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RESEARCH ARTICLE

Changes in soil carbon, nitrogen, and phosphorus contents, storages, and stoichiometry during land degradation in jasmine croplands in subtropical China

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Abstract

Soil degradation is characterized by loss of soil organic matter, decline in fertility, imbalance in elemental content, deterioration of soil structure, and overall a deterioration of soil environment. According to the classification method of Pieri *et al.* (1992), the soil is classified into different degradation classes by calculating the soil structural stability index (St) of each sample point. We aimed to investigate changes in the contents, storages and stoichiometry of soil carbon (C), nitrogen (N), and phosphorus (P) together with changes in soil physical traits along a soil degradation gradient in jasmine croplands in Fuzhou area (China). The content and storage of soil C and N decreased with increasing intensity of land degradation. Soil organic C content was 15.4%, 32.3%, and 38.8% lower, respectively, in the low, medium, and high degree of degradation soils, than in the nondegraded soils. The soil C:N ratio was 18.5% higher in soils in the middle degree of degradation than in the nondegraded soils. Compared with nondegraded soils, the bulk density of the degraded soils increased and water content decreased. The decrease of soil pH coupled with salinity (conductivity) and the loss of aggregate stability are the main traits that distinguish degraded from nondegraded soils. We also detected a general N and P deficiency that is aggravated by the degradation process. Unreasonable management easily leads to degradation associated with a loss of organic C and total soil nutrients, thus impairing even more a general N and P deficiency in this area. Therefore, higher inputs of organic fertilizer should be added to alleviate the lack of organic matter, and appropriate burial should be conducted to reduce nutrient loss. Moreover, a rise of N and P fertilizer application is also advisable.

Keywords: Soil degradation index; Carbon; Nitrogen; Phosphorus; Storage; Stoichiometry; Jasmine

Introduction

China was growing jasmine area in 1334 ha^2 in 2015. China is one of the major producers of jasmine in the world accounting for about two-thirds of global planting area, and jasmine tea produced in Fuzhou accounts for more than half of Chinese production (Mei and Lin, 2016). Fuzhou jasmine has the longest planting history, and it plays an important role in conserving water sources, protecting shores and promoting siltation, and ensuring biodiversity. In 2014, the Fuzhou Jasmine and Tea Culture System was listed as an important agricultural cultural heritage in the world, and its traditional jasmine tea tanning process was also rated as a national intangible cultural heritage (Min and Zhang, 2015). Soil degradation is mainly manifested in the loss of soil organic matter (SOM), decline of fertility, element imbalance, deterioration of soil structure, and overall deterioration of soil environment (Jie *et al.*, 2002; Selby, 1993; Tamene *et al.*, 2019). However, there are some problems of soil degradation such as changes in soil carbon (C), nitrogen (N), and phosphorus (P) contents and stoichiometries that still remain to be studied. Therefore, research on the soil C, N, P contents, storages, and ecological stoichiometry of jasmine croplands in Fuzhou under different degrees of degradation is of great significance for the future protection and sustainable use of agricultural cultural heritage.

C, N, and P play an important role in improving soil quality and maintaining terrestrial ecosystem productivity and vegetation growth (Gao *et al.*, 2014; Peñuelas *et al.*, 2013, 2020; Sun *et al.*, 2015; Wen *et al.*, 2013). Dynamic changes in soil C, N, and P storage and availability can directly affect soil fertility (Musinguzi *et al.*, 2016), which in turn affects ecosystem stability and recovery (Xu *et al.*, 2019; Zhao *et al.*, 2017). Previous studies have found that different management modes have significant effects on soil nutrient content and its stoichiometric ratio of jasmine (Wang *et al.*, 2016). However, how soil nutrient content and its stoichiometric ratio change under the background of different degrees of degradation requires further research.

The stoichiometrical relationships of C:N:P are key for plant–soil interactions and their associated links with nutrient cycling, limiting elements, and global climate change impacts (Elser *et al.*, 2000; Mooshammer *et al.*, 2014; Peñuelas *et al.*, 2020; Sardans and Peñuelas, 2013; Tian *et al.*, 2010; Xia *et al.*, 2014; Zechmeister-Boltenstern *et al.*, 2015). Current research on soil C, N, and P contents and storage has been mainly focused on different land types (Zhao *et al.*, 2018), different years (Muhammed *et al.*, 2018), and different management methods (Fahey *et al.*, 2010; Knops and Tilman, 2000) but less on the effects of soil degradation in sites that used the same management mode and grow the same crop species.

The objectives of this study were to investigate: (1) soil C, N, and P contents and stocks and their stoichiometrical relationships under different degrees of soil physical degradation in jasmine croplands of Fuzhou; (2) the correlation of contents, stocks, and stoichiometries with soil factors (bulk density, pH, water content, salinity, clay, silt, and sand) under different degrees of degradation; and (3) the key physicochemical factors associated to soil degradation in the jasmine planting area. We also aimed to use this investigation as a tool to propose changes in cropland management.

Materials and Methods

Study sites

This study was located in the Fuzhou main jasmine planting area in southeastern China (118°45′13′′˜119°39′19′′ E; 25°36′24′′˜26°20′22′′ N) (Figure S1). The basic information of each sampling point is shown in Table S1. The main jasmine planting areas are located in the Minjiang River basin, which is a warm and humid subtropical monsoon climate with a frost-free period of 326 days and an average annual precipitation of 1349 mm (Wang *et al.*, 2016). The soil is mainly composed of slightly acidic red soil and is suitable for jasmine growth.

Sample collection and determination

To conduct this study, we first selected randomly 11 jasmine planting sites (one without soil degradation, five with low level of soil degradation, two with medium levels of soil degradation, and three with high level of soil degradation) in Fuzhou area. We based the selection on the principle of equal, random, and multipoint mixing. We classified these sites in different groups depending on their level of soil degradation following the classification method of Pieri (Pieri, 1992). The area (Figure S1) was sampled during the jasmine-growing season from February to July 2017. We took 5 different soil sample replicates in each one of the 11 jasmine-growing areas. To standardize the study, the jasmine genotype used in all the 11 jasmine-planting areas was the same one: *double-jasmine* genotype. Plant and row space is 30 × 35 cm.

Fertilization: Compound fertilizer ($N\text{-}P_2O_5\text{-}K_2O = 16–16–16$) and urea (46% N) are the main fertilizer applied in this study. Every year, from February to March after cutting branches, urea is applied at a dosage of 4.2 t N km^{-2}, whereas after flowering peak, compound fertilizer is applied at a dosage of 18 t km^{-2}, 7.5 t K_2O $km^{-2,}$ and 30 t P_2O_5 km^{-2}.

Water management: As stated earlier, the jasmine in Fuzhou is mostly planted in riverside wetlands and shoals, and the altitude and topography are relatively low (Table S1). Therefore, jasmine basically does not need to be watered, but it is watered when it is particularly dry (Wang *et al.*, 2016). This mostly occurs in summer and autumn when watering is applied in the early morning.

Pruning: At the end of the annual flowering period, some branches are pruned. Due to the differences in the specific conditions of each sampling site (geographical location, altitude, small terrain, etc., Table S1), there are subtle differences in management measures (Table S1). Using a small core sampler (length and diameter of 0.5 and 0.1 m, respectively), the soil of the 0˜15 cm was collected and introduced into a ziplock bag, and immediately transported to the laboratory. After picking up the roots of the plant residue, each sample was divided into two parts. One part was placed in a refrigerator at 4 °C to be later used to measure soil pH, bulk density, and water content. The other part was air dried, put it into a ziplock bag, and kept until analysis of soil particle size, soil organic carbon (SOC), total nitrogen (TN), and total phosphorus (TP).

After the samples were taken back to the laboratory, impurities (stones, dead leaves, etc.) in the soil were removed. (1) The samples were naturally dried indoors and ground through a 10-mesh sieve; (2) take a certain amount of samples, add 5% dilute hydrochloric acid to stir for many times, add dilute hydrochloric acid to the reaction is complete, and soak for 24 hr; and (3) wash with neutral deionized water until neutral (pH = 7). After drying, grind the sample to powder in an agate mortar and pass it through a 100-mesh sieve. SOC and TN were determined using a CN elemental analyzer (Elementar Vario MAX CN, Hanau, Germany), and TP was decongested by $HClO_4–H_2SO_4$ method in a continuous flow analyzer (San++, SKALAR Corporation production, Breda, Netherlands). SOC data were converted to SOM using the van Bemmelen factor of 1.724 (Heaton *et al.*, 2016).

Other soil variables were also analyzed. Soil water content was determined by the drying method (Lu, 1999), and bulk density was measured for the three bulked cores (5-cm diameter and 3-cm depth) collected from each soil layer. Soil salinity and pH were measured using a 2265FS salinity meter (Spectrum Technologies Inc., Paxinos, USA) and a handheld pH meter (STARTER 300, Parsippany, USA), respectively. Particle size (clay, silt, and sand) was measured by a Mastersizer 2000 laser particle-size analyzer (Malvern Scientific Instruments, Suffolk, UK). (1) An amount of 0.5 g of soil sample were weighed, then 30% hydrogen peroxide was added, organic matter was removed at 72 °C, and hydrochloric acid was added to remove carbonate. (2) Ultrapure water was added to dilute until pH was 6.5–7. (3) Then, sodium hexametaphosphate was added, ultrasonication was conducted for 30 s, and afterwards the laser particle-size analyzer Mastersizer 2000 measured the volume percentage of soil particle size.

Calculation of soil C, N, and P storages

The C, N, and P storages of the soil surface profile at a certain depth per unit area were calculated by the following equation:

$$T_x = \Sigma dx \times M_x \times d \times 10, \tag{1}$$

where x of T_x, D_x, and M_x represents a substitution for C, N, or P. T_x is the soil C (T_C), T (T_N), P (T_P) storages (t km^{-2}), D_x is the soil surface bulk density (g cm^{-3}), M_x is the soil surface C, N, and P content (g kg^{-1}), and d is the soil depth (cm).

Soil degradation index and threshold

The soil structural stability index (St) is an important indicator of soil structural degradation and an important indicator of SOM to maintain soil structural stability (Pieri, 1992). This indicator was calculated using the following equation:

$$St = 100\% \times \frac{\mathrm{SOM}(\%)}{\mathrm{Clay}(\%) + \mathrm{Silt}(\%)}. \qquad (2)$$

In the formula, when $\mathrm{St} \le 5\%$, it indicates that the soil structure is degraded due to the large loss of SOM; when $\mathrm{St} > 5\%$, there is no risk of degradation of soil structure (Pieri, 1992). In this study, the $\mathrm{St} \le 5\%$ (degraded structure) was further subdivided, when $4\% \le \mathrm{St} < 5\%$, the soil structure degradation was considered low degree; when $3\% \le \mathrm{St} < 4\%$, middle degree; when $\mathrm{St} < 3\%$, high degree. Therefore, the S1 site belonged to high-risk degradation but without current degradation; the S2, S3, S4, S5, and S6 sites to low degree of degradation; the S7 and S8 sites to middle degree of degradation; and the S9, S10, and S11 sites to high degree of degradation (Figure S2).

Statistical analyses

We conducted a one-way analysis of variance using SPSS 20.0 to analyze the data difference between among the degrees of degradation. The correlations between different degrees of degradation and soil properties were determined by Pearson correlation analysis. We also performed multivariate statistical analyses using functional discriminant analysis (FDA) to determine the overall differences of soil clay, silt and sand contents, total C, N, and P contents, soil C:N, C:P, and N:P ratios, soil bulk density, salinity, pH, and water content among the different levels of soil degradation. Discriminant analyses consist of a supervised statistical algorithm that derives an optimal separation between groups established a priori by maximizing between-group variance while minimizing within-group variance. FDA is thus an appropriate tool for identifying the variables most responsible for the differences among groups. The FDA was performed using Statistica 8.0 (StatSoft, Inc., Tulsa, USA).

Results

Analysis of soil C, N, and P contents in jasmine cropland under different degrees of degradation

Compared with nondegraded soil, the contents of degraded SOC showed a significant decrease trend ($P < 0.05$, Figure 1a). We have also observed that TN contents in the middle degree of degradation and high degree of degradation were 42.2% and 33.3% lower, respectively, than in the nondegraded soils ($P < 0.05$, Figure 1b). However, no differences in soil TP contents were observed among all treatments ($P > 0.05$, Figure 1c).

Analysis of soil C, N, and P storages in jasmine cropland under different degrees of degradation

Compared with nondegraded soils, the soil C and N storages showed a significant decrease trend in the middle degree of degradation and the high degree of degradation ($P < 0.05$, Figure 1d, 1e). However, there were no differences in soil P storages among all treatments ($P > 0.05$, Figure 1f).

Characteristics and analysis of soil C, N, and P ecological stoichiometry in jasmine cropland of Fuzhou under different degrees of degradation

The soil C:N ratio was 18.5% higher in the middle degree of degradation than in the nondegraded soils ($P < 0.05$, Figure 1g), and compared with nondegraded soils, the degraded soils C:P and N:P ratios increased to a certain extent ($P > 0.05$, Figure 1h, 1i).

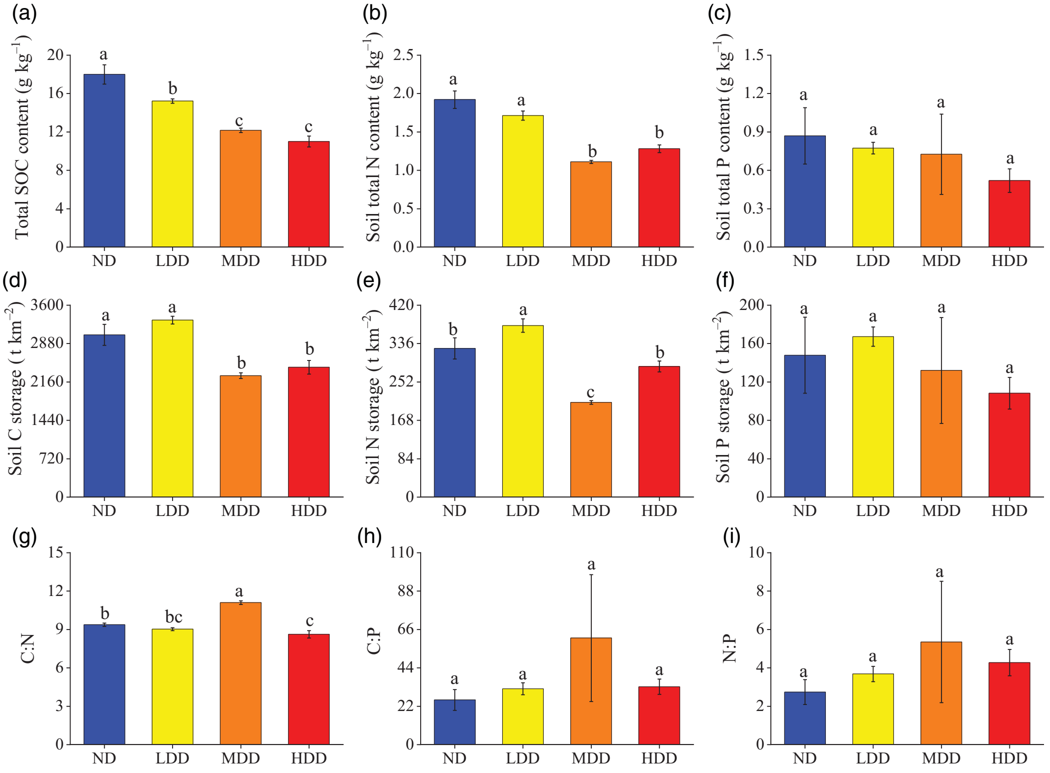


Figure 1. Soil C (a), N (b), and P (c) contents, soil C (d), N (e) and P (f) storages and soil C:N (g), C:P (h) and N:P (i) ratios in jasmine croplands of Fuzhou under different degrees of degradation (same for other captions). Different lowercase letters in the figure indicate significant differences between sampling points ($P < 0.05$). Error bars represent standard errors of the means ($n = 5$). HDD, high degree of degradation; LDD, low degree of degradation; MDD, middle degree of degradation; ND, no degradation.

Regression analysis of soil C, N, and P contents in different jasmine planting areas in Fuzhou

C, N, and P contents were strongly correlated ($P < 0.01$, Figure 2a–2c). Along the studied sites, the relationship between C and N was stronger than the coupling relationships between C and P and between N and P.

Analysis of soil properties in jasmine cropland of Fuzhou under different degrees of degradation

Compared with nondegraded soils, the degraded soils bulk density showed a significant increase trend, but water content showed a significant decrease trend ($P < 0.05$, Figure 3a, 3b). The soil pH in the middle degree of degradation was 9.18% higher than in the nondegraded soils ($P < 0.05$, Figure 3c). The soil clay and silt in the high degree of degradation were 33.1% and 25.3% higher, respectively, than in the nondegraded soils ($P < 0.05$, Figure 3e). The soil sand in the high degree of degradation was 32.6% lower than in the nondegraded soils ($P < 0.05$, Figure 3g).

Correlation analysis between different soil degradation degrees and soil variables

The soil structural stability index was positively correlated with SOC, TN, T_C, water content, and sand ($P < 0.01$), and negatively correlated with bulk density and silt ($P < 0.01$) and clay ($P < 0.05$) (Figure 4).

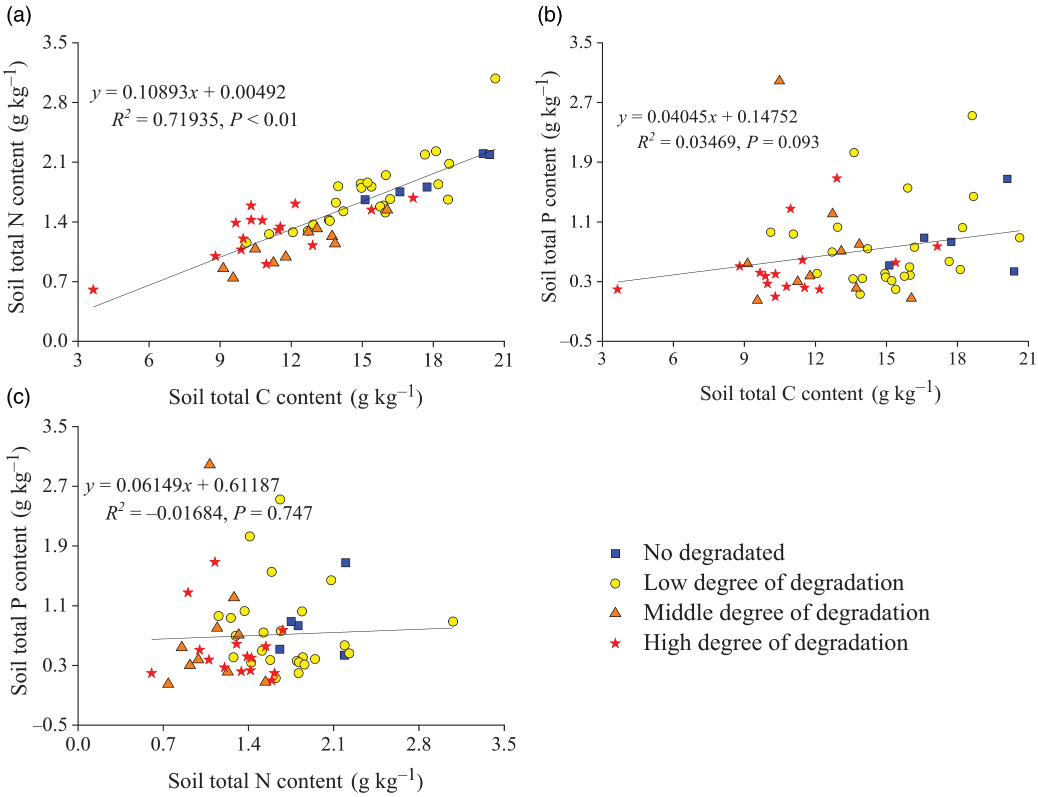


Figure 2. Regression analysis of soil C (a), N (b), and P (c) contents in jasmine croplands of Fuzhou under different degrees of degradation.

FDA

Soil pH was the main variable, followed by soil salinity, stability, and bulk density explaining the differences between soil samples of nondegraded soils and those of degraded soils (Figure 5, Table 1). Samples of middle- and high-degraded soils were not significantly different according with the FDA (Table 2).

Discussion

Effects of different soil degradation degrees on chemicophysical soil traits

The decrease of soil pH coupled with salinity (conductivity) and the loss of aggregate stability are the main variables that distinguished degraded from nondegraded soils. The shifts in soil physical properties, for example, in soil density and porosity, were associated to a loss of SOC as observed normally under soil degradation processes (Ola *et al.*, 2018). The current management based on a certain level of organic matter incorporation but with a constant cut of aboveground plants leaves bare soil vulnerable to be easily loss by runoff and with scarce natural incorporation of organic matter. It is thus inadequate in this most important growing area of this crop. It leads to loose soil structure, increased soil porosity and oxygen content, and enhanced aerobic microbial activity (Zhang *et al.*, 2018), which accelerates the decomposition rate of microorganisms on C, N, and other nutrients, resulting in less accumulation of soil C and N. Moreover, the surface of bare soil under long-term jasmine cultivation should favor runoff of water leading to further loss of C and N in jasmine soil contributing to increase the level of soil degradation.

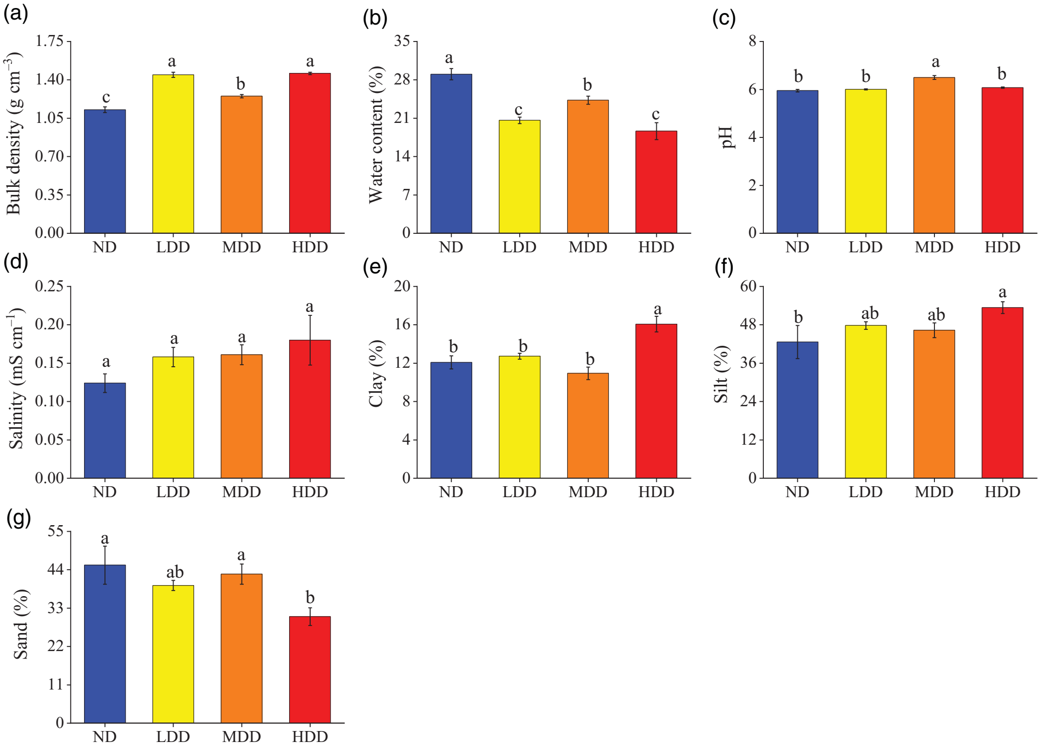
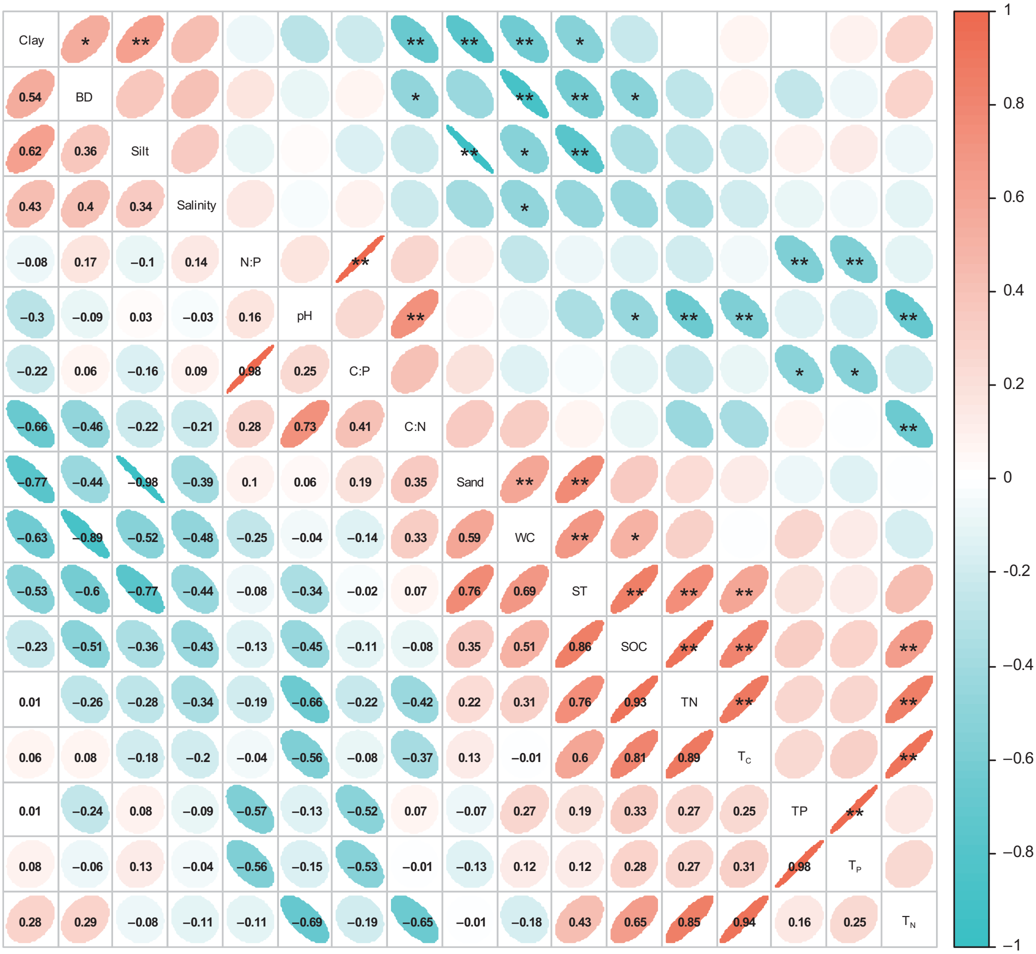


Figure 3. Soil bulk density (a), water content (b), pH (c), salinity (d), and clay (e), silt (f) and sand (g) concentrations in jasmine croplands of Fuzhou under different degrees of degradation (ND, LDD, MDD, and HDD). Different lowercase letters in the figure indicate significant differences between sampling points ($P < 0.05$). Error bars represent standard errors of the means ($n = 5$).

These results should be taken into account to shift the current management towards larger inputs of organic matter. It would be advisable to lead underground growth and cut it and spread for soil when the jasmine plant begins to build the flowers to avoid competing underground vegetation with jasmine plants in this moment, and at the same time also achieve higher organic matter inputs to soil.

Effects of different soil degradation degrees on C, N, and P contents and storages in jasmine cropland

The total amount of soil nutrient is a general reference to characterize the potential level of soil nutrient supply at medium and long term (Bai *et al.*, 2016). In this study, the C, N, and P contents and storages were different in the distinct soil degradation degrees. Soil C and N contents and storages were lower in degraded than in nondegraded soils. Soil C and N are affected by many factors such as decomposition of soil parent material, litter, plant roots, and absorption and utilization of plants (Lane *et al.*, 2011). In general, higher rates of soil degradation mean lower productivity, usually as a decline in aboveground and below biomass production (Jiang *et al.*, 2006; Zhou *et al.*, 2008). The deepening of soil degradation leads to limited vegetation growth, which reduces the content of litter, resulting in a decrease in C and N contents in the soil (Xu *et al.*, 2019). Barren land together with monsoon climate with heavy rains results in a not-adequate combination to the accumulation of organic matter. The soil N input is mainly dependent on the return of plant residues, biological N fixation, and the input derived from the dry and wet deposition of the atmosphere (Abaker *et al.*, 2018). However, due to the influence of artificial picking and other



Clay	*	**					**	**	**	*						
0.54	BD						*		**	**	*					
0.62	0.36	Silt						**	*	**						
0.43	0.4	0.34	Salinity						*							
−0.08	0.17	−0.1	0.14	N:P		**								**	**	
−0.3	−0.09	0.03	−0.03	0.16	pH		**				*	**	**			**
−0.22	0.06	−0.16	0.09	0.98	0.25	C:P								*	*	
−0.66	−0.46	−0.22	−0.21	0.28	0.73	0.41	C:N									**
−0.77	−0.44	−0.98	−0.39	0.1	0.06	0.19	0.35	Sand	**	**						
−0.63	−0.89	−0.52	−0.48	−0.25	−0.04	−0.14	0.33	0.59	WC	**	*					
−0.53	−0.6	−0.77	−0.44	−0.08	−0.34	−0.02	0.07	0.76	0.69	ST	**	**	**			
−0.23	−0.51	−0.36	−0.43	−0.13	−0.45	−0.11	−0.08	0.35	0.51	0.86	SOC	**	**			**
0.01	−0.26	−0.28	−0.34	−0.19	−0.66	−0.22	−0.42	0.22	0.31	0.76	0.93	TN	**			**
0.06	0.08	−0.18	−0.2	−0.04	−0.56	−0.08	−0.37	0.13	−0.01	0.6	0.81	0.89	T_C			**
0.01	−0.24	0.08	−0.09	−0.57	−0.13	−0.52	0.07	−0.07	0.27	0.19	0.33	0.27	0.25	TP	**	
0.08	−0.06	0.13	−0.04	−0.56	−0.15	−0.53	−0.01	−0.13	0.12	0.12	0.28	0.27	0.31	0.98	T_P	
0.28	0.29	−0.08	−0.11	−0.11	−0.69	−0.19	−0.65	−0.01	−0.18	0.43	0.65	0.85	0.94	0.16	0.25	T_N

Figure 4. *R* values showing the Pearson correlations coefficients between soil degradation degrees and soil variables. The TN, TP, T_C, T_N, T_P, BD, and WC represent total nitrogen content, total phosphorus content, total C storage, total N storage, total P storage, bulk density, and water content, respectively. Symbols * and ** indicate significant correlations at the 0.05, and 0.01 levels, respectively.

factors, the amount of jasmine plant residues is small, and the hilly topography is not conducive to the accumulation of N, so that the observed C and N storages were lower. Other studies have also shown that higher soil structural degradation drives to lower SOC content (Tamene *et al.*, 2019), consistent with our observations. This also should in great part be due to the intensive agricultural model of the jasmine crops, which mainly exports materials and energy, and the lost materials are not supplemented in time and effectively, resulting in continuous loss of SOC and lower stability of soil aggregates. In addition, the leaching of long-term rainwater easily leads to the loss of some surface organic matter. Previous studies have demonstrated that organic cultivation improves soil fertility and C accumulation in jasmine croplands of Fujian Province (Wang *et al.*, 2016). Therefore, organic fertilizer can be appropriately added to alleviate the lack of organic matter, and appropriate burial can be conducted to reduce nutrient loss.

However, there was no significant difference in soil P content under different degrees of degradation in this study, and the overall P contents (0.70 g kg^{-1}) were lower than the average level of soil TP in China (0.975 g kg^{-1}) (Tian *et al.*, 2010). These low contents of soil P also strongly suggest an inadequate management and fertilization strategies. Moreover, when the content of certain

Table 1. Statistical significance of the independent variables in the functional discriminant analysis with the soils with different level of degradation as the dependent categorical grouping variable

Soil variables	Wilk's Lambda	*F*	*P* value
Stability	**0.748**	**0.677**	**0.0157**
Clay	0.874	1.78	0.17
Silt	0.873	1.79	0.17
Sand	0.874	1.78	0.17
SOC	0.992	0.101	0.96
TN	0.917	1.12	0.35
TP	**0.780**	**3.47**	**0.026**
C:N	0.958	0.537	0.66
C:P	0.888	1.56	0.21
N:P	0.888	1.55	0.22
Bulk density	**0.690**	**5.54**	**0.0030**
WC	0.973	0.341	0.80
pH	**0.241**	**38.8**	<**0.00001**
Salinity	**0.766**	**3.76**	**0.019**

Bold type indicates significant differences (*P* old type TN, TP, and WC represent total nitrogen content, total phosphorus content, and water content, respectively.

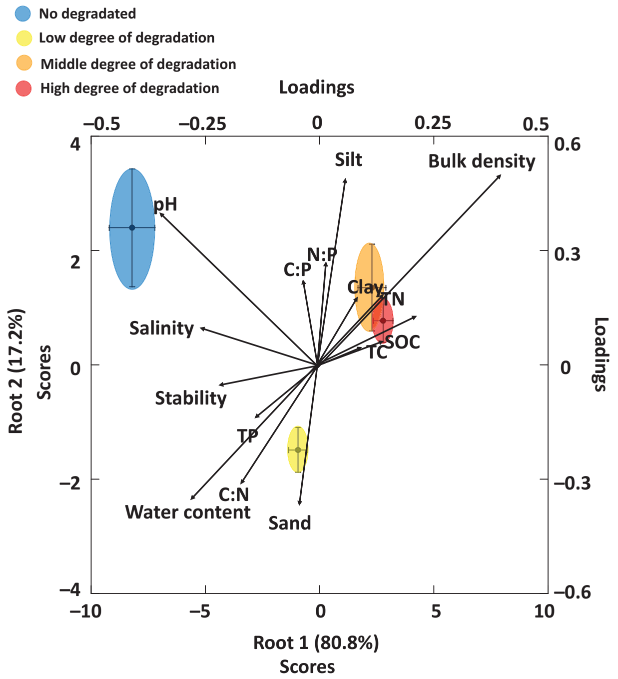


Figure 5. Functional discriminant analysis (FDA) 2D layout (showing the plot formed by the scores and layouts of the two first roots, explaining a 98% of the total variance) with soil clay, silt and sand contents, total C, N, and P contents, soil C:N, C:,P and N:P ratios, soil bulk density, salinity, pH, and water content as independent continuous variables and different levels of soil degradation as categorical dependent variables.

essential elements in the soil is low, the plants will maximize the uptake of this element to counteract the leaching of the nutrients in the soil and thus maintain the normal growth of the plant (Lambers *et al.*, 2008). Anyway, this observed general lower P soil content is also consistent with the geographical distribution pattern of soil TP content in low latitudes of Houlton and Tian et al.

Table 2. Test statistics for squared Mahalanobis distances among the soil groups with different level of degradation with soil clay, silt, and sand contents, total C, N, and P contents, soil C:N, C:P, and N:P ratios, soil bulk density, salinity, pH, and water content as independent continuous variable

	Degree of soil degradation		
Degree of soil degradation	Low	Middle	High
No	**MH = 68.0** **F = 13.7** **$P < 0.0001$**	**MH = 113** **F = 18.1** **$P < 0.0001$**	**MH = 124** **F = 22.4** **$P < 0.0001$**
Low		**MH = 19.2** **F = 6.63** **$P < 0.0001$**	**MH = 19.5** **F = 8.83** **$P < 0.0001$**
Middle			MH = 2.83 F = 0.821 P = 0.65

Bold type indicates a significant effect of the variable in the model ($P < 0.05$).

(Houlton *et al.*, 2008; Tian *et al.*, 2010). In this study, the overall soil P storages are relatively low, as common in subtropical regions (Chen *et al.*, 2015). Although planting jasmine increases the input of P into the soil in litter, the available P from decomposition is easily reabsorbed by plants (Xu *et al.*, 2019), resulting in relatively low levels of P and P storages in the soil.

Effects of different soil degradation degrees on soil stoichiometry in jasmine croplands

Soil C:N:P stoichiometry is an important soil trait related to basical soil functions such as mineralization capacity and soil microbial community structure (Drenovsky and Richards, 2006; Mooshammer *et al.*, 2014). When the soil C:N < 25, microbial activity is enhanced and the organic matter is easy to decompose (Mooshammer *et al.*, 2014). In this study, the soil C:N ratio is lower than 25 under different degrees of degradation, which together with the high temperatures and abundant precipitation allowing high microbial activity favoring faster rate of organic matter and lowering of the C:N ratio. The soil N:P ratio can often be used to characterize the limiting role of these nutrients (Elser *et al.*, 2007; Peñuelas *et al.*, 2013, 2020), and the balance between the availability of N and P in soil also generally determines the plant's N:P ratio (Wassen *et al.*, 1995). The N:P ratio of the study (4.01) is lower than that of global grassland (12.3) and forests (14.6) (Cleveland and Liptzin, 2007), indicating that N may be the main limiting nutrient in jasmine cropland soil, consistently with the observed in previous studies (Guo and Jiang, 2019; Wang *et al.*, 2015).

Environmental effects of the soil degradation

Soil degradation was accompanied by decreased soil water content, organic matter, N content and storage, whereas the bulk density increased. The reduction of soil C storage indicates an increase of the emission of carbon dioxide to the atmosphere and thus a decreased ability to mitigate greenhouse gases (Makhalanyane *et al.*, 2015). The loss of vegetation cover and the subsequent loss of SOC are the root causes of soil degradation (FAO and ITPS, 2015).

The lower N:P ratio than in the global grasslands and woodlands (Cleveland and Liptzin, 2007) indicates that there may be N limitation in the jasmine soil, and therefore soil degradation will further aggravate it. Weesies *et al.* (1994) found that soil degradation reduced the SOM content of various Indiana soils by 16–39%, TP by 29–38%, and clay content by 11–53%, which in turn led to crop yield reduction. Organic cultivation improves soil fertility and C accumulation in jasmine croplands of Fujian Province (Wang *et al.*, 2016).Therefore, organic fertilizer can be appropriately added to alleviate the lack of organic matter, and appropriately buried to reduce nutrient loss. Moreover, steel slag and biochar also can decrease greenhouse gases emission and improve the

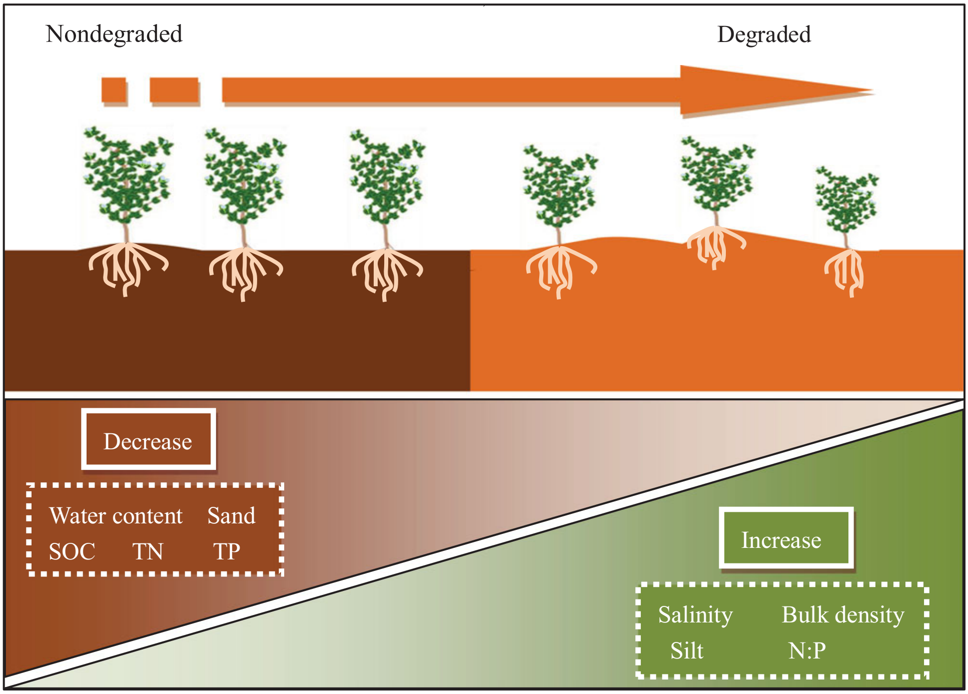


Figure 6. A conceptual diagram of C, N, and P content, storage, and stoichiometry in the process of soil degradation in jasmine croplands in subtropical China. The figure above shows the sampling points of jasmine and physical factors that we observed at different degrees of degradation. The brown triangle shows that as the soil gradually degrades, the soil water content, sand, SOC, TN, and TP all show a decrease trend. By contrast, the green triangle represents soil salinity, soil bulk density, silt, and N:P ratio increasing with soil degradation.

soil acid problem and enhance nutrient availability in jasmine field (Jin *et al*., 2020), so they can become effective methods to restore the degraded jasmine land.

Conclusions

Our research provides theoretical and practical guidance for clarifying the spatial distribution and driving factors of soil degradation in jasmine croplands in Fuzhou, China. The results show that the level of degradation in jasmine croplands in Fuzhou is considerable and it is characterized by soil acidification and soil compaction with higher clay content and bulk density. The process of physical degradation is accompanied by important decreases of soil C and N contents. The decrease of N content is especially critical for this N-limited region (Figure 6). Moreover, Fuzhou jasmine region is also P deficient, which is aggravated by degradation process. The jasmine soils in Fuzhou are being increasingly degraded and losing organic C. Thus, higher inputs of organic fertilizer should be considered to alleviate the lack of organic matter, and appropriate burial should be conducted to reduce nutrient loss, and to, at least partially, cover the bare soil. Moreover, a rise of N and P fertilizers is also advisable.

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