest types; results were expressed as mean ± standard error ($N = 6$), with the annual average calculated from all observations ($N = 42$)

Table 1. Characteristics of soil properties among different forest types (mean ± SE, $N = 42$)

Soil properties	Natural forest	Secondary forest	*Castanopsis carlesii* plantation	*Cunninghamia lanceolata* plantation	ANOVA across different forest types	
					F	*P*
Capillary porosity (%)	34.90 ± 0.93^{ab}	36.91 ± 1.24^{a}	34.58 ± 0.62^{ab}	34.04 ± 0.83^{b}	1.559	0.201
Non-capillary porosity (%)	13.39 ± 0.93^{a}	14.00 ± 0.85^{a}	13.84 ± 0.63^{a}	12.99 ± 0.71^{a}	0.336	0.799
BD (g·cm^{-3})	1.30 ± 0.03^{b}	1.13 ± 0.03^{bc}	1.20 ± 0.04^{c}	1.32 ± 0.03^{a}	8.905	< 0.001
Clay (%)	2.41 ± 0.15^{a}	2.93 ± 0.12^{b}	3.04 ± 0.11^{b}	3.24 ± 0.25^{a}	8.074	< 0.001
Silt (%)	7.64 ± 0.40^{c}	9.26 ± 0.45^{a}	10.34 ± 0.30^{d}	11.51 ± 1.06^{b}	51.250	< 0.001
Sand (%)	89.94 ± 0.49^{b}	87.80 ± 0.53^{a}	86.62 ± 0.39^{c}	85.24 ± 1.27^{b}	42.880	< 0.001
pH	4.75 ± 0.04^{b}	4.68 ± 0.03^{a}	4.62 ± 0.03^{a}	4.85 ± 0.03^{a}	6.327	< 0.001
SOC (g·kg^{-1})	24.86 ± 0.38^{c}	27.20 ± 0.30^{b}	22.47 ± 0.18^{ab}	25.60 ± 0.23^{a}	9.439	< 0.001
TN (g·kg^{-1})	1.68 ± 0.03^{a}	1.85 ± 0.02^{ab}	1.48 ± 0.02^{bc}	1.66 ± 0.02^{c}	5.277	< 0.010

[a–c]significant differences ($P < 0.05$) between forest types; ANOVA – analysis of variance; *BD* – bulk density; *N* – number of samples; SE – standard error; *SOC* – soil organic carbon; *TN* – soil total nitrogen

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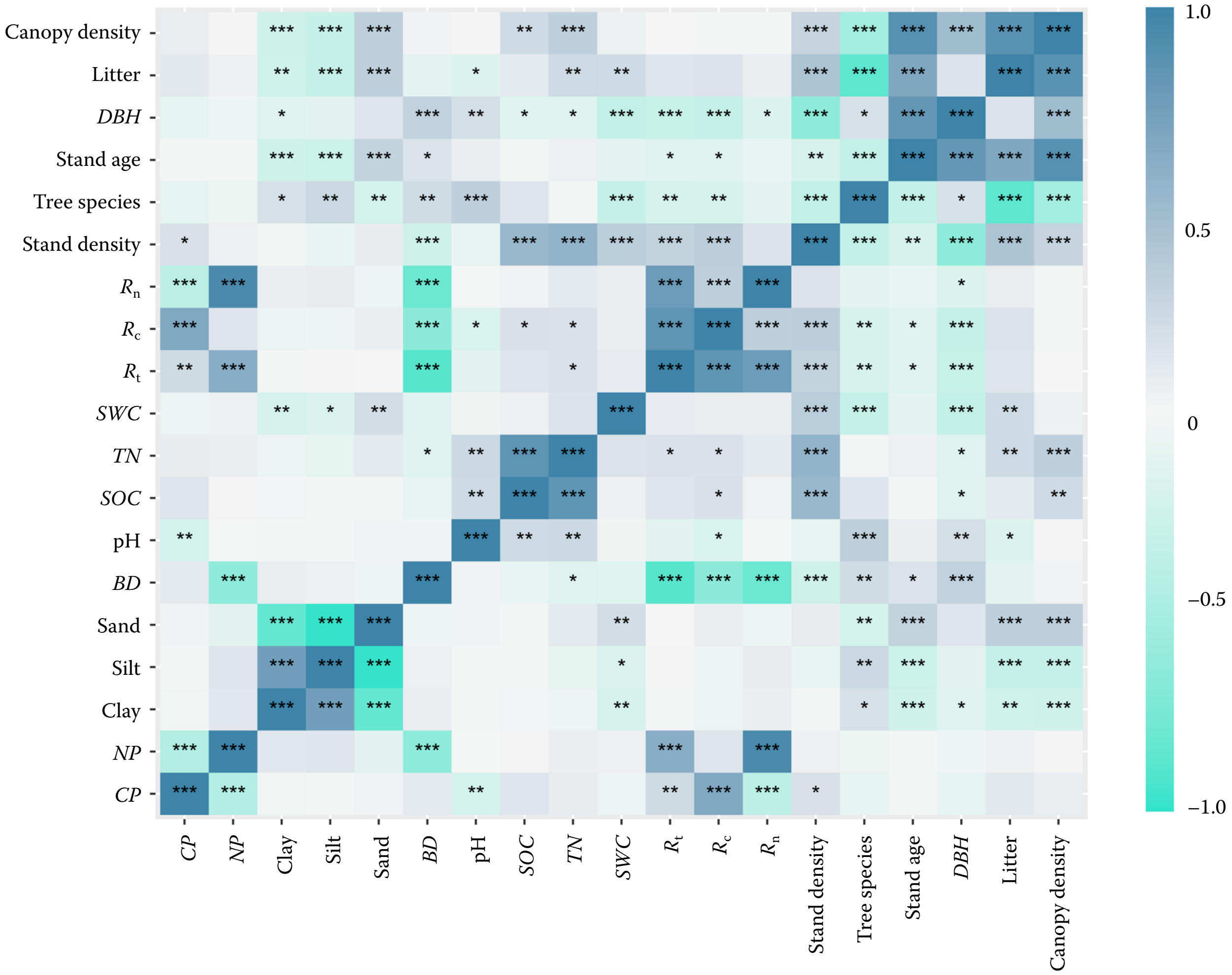

Figure 3. Pearson correlation between soil water-holding capacity and various environmental factors

*P < 0.05; **P < 0.01; ***P < 0.001; *CP* – soil capillary porosity; *BD* – soil bulk density; *DBH* – diameter at breast height; litter – litterfall amount; *NP* – soil non-capillary porosity; R_c – capillary holding rate; R_n – non-capillary water holding rate; R_t – maximum water holding rate; *SD* – stand density; *SOC* – soil organic carbon; *SWC* – soil water content; *TN* – soil total nitrogen

the second axis (Dim2) explained 36.5%, 21.3%, 36.7%, 20.6%, 32.0%, and 24.5%, respectively (Figure 4). The soil texture and *BD* had relatively strong contributions to the stand characteristics, whereas the other soil physical properties, such as the capillary porosity, contributed to a lesser extent. Compared with the soil physical properties, the stand characteristics had more substantial effects than chemical properties, especially the *DBH* and stand density. Among the chemical properties, the pH, *SOC*, and *TN* concentrations were notably influenced by the stand density and *DBH*. Regarding the soil water-holding capacity, the stand characteristics exerted a greater impact on the soil maximum water holding rate, capillary holding rate and non-capillary holding rate, but a smaller effect on the soil water content.

Using linear mixed-effects models with the sampling time as the random effect, we further evaluated the impacts of the soil properties and stand characteristics on the soil water-holding capacity (Table 2). The soil water content, maximum water holding rate, capillary holding rate, and non-capillary water holding rate were used as the fixed variables, while the soil parameters and stand characteristics were used as the variable variables, all based on the PCA plots above (Figure 3). The results showed that the soil physical properties, including the soil porosity and *BD*, exhibited strong correlations with the soil

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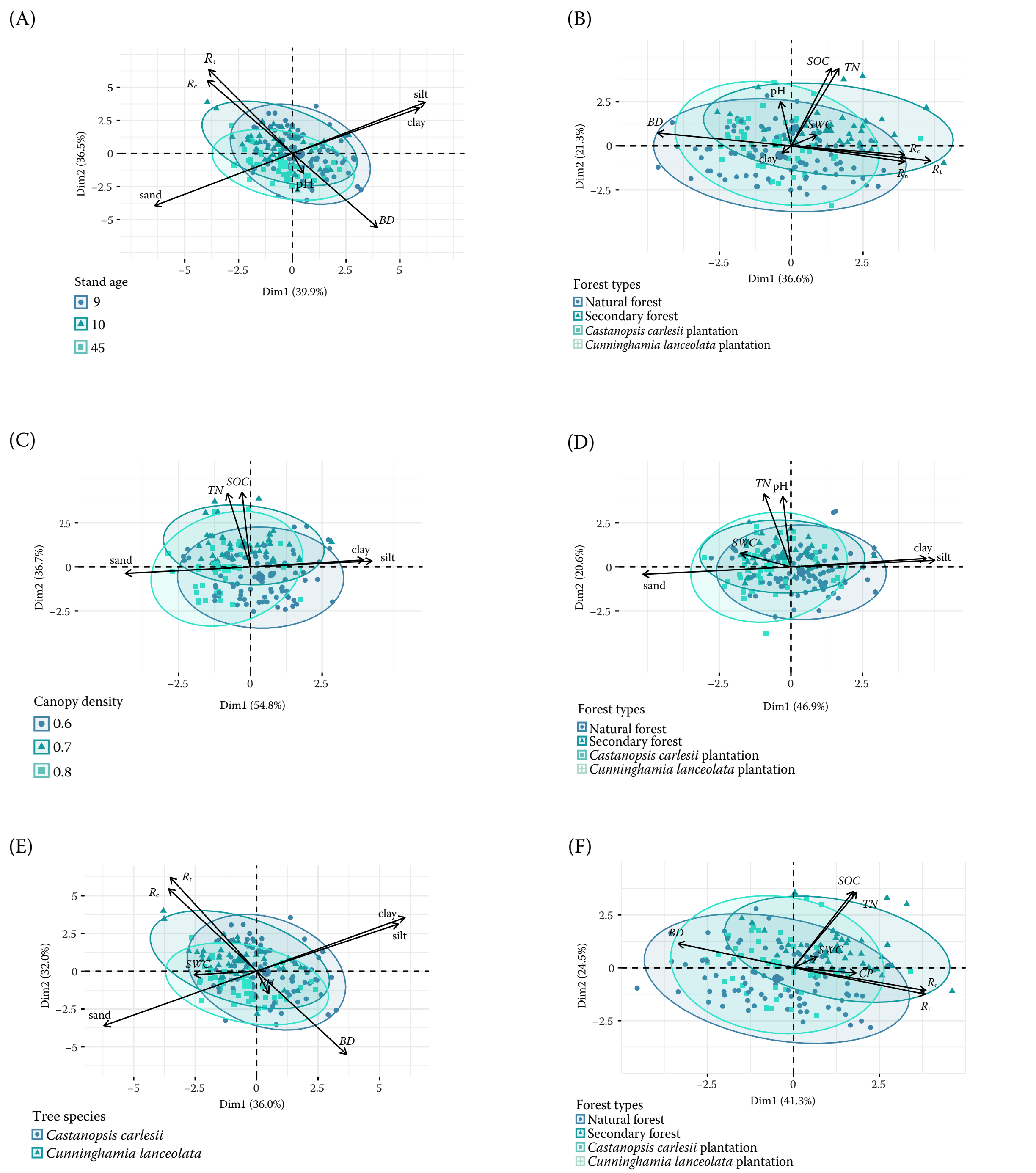

Figure 4. Principal component analysis (PCA) showing relationships between (A) soil properties and stand age, (B) diameter at breast height, (C) canopy density, (D) litterfall amount, (E) tree species, and (F) stand density

BD – soil bulk density; *CP* – the capillary porosity of soil; Dim1, Dim2 – the first and second principal components, respectively; R_c – capillary holding rate; R_n – non-capillary water holding rate; R_t – maximum water holding rate; *SOC* – soil organic carbon; *SWC* – soil water content; *TN* – soil total nitrogen

water-holding capacity, while the soil chemical properties, such as the *SOC* and *TN* concentrations, showed weak or non-significant impacts. The stand characteristics, including the tree species, stand density, and *DBH*, showed significant impacts on the soil water holding capacity, while the soil texture showed limited impacts on the water-holding capacity.

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Table 2. Effects of environmental factors on soil water-holding capacity as assessed using linear mixed-effects models

Environmental factors	*SWC*	R_t	R_c	R_n
Capillary porosity	1.23	2.34	11.96***	–6.48***
Non-capillary porosity	0.48	10.42***	1.15	39.08***
Clay	–0.18	0.97	0.10	1.50
Silt	–1.71	1.23	0.41	1.57
Sand	1.48	–1.23	–0.36	–1.63
Bulk density	–3.04**	–23.75***	–9.01***	–18.12***
pH	–1.18	–1.54	–2.91**	0.59
SOC	2.37*	1.59	1.85	0.58
TN	3.35**	1.85	1.65	12.23
Stand age	–2.24*	–2.26*	–2.24*	–1.25
Canopy density	0.79	–0.05	0.16	–0.26
Tree species	–6.24***	–3.23**	–3.27**	–1.70
Stand density	6.79***	4.65***	5.14***	1.98*
DBH	–6.74***	–4.86***	–5.03***	–2.39*
Litter	4.11***	2.00*	2.176*	0.91

*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$; *DBH* – diameter at breast height; litter – litterfall amount; R_c – capillary holding rate; R_n – non-capillary water holding rate; R_t – maximum water holding rate; *SOC* – soil organic carbon; *SWC* – soil water content; *TN* – soil total nitrogen

DISCUSSION

Consistent with our hypothesis, we found that the soil water-holding capacity generally increased in the secondary forests and *Castanopsis carlesii* plantations, but decreased in the *Cunninghamia lanceolata* plantations following forest transformation, and changes in the soil properties and forest stand characteristics were the major drivers of the forest transformation effects. The impact of the stand density on the soil properties such as the bulk density, pH, and nutrient content was considerable (Duan et al. 2019). For example, the stand density could influence the decomposition and stabilisation process of the litterfall, which plays a critical role in the accumulation of the soil organic matter (Menyailo et al. 2022). This process could also increase the soil porosity and *TN* concentration (Liu et al. 2009; Mouhamad et al. 2015). Organic acids released during decomposition may also have strong impacts on the soil pH (Shen et al. 2021). Different tree species can affect the soil structure through variations in the root system and growth patterns (Pawlik, Šamonil 2018). For example, larger trees usually contribute to higher soil organic matter via a greater amount of root exudates (Niiyama et al. 2010), and a larger amount of litterfall would increase the soil texture (Rodríguez et al. 2009). In addition, the stand age is closely related to the root system efficiency and organic matter accumulation (Pei et al. 2018), with mature natural forests and secondary forests exhibiting looser soils with superior texture. Therefore, forest transformation can lead to variations in the stand characteristics, such as the stand density, canopy structure, stand age, and litterfall amount, and thus indirectly affect the soil properties and water-holding capacity.

The stand characteristics of different forests significantly influenced the soil water-holding capacity by regulating the input and infiltration of the soil water. Precipitation, as the primary source of soil water (Hoang, Lu 2019), showed a strong positive correlation with the soil water content. In our study areas, the lower *DBH* coupled with the smaller canopy densities of the secondary forests and *Castanopsis carlesii* plantations compared with the natural forests would mean a higher throughfall, and thus can support larger soil moisture (Llorens, Domingo 2007; Sun et al. 2018). Furthermore, plant litter covering the forest floor can facilitate the slow and effective water infiltration (Wang et al. 2020), reducing the surface runoff and thus contribute to an increase in the soil water content

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(Tang et al. 2019; Chang et al. 2021). Following the transformation of natural forests to *Cunninghamia lanceolata* plantations, the soil water-holding capacity was reduced, which can be due to the reduced litterfall amount that restricted the retention of rainfall water (Liu et al. 2004).

The forest stand characteristics influenced the soil water-holding capacity mainly through their regulation of water infiltration and retention. Previous studies have shown that the stand density can enhance the soil water-holding capacity by increasing the soil porosity (Yu et al. 2018). The water storage capacity of non-capillary pores was primarily influenced by gravity, the storage capacity, and movement velocity (Alkan et al. 2010). In our study areas, the secondary forests exhibited the highest stand density, which would be beneficial for the soil porosity expansion, thereby improving the soil water infiltration and retention and improving the water-holding capacity (Tang et al. 2019). Moreover, we observed a negative correlation between the soil water-holding capacity and soil bulk density. This behaviour aligned with the findings of previous research (Yang et al. 2023), which attributed the reduction in the soil water-holding capacity to the lower porosity caused by the increased bulk density, an effect detrimental to soil water retention (Che et al. 2013). The stand characteristics also showed stronger correlations with the soil chemical properties that are closely related to the soil water-holding capacity (Hall, Marchand 2010). The research indicated a linear relationship between the *SOC* and the soil porosity (Naveed et al. 2014), indicating a decrease in the soil bulk density (Marschner et al. 2011), and thereby indirectly reinforcing the soil water-holding capacity.

Our results showed that stand characteristics were also important in regulating the soil water-holding capacity by regulating the moisture loss. The stand density showed significantly positive effects on the soil water holding capacity, which may be because a higher stand density usually means larger productivity and litterfall amount. Also, the stand density usually positively correlates with a more complex canopy structure, and thus can indirectly regulate the understory microclimate and rainfall partitioning (Yue et al. 2021; Chen et al. 2024) and thereby indirectly affect the soil water-holding capacity. As a result, the secondary forests with larger stand density generally exhibited a higher soil water-holding capacity compared to plantations. Moreover, the accumulation of litter on the soil surface served as a physical barrier, reducing the soil moisture evaporation (Sharafatmandrad et al. 2010). For instance, in *Cunninghamia lanceolata* plantations, limited litter production would elevate the soil evaporation rates, leading to a relatively lower soil water content compared to other forests. However, excessively thick layers of organic litter could hinder the water infiltration into the topsoil, paradoxically reducing the moisture in this layer despite the increased organic matter content (Franzluebbers 2002; Zhu et al. 2020).

Despite the patterns found in our study, there are still several uncertainties and limitations that should be taken into account in future studies. Firstly, the extreme weather conditions during the experimental period, where the rainfall mainly occurred in June, with little rainfall occurring in July may bias our results for obtaining a general pattern on a larger spatial scale. Also, the one-year duration in our study may limit our ability to capture the temporal variations in the soil water-holding capacity following the forest transformation, leading to uncertainties in the generated conclusions. Therefore, we will continue to perform the field experiments for a longer period to explore the long-term dynamic changes in the soil water holding capacity following the forest transformation.

CONCLUSION

Through performing a one-year field experiment, our results showed that the transformation of a natural forest to a secondary forest, a *Castanopsis carlesii* plantation and *Cunninghamia lanceolata* plantation, significantly increased the soil water content, maximum water-holding rate, capillary holding rate, and non-capillary water holding rate, but the transformation of the natural forest to the *Cunninghamia lanceolata* plantation showed an opposite trend. The changes in the soil water-holding capacity following the forest transformation were positively correlated with the soil porosity, *SOC*, *TN*, stand density, and litterfall, but negatively with the soil bulk density and *DBH*. Overall, our results clearly showed how transforming natural forests to different types of forests would affect the soil water holding capacity, indicating the importance of soil properties and stand characteristics. These results would be useful for a better understanding of quantifying the role

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of forests in soil and water conservation and can also provide valuable insights for forest management and sustainable development under the current global environmental change scenarios.

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