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Assessment of Soil Quality in the Transformation from Pure Chinese Fir Plantation to Mixed Broad-Leaved and *Cunninghamia lanceolata* Plantation in Subtropical China

Xiaoyu Cao [1,2], Zelian Zhang [1], Wende Yan [3,*], Yongjun Mo [1], Shuping Wu [1], Menglei Wang [1] and Yuanying Peng [4,*]

1 Faculty of Forestry, Central South University of Forestry and Technology, Changsha 410004, China; cxy7723@csuft.edu.cn (X.C.); zzl1998@csuft.edu.cn (Z.Z.); myj123@csuft.edu.cn (Y.M.); 20221100021@csuft.edu.cn (S.W.); 20221200093@csuft.edu.cn (M.W.)
2 Key Laboratory of State Forestry Administration on Forest Resources Management and Monitoring in Southern Area, Changsha 410004, China
3 National Engineering Laboratory of Applied Technology for Forestry and Ecology in Southern China, Changsha 410004, China
4 College of Arts and Sciences, Saint Xavier University, Chicago, IL 60655, USA
* Correspondence: chongdelou716@csuft.edu.cn (W.Y.); pengyu@lewisu.edu (Y.P.)

Abstract: To assess the alterations in soil properties resulting from the interplanting of broad-leaved tree species within coniferous forests, we conducted an investigation into soil quality in a mixed Chinese fir and broad-leaved forest, as well as in a Chinese fir pure forest (used as a control) in subtropical China. A total of 15 soil physicochemical properties were assessed across three soil depths—0–15 cm, 15–30 cm, and 30–45 cm—for the two forest types in the experimental study. Principal component analysis in conjunction with the Norm value was employed to create a minimal data set (MDS) for assessing six indicators, including bulk density (BD), total nitrogen (TN), total phosphate (TP), available potassium (AK), soil pH, and catalase (CAT). The soil quality index (SQI) was calculated for both forest types. The results demonstrated that following the interplanting of broad-leaved tree species in the Chinese fir forest, all soil physicochemical indicators were significantly improved compared to the control, and significant differences were also observed in the 0–15 cm and 15–30 cm soil layers ($p < 0.05$). The overall average of the SQI of the mixed forest (0.8523, 0.6636) was significantly higher than that of the control (0.4477, 0.3823) ($p < 0.05$) in the 0–15 cm and 15–30 cm soil layers, respectively. However, there was no significant difference in the SQI in the 30–45 cm soil layer ($p > 0.05$) between the two forest types. The results indicated that the SQI based on the minimal dataset (MDS) can reflect the SQI of the total dataset (TDS) when assessing soil quality in forests. Our research provides valuable scientific insights into soil science and an understanding of the relationships between soil properties, forest structure, and species composition in sustainable forest management.

Keywords: Chinese fir; broad-leaved tree species; interplanting; minimal data set; principal component analysis; SQI

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1. Introduction

Soils are the main source of water and nutrients for plant growth. The primary macronutrients in soil include nitrogen (N), phosphorus (P), and potassium (K), and there are important micronutrients such as iron (Fe), manganese (Mg), and zinc (Zn) [1]. Soil fertility is the ability of a soil to provide the nutrients needed by plants to grow [2]. When residual waste is broken down by microorganisms to release inorganic nutrients into the soil solution, this is called the mineralization process [3,4]. Forest soil quality, the availability of soil nutrients, water, and biotic factors are important factors controlling forest structure, functions, and productivity [3,5]. Different forest types can have a dramatic impact on soil properties [6]. Soil quality is affected by forest types through changing physiological soil properties [7,8]. Soil quality has the potential to be an indicator for managing ecosystem health and sustainability [9,10].

Soil quality reflects the comprehensive capacity of soil [11], and it is impossible to describe the properties of soil by relying only on a single index, such as physical, chemical, or biological parameters [12–14]. At present, there are many evaluation methods for assessing forest soil quality, such as the soil quality index (SQI) method [15,16], the soil management evaluation method [17], the fuzzy association rule method [18], and the minimal data set method [19]. Among them, the SQI method is a widely accepted assessment approach due to its simplicity and quantitative flexibility [20,21]. However, the SQI method requires the measurement of a large number of physical, chemical, and biological variables of the soil to enable a practical, effective, and comprehensive soil quality evaluation [22]. The significant time and cost involved in soil data collection and analysis indicate the need to develop a minimal data set (MDS) that maximizes relevant information and reduces data redundancy [12,23]. The MDS involves the selection of relatively independent and sensitive indicators that impact soil quality from a large number of soil quality evaluation parameters and establishing a set of index parameters that can reflect the minimal soil quality. This approach has been extensively utilized in soil quality evaluation and monitoring work [24,25]. However, a quantitative evaluation method of the SQI with regard to comparing tree species' composition and forest structure within forest ecosystems remains unknown.

Plantations, as one of the most important forest resources on earth, play a vital role in providing timber production and ecosystem services and mitigating climate change [26,27]. The active afforestation policy in China has led to the largest planted forest area in the world. In 2018, the planted forest area accounted for 8.0×10^7 ha, accounting for one-third of the world's planted forest area [28]. Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook) plays a significant role in afforestation in southern China. Due to its fast growth, economic value, excellent wood quality, and high production, Chinese fir has been extensively planted in China [29], with more than 1000 years of cultivation history [30,31]. So far, the total area of Chinese fir plantations is about 9.9×10^6 ha, with a stock volume of 7.6×10^8 m^3, ranking in first place among all plantations in the nation [28]. However, the soil quality and wood production of Chinese fir forests have declined sharply due to the monoculture cultivation and continuous cropping with insufficient fallow periods [30,32]. Therefore, various afforestation strategies have being actively explored to maintain the soil quality and ecosystem sustainability of Chinese fir forests to meet the challenges of global climate change [33,34].

Recently, replanting broad-leaved tree species in coniferous forests to form mixed forests has become an important silviculture strategy to improve soil fertility and promote nutrient cycling in forest plantations [35–37]. Converting Chinese fir monocultures to mixed forests with broad-leaved trees has become a general silviculture practice in forest management, as trees in mixed-species forests are often better supplied with light, water, and soil nutrients via their complementary crown and root systems, higher rates of litter decomposition, and the maintenance of soil nutrient cycling [38–40]. As early as 1996, scholars first proposed that the transformation of pure plantation forests into near-natural forests was an important forest management choice for sustainable forest development in China [41]. Mixed forests can promote carbon sequestration and enhance soil quality by altering soil physicochemical processes in forest ecosystems [10]. Many scholars have carried out afforestation experiments and studied the changes in soil quality after the conversion from a pure fir forest to broad-leaved and mixed fir forests [42]. However, these studies basically describe changes in a single indicator of soil quality and rarely assess changes in soil quality as a whole [43–46].

The main purposes of this study were to compare and evaluate the changes in soil quality after the conversion of Chinese fir pure forests into broad-leaved and Chinese fir mixed forests. The study objectives were: (1) to compare the variations in soil physicochemical properties across distinct soil layers in both the pure and the mixed forests; (2) to establish a minimal data set (MDS) and evaluate the suitability of the MDS for assessing soil quality; and (3) to use the MDS to assess soil quality in the examined forest types.

2. Materials and Methods

2.1. Site Description

The study was conducted in Fushou Forest Farm located in the middle and upper layer of Fushou Mountain in the southern part of Pingjiang County, located in Hunan Province, China (28°03′00″ N–28°32′30″ N, 113°41′15″ E–113°45′00″ E) (see Figure 1). The study area belongs to a site of evergreen broad-leaved subtropical forests. The climate of the study region is characterized as a typical subtropical humid monsoon climate, featuring an annual average temperature of 12.1 °C and an annual precipitation of 2100 mm. The 7-year-old Chinese fir plantation forest in the experiment covers an area of 14.5 hectares. It is situated at an elevation ranging from 800 to 830 m and occupies the middle and upper slope positions of the forest farm, with a slope gradient ranging from 20 to 28 degrees. The soil type within the experimental area was identified as mountain yellow brown soil. The Chinese fir forests in the study plots were artificial plantations, and the shrubs in the understand of stands were *Rhododendron simsii* Planch, *Rhus chinensis* Mill, etc.; the understory herbaceous vegetation mainly included *Miscanthus floridulus* (Lab.) Warb. ex-Schum et Laut)), ferns (*Pteridium aquilinum* (L.) Kuhn var. *latiusculum* (Desv.) Underw. ex Heller), etc.

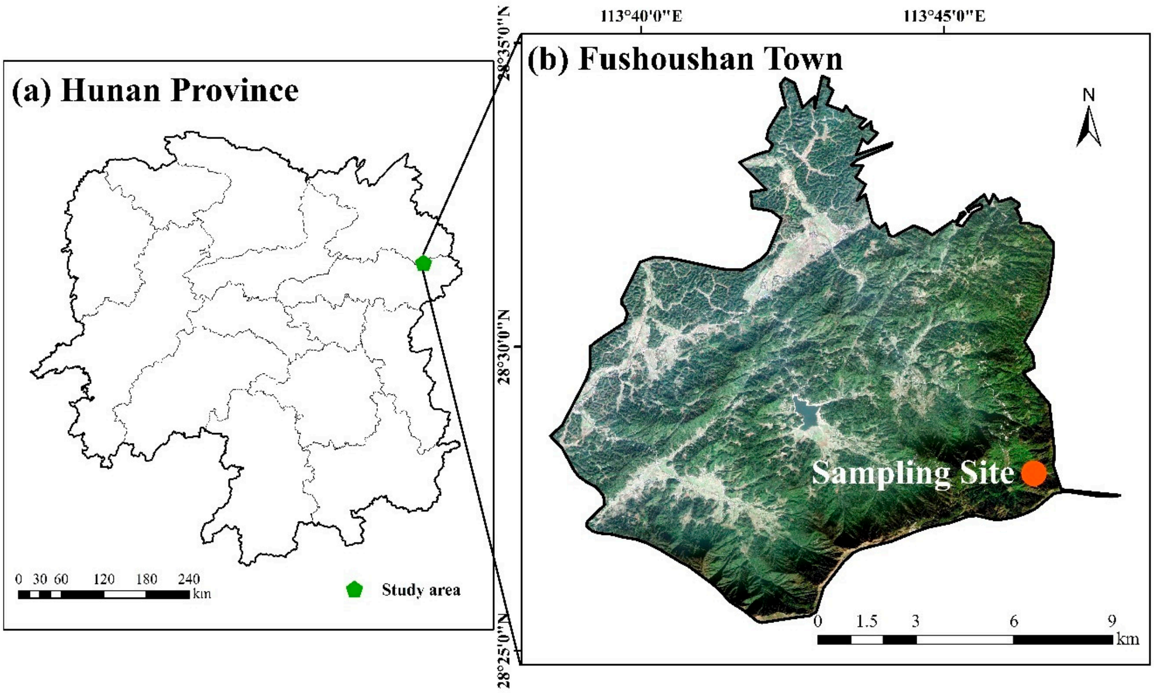

Figure 1. The geographical location map depicts the study area in Fushoushan Town, located within Pingjiang County, Hunan Province, China. It provides an overview of (**a**) the geography of Hunan Province and (**b**) the specific geography of Fushoushan Town.

2.2. Experimental Design

In 2016, a total of 10 plots measuring 20 × 30 m (including 5 test plots and 5 control plots) were established within a young Chinese fir (7-year-old), which was planted on a clear-cut site in 2009. The plantation shared similar site conditions with a yellow brown soil type. In 2017, thinning was first carried out on 5 test plots with a thinning intensity of 30%, and then 3-year-old *Michelia maudiae* Dunn, *Koelreuteria paniculata* Laxm, and *Liriodendron chinense* (Hemsl.) Sarg. broad-leaved tree species were interplanted into these thinned

Chinese young fir forests to form broad-leaved tree species and Chinese fir mixed forests. The ratio of the three species was about 1:1:1. An annual tending process (involving soil loosening and weed clearance) was carried out from August to September in the mixed forests for three years after planting. This action was undertaken to promote the growth of trees in mixed stand plots in the broad-leaved and Chinese fir forest.

A split-plot design was carried out in July of 2021 to compare the soil quality between the two types of forests. The main factor in the study was the forest types: the broad-leaved tree species and Chinese fir mixed forests versus the Chinese fir pure forests. Each forest type had 5 replications. The subfactor was the soil depth, categorized as 0–15 cm, 15–30 cm, and 30–45 cm and nested within the two forest types. Soil samples were taken from five X-shaped soil sampling points in a plot (see Figure 2). Thus, a total of 150 soil sampling points (2 forest types × 5 plots × 5 soil sampling points) were set up, and 150 soil samples (50 soil sampling points × 3 soil depths) were taken in the present study. Aboveground measurements were taken for each individual tree species within each plot, including the diameter at the breath height (DBH) and tree height. The characteristics of the studied forests were collected (see Table 1).

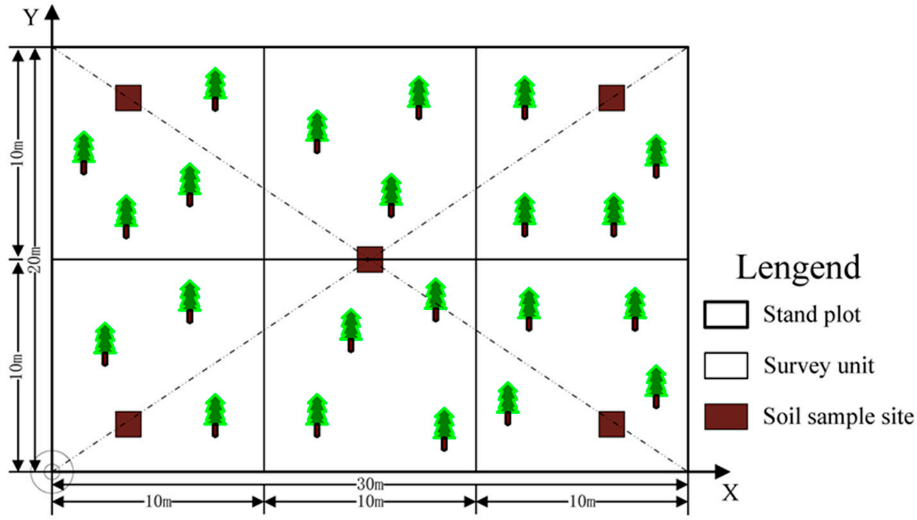

Figure 2. Soil sampling sites.

Table 1. Characteristics of the two forest types in the study site.

Forest Types	Species	Aspect	Slope	Altitude	Slope	Height	DBH	Stand Density	Coverage
				(m)	(°)	(m)	(cm)	(plants·ha^{-1})	(%)
Pure stand	*C. lanceolata*	Northeast	Mesoslope	815	25	7.9	10.2	2386	61
Mixed stand	*C. lanceolata* *M maudiae* *K. paniculata* *L. chinense*	East	Mesoslope	803	21	8.7 6.18 5.8 11.6	11.6 5.94 6.9 10.4	1685 215 209 212	72

Note: C. lanceolata: Cunninghamia lanceolata (Lamb.) Hook; M maudiae: Michelia maudiae Dunn; K. paniculate: Koelreuteria paniculata Laxm; L. chinense: Liriodendron chinense (Hemsl.) Sarg.

2.3. Soil Sample Collection

Soil samples were collected from each plot using an X-shaped pattern with five sampling points (comprising four directional points and one central point, as illustrated in Figure 2). Soil samples at the same soil layer in a plot were pooled to form a mixed soil sample. Soil samples were loaded into labeled clean Ziplock bags and transported to the laboratory for the determination of soil quality parameters. The fresh soil samples were stored in a refrigerator at 4 °C for the measurement of soil enzyme activities. A section of the soil samples was air-dried and then passed through a 100-mesh sieve for the measurement of soil chemical properties.

2.4. The Determination of Soil Properties

Soil bulk density (BD), capillary porosity (CP), non-capillary porosity (NCP), total porosity (TP), and water-holding capacity (WHC) were measured as physical soil properties by a ring knife method [47]. The potassium chromate oxidation method was used for determining soil organic matter (SOM). The Kjeldahl method was applied for total nitrogen (TN) measurement. The sodium hydroxide alkali solution-molybdenum antimony colorimetric method was used for the measurement of total phosphorus (TP). The alkaline solution diffusion method was used for determining soil alkaline nitrogen (AN). The available phosphorus (AP) content measurement was carried out using the sodium bicarbonate leaching-molybdenum antimony colorimetric method, and available potassium (AK) content was measured through the ammonium acetate leaching-flame photometry method. Soil pH was measured with a potentiometric method, employing a water-to-soil ratio of 1:2.5. Additionally, soil enzyme activities were determined using various techniques: urease (URE) activity was assessed using the sodium phenoxide-sodium hypochlorite chromogenic method, invertase (INV) activity through the 3,5-dinitrosalicylic acid chromogenic method, acid phosphatase (ACP) activity was measured using the phenyldisodium phosphate colorimetric determination method, and catalase (CAT) activity was determined via the potassium permanganate titration method [48,49].

2.5. The Determination of Soil Properties

2.5.1. Principal Component Analysis Method to Construct the Minimal Data Set

To conduct a thorough assessment of soil quality, it is imperative to meticulously choose the most fitting soil quality indicators. These indicators should demonstrate a notable influence on soil function and the eventual outcomes of the evaluation [50]. Consequently, they have been chosen to constitute the MDS. Principal component analysis (PCA) is a dimensionality reduction technique that condenses multiple metrics into a smaller set. It was employed in creating the minimal data set (MDS). [51]. The general idea of PCA is to extract principal components with eigenvalues ≥ 1 and grouping those with index loads > 0.5 [52,53]. If an indicator exhibited a loading value greater than 0.5 across different principal components, it was grouped with indicators that exhibited weaker correlations with other variables [54]. We calculated the Norm value for each group of indicators separately and selected the indicators whose Norm value within each group was within 10% of the maximum Norm value. The Pearson correlation coefficient can be employed to assess whether each indicator should be retained. If the correlation coefficient is <0.5 or it is negatively correlated between indicators, all indicators can be retained. If each index is significant in the principal component correlation ($r \geq 0.5$), the index with the highest Norm value is selected to enter the MDS [55,56]. Among them, the larger the Norm value, the greater the comprehensive load of the index on all principal components, and the more soil quality information the index contains.

The formula for calculating the Norm value is as follows [19,20]:

$$N_{ik} = \sqrt{\sum_{j=1}^{k} (u_{ik}^2 e_k)} \quad (1)$$

where N_{ik} indicates the Norm value of the ith parameters at the first k principal component whose eigenvalue is greater than 1; u_{ik} represents the loading of the ith parameters at the kth principal component; e_k is the eigenvalue of the kth principal component.

2.5.2. Calculation of Soil Quality Index (SQI)

There are three steps for calculating the SQI. First, the index score was computed using the standard scoring function. Second, the weight of the index was computed based on the common factor variance of the PCA. Finally, the soil SQI was obtained by weighted summation [57].

All index scores were calculated using both an increasing function (Equation (2)) and a decreasing function (Equation (3)) to ensure comparability of each soil index across different units [24].

$$f(x) = \begin{cases} 0.1 \quad (x \leq L) \\ 0.9 \times \dfrac{x-L}{U-L} + 0.1(L < x < U) \\ 1 \quad (x \geq U) \end{cases} \tag{2}$$

$$f(x) = \begin{cases} 1 \quad (x \leq L) \\ 1 - 0.9 \times \dfrac{x-L}{U-L}(L < x < U) \\ 0.1 \quad (x \geq U) \end{cases} \tag{3}$$

In the formula, $f\ (x)$ represents the worth of each assessment index; x represents the quantified worth of each assessment index; U and L represent the maximum value and minimum value of each assessment index.

Each indicator calculates its corresponding weight through Formula (4):

$$W_i = C_i \Big/ \sum_{i=1}^{n} C_i \tag{4}$$

In the formula, W_i represents the weight of each indicator; C_i signifies the common factor variance of each evaluation indicator; n denotes the number of indicators included in the MDS [11,21].

Then, the soil quality index (SQI) is calculated based on the Formula (5):

$$SQI = \sum_{i=1}^{n} W_i \times f_i \tag{5}$$

In the formula, f_i signifies the score value of each evaluation indicator, n is the number of indicators, and W_i represents the index weight. The higher the SQI value, the better the soil quality [21].

2.6. Statitical Data Analysis

The analysis of variance (two-way ANOVA) was employed to assess significant differences in soil physicochemical indicators across various soil layers (0–15 cm, 15–30 cm, 30–45 cm) in both forest types. The original soil indicator data were subjected to a log transformation to fulfill the assumptions of normality and homoscedasticity required for ANOVA. Pearson regression analysis was used to explore the variation in the total dataset for 15 indicators (TDS) with the SQI and the MDS-SQI. The linear fit on the TDS-SQI (soil quality index based on the total dataset) and the MDI-SQI was carried out in this study. Regression weights predicted by the model were compared with the observed correlation matrix for the variables, and a goodness-of-fit statistic was calculated. Regression analysis was employed to examine relationships between the SQI and the soil MDS and between the SQI and the soil TDS. Statistical analyses were conducted using SPSS 22.0.

3. Results

3.1. Changes in Soil Quality Index after Interplanting Broad-Leaved Tree Species into a Chinese Fir Pure Forest

The forest type and soil depth as well as their interactions had significant effects on soil physiochemical indicators (p < 0.05) (Figure 3). The soil properties in the broad-leaved tree species and Chinese fir mixed forests were significantly improved when compared to the control, i.e., the Chinese fir pure forests ($p < 0.05$, Figure 3).

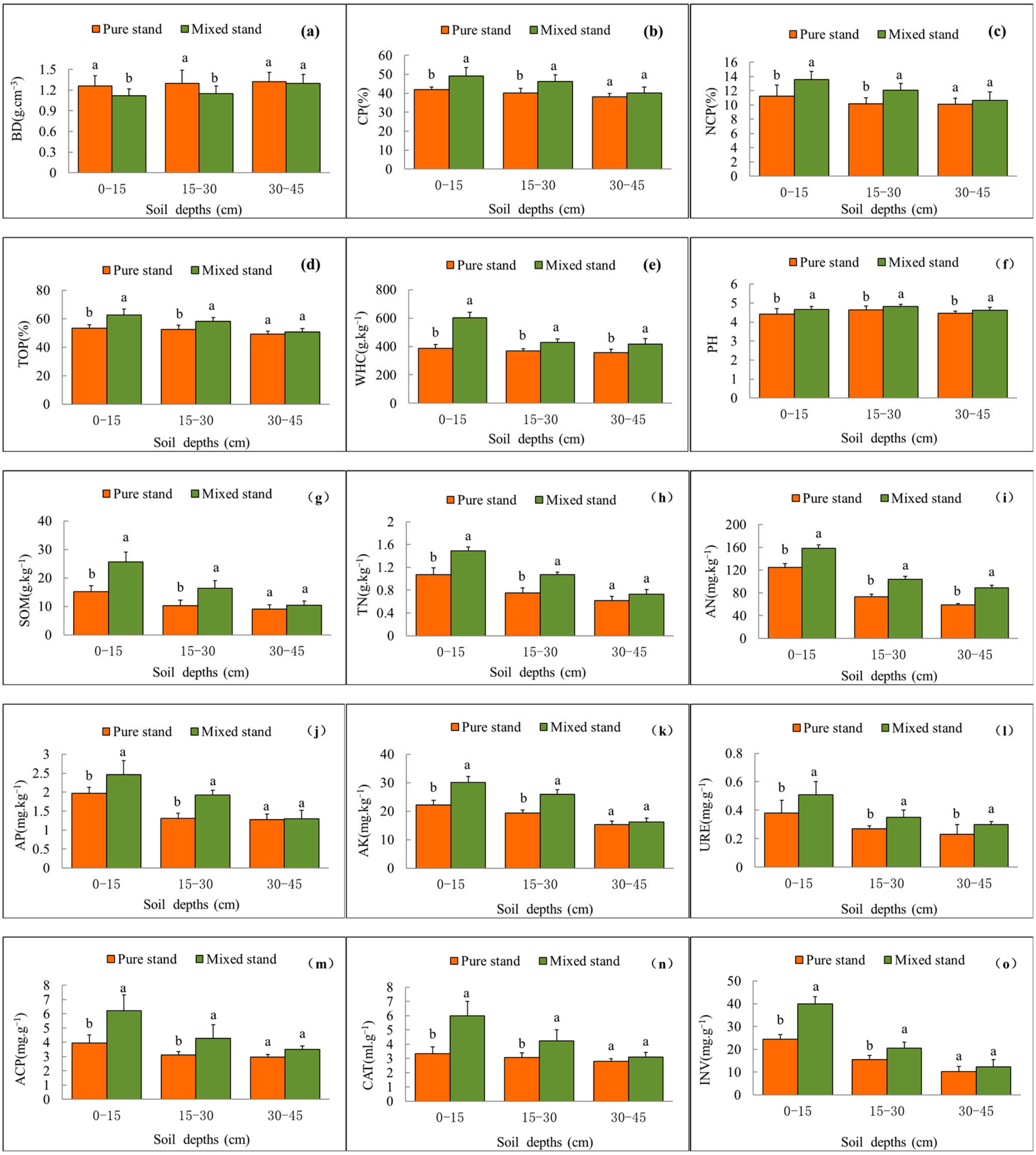

Figure 3. Physical, chemical, and biological characteristics of soil at 0–15, 15–30, 30–45 cm layers in two types of forests. Note: Varied lowercase letters indicate significant distinctions among the same soil layer within the two types of forest stands ($p < 0.05$).

The soil properties varied along the soil depth. As the soil depth increased, the soil's physical, chemical, and biological indicators exhibited a declining trend, with a clear surface aggregation phenomenon in both forest types (Figure 3). In the 0–15 cm soil layer, the mixed forests exhibited increases of 20.75%, 17.04%, 17.60%, and 55.46% in soil NCP, CP, TOP, and WHC, respectively, when compared to the control (Figure 3b–e). However, the soil BD decreased by 11.12% when contrasting mixed forests with pure forests (Figure 3a). The soil BD, NCP, CP, TOP, and WHC had significant differences between the two forest types in the 0–15 cm and 15–30 cm soil layers ($p < 0.05$, Figure 3a–e), and the soil WHC had a significant difference between the two forests at the 30–45 cm soil layer ($p < 0.05$, Figure 3e). The mixed forests exhibited increases of 68.77% in SOM, 39.25% in TN, 24.87% in AP, 26.65% in AN, and 35.98% in AK compared to the pure forests (Figure 3g–k).

Significant differences were observed in terms of SOM, TN, AP, AN, and AK contents in both the 0–15 cm and 15–30 cm soil layers between the two forest types ($p < 0.05$, Figure 3g–k). Soil AN also had a significant difference at the 30–45 cm layer between the two forest types ($p < 0.05$), as illustrated in Figure 3i. The soil pH was higher in the mixed forests than in the pure forests throughout all the soil layers as well (Figure 3f).

The soil URE, INV, ACP, and CAT enzyme activities at the 0–15 cm and 15–30 cm soil layers significantly increased in the mixed forests compared to the control ($p < 0.05$). On average, these four enzyme activities increased by 34.21%, 63.47%, 56.82%, and 78.51% in the mixed forests, respectively, when compared to the control (Figure 3l–n). However, the soil enzyme activity of URE in the 30–45 cm soil layer was significantly different between the two types of forests ($p < 0.05$) (Figure 3l).

3.2. Screening of Minimum Data Set (MDS) Indicators for Soil Quality Evaluation

In the current study, we conducted a principal component analysis on the 15 indicators of soil physical, chemical, and biological properties (Table 2). It was found that only the first four principal component eigenvalues were greater than 1. These eigenvalues accounted for 85.249% of the cumulative variance contribution (Table 2). Each principal component of the PC (PC1, PC2, PC3, and PC4) accounted for 39.746%, 20.529%, 15.072%, and 9.902% of the variance contribution, respectively. There were four groups in the analysis: the first group included TN, WHC, SOM, AN, and ACP; the second group included BD and TOP; the third group included CAT and pH; and the fourth group included AK. When the absolute load value is >0.5 in each principal component in the grouping of indicators, then the Norm value is calculated and the MDS candidate indicators are determined based on the selection principle of the Norm value in each group within 10% of the highest value.

Table 2. The loading matrix and the corresponding Norm values for each indicator.

Indicators	PC1	PC2	PC3	PC4	Group	Norm
BD	−0.771	0.549	0.066	−0.069	2	2.1671
TOP	0.729	−0.636	0.047	0.128	2	2.1591
CP	0.373	−0.550	−0.375	0.499	2	1.6261
NCP	0.503	−0.162	0.524	−0.445	3	1.6371
WHC	0.812	−0.559	−0.026	−0.015	1	2.6223
AK	0.211	0.550	−0.089	0.651	4	1.4263
TN	0.837	0.480	0.109	−0.096	1	2.2684
AN	0.955	0.211	0.029	−0.038	1	2.4083
AP	−0.039	0.251	0.819	0.440	3	1.4896
SOM	0.893	0.243	0.007	−0.023	1	2.2660
PH	−0.482	−0.325	0.707	0.189	3	1.7578
ACP	0.805	0.356	−0.161	−0.262	1	2.1485
INV	0.303	0.871	0.065	−0.014	2	1.7567
CAT	0.590	−0.043	0.579	0.313	3	1.7788
URE	−0.098	−0.197	0.531	−0.431	2	1.1010
Eigenvalue	5.962	3.079	2.261	1.485		
Variance contribution/%	39.746	20.529	15.072	9.902		
Cumulative variance contribution/%	39.746	60.275	75.346	85.249		

The Norm value and correlation analysis of the indicators found that the TN had the largest Norm value in the first group, and it was highly significantly positively correlated with other alternative indicators of WHC, AN, SOM, and ACP ($p < 0.01$, Table 3). Thus, TN was kept in group 1 only. Similarly, the largest Norm value of BD was in group 2. Because BD and TOP were highly significantly negatively correlated with each other ($p < 0.01$), both BD and TOP were retained in group 2. The Norm value of CAT was the highest in group 3, and there was no significant correlation between pH and CAT ($p > 0.05$), so both CAT and pH were retained in group 3. The fourth group consisted solely of AK, so it was maintained. The indicators of the final MDS including BD, TOP, AK, TN, PH value, and CAT are displayed in Table 4.

Table 3. Matrix of evaluation in soil quality index and the correlation coefficient.

	BD	TOP	CP	NCP	WHC	AK	TN	AN	AP	SOM	PH	ACP	INV	CAT	URE
BD	1														
TOP	−0.91 **	1													
CP	−0.55 *	0.70 **	1												
NCP	−0.53 *	0.46 *	−0.31	1											
WHC	−0.95 **	0.94 **	0.58 **	0.53 **	1										
AK	−0.02	−0.10	0.05	−0.19	−0.19	1									
TN	−0.37	0.31	−0.04	0.41 *	0.51 **	0.35 *	1								
AN	−0.59 **	0.53 **	0.23	0.43 **	0.66 **	0.23	0.91 **	1							
AP	0.22	−0.07	−0.26	0.23	−0.20	0.33 *	0.11	0.02	1						
SOM	−0.49 *	0.53 **	0.30	0.33 *	0.58 **	0.23	0.88 **	0.91 **	0.01	1					
PH	0.22	−0.09	−0.14	0.06	−0.20	−0.28	−0.43 **	−0.49 **	0.54 *	−0.47	1				
ACP	−0.40 *	0.28	0.02	0.35 *	0.43 **	0.23	0.81 **	0.86 **	−0.18	0.73 **	0.75 **	1			
INV	0.28	−0.29	−0.32	0.01	−0.22	0.45 **	0.74 **	0.48 **	0.23	0.59 **	−0.28	0.43 **	1		
CAT	−0.43 **	0.44 *	0.18	0.36 *	0.45 **	0.19	0.47 **	0.59 *	0.55 **	0.46 **	0.15	0.41 **	0.08	1	
URE	0.19	0.05	−0.12	0.21	−0.07	−0.41 **	−0.05	−0.12	0.01	0.01	0.38 *	−0.08	−0.14	0.15	1

Note: * represents the significant correlation at $p < 0.05$; ** represents the significant correlation at $p < 0.01$.

Table 4. Advocacy and weighting of soil quality assessment minimum and total data.

Indicators	TDS		MDS	
	Communality	Weight	Communality	Weight
BD	0.905	0.071	0.911	0.179
TOP	0.954	0.075	0.930	0.183
CP	0.831	0.065		
NCP	0.752	0.059		
WHC	0.973	0.076		
AK	0.778	0.061	0.735	0.144
TN	0.951	0.074	0.724	0.142
AN	0.959	0.075		
AP	0.930	0.073		
SOM	0.857	0.067		
PH	0.873	0.068	0.916	0.181
ACP	0.869	0.068		
INV	0.856	0.067		
CAT	0.783	0.061	0.872	0.171
URE	0.516	0.040		

3.3. Comprehensive Evaluation of Soil Quality

The variance of the share factors of each index was acquired through principal component analysis conducted on the MDS. The weight of each index was calculated using Formula (4) (see Table 4). The weight values for the smallest datasets were 0.179, 0.183, 0.144, 0.142, 0.181, and 0.171 in BD, TOP, AK, TN, PH, and CAT, respectively.

The MDS indicators were transformed into scores ranging from 0 to 1 utilizing both an increasing function (Equation (2)) and a decreasing function (Equation (3)). In this study, the descending function was applied to BD, and the ascending function was applied to TOP, AK, TN, and CAT. An ascending function was adopted in this research due to the acidic soil pH value in the experimental site. Consequently, the calculation of the soil quality index (Formula (5)) was conducted using the weight results from Table 4. The overall mean values of the SQI showed a significant increase in the mixed forests when compared to the control in the 0–15 cm and 15–30 cm layers of soil, but not in the 30–45 cm layer of soil ($p < 0.05$, Figure 4). The overall average of the SQI value ranged from 0.224 to 0.8523 in the two types of forests (Figure 4). The overall averages of the SQI were 0.8523 in the 0–15 cm soil layer and 0.6636 in the 15–30 cm soil layer in the mixed forests. In comparison, the average of the SQI was 0.4477 in the 0–15 cm soil layer and 0.3823 in the 15–30 cm soil layer in the pure forests (Figure 4).

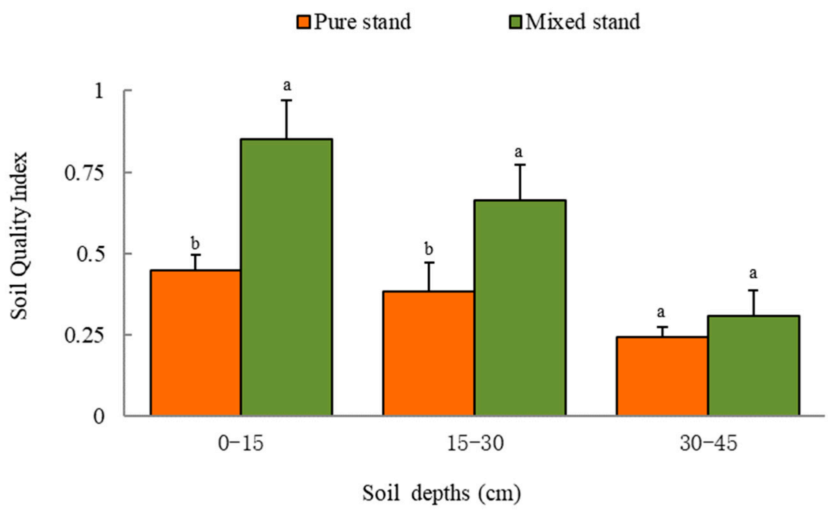

Figure 4. Soil quality indexes (SQI) in two types of forest stands. Note: Bars represent the mean values of soil quality index (SQI). Distinct lowercase letters indicate significant differences at a significance level of $p < 0.05$. To assess the precision of the MDS approach in estimating the SQI, the linear fit on TDS-SQI (soil quality index based on the total data set) and MDS-SQI (soil quality index based on the minimum data set) was carried out in this study (Figure 5). A highly significant correlation was observed between TDS-SQI and MDS-SQI ($p < 0.001$) (Figure 5). The linear fit equation yielded an R^2 value of 0.9218. This suggests that the chosen MDS soil quality evaluation index system is highly representative and effectively reflects the soil quality within the experiments.

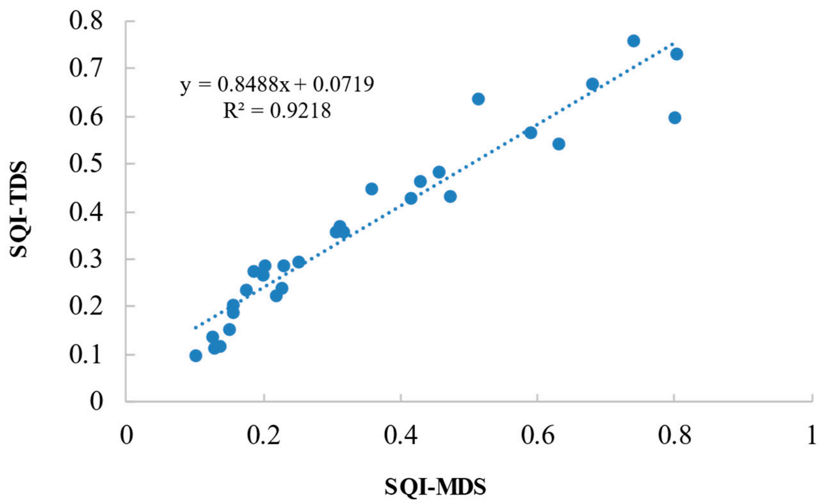

Figure 5. Linear fitting of TDS-SQI and MDS-SQI ($n = 30$).

4. Discussion

4.1. Changes in Soil Physical, Chemical, and Biological Properties in Two Types of Forest Stands

In this study, we discovered that the transition from a pure forest to a mixed forest through the interplanting of broad-leaved tree species such as *M. maudiae*, *K. paniculata*, and *L. chinense* with a Chinese fir forest resulted in a substantial improvement in soil quality in the mixed forests compared to the pure forests. This indicates that the composition of tree species is a key factor affecting soil quality in forest ecosystems. The different tree species have different leaf decomposition rates and changes in chemical composition, as well as root turnover and decomposition rates, resulting in great differences in the amount and return rates of nutrients returned to the soil [58–62]. Therefore, the quality of forest soils is highly related to factors such as tree species' composition, stand structure, and tree species' characteristics. Similarly, stand growth status can also reflect the levels of soil quality, resulting in significant variations in the soil quality of different stands [63–65]. Our findings align with the results reported from previous studies that the soil quality is significantly higher in mixed forests than in pure forests [66]. The polyculture tree species in mixed forests is a crucial silvicultural approach and pathway to enhancing soil fertility when contrasted with the monoculture of pure coniferous forests [37,67,68]. The previous studies found that the physiological properties of the soil, the enzyme activity, bacterial composition, and function of the soil were significantly improved after the Chinese fir pure forests were transformed into mixed forests [46]. The contents of soil organic carbon and nutrients were significantly higher in Chinese fir and *M. maudiae* mixed forests than in the Chinese fir pure forests [69]. The enzyme activities of β-N-acetylglucosaminidase (NAG) and acid phosphatase (AP) in the soil were significantly increased after Chinese fir pure forests were interplanted with broad-leaved tree species as well [70].

Our research reveals that the soil physiological indicators of the mixed Chinese fir plantation were significantly influenced by the topsoil, particularly within the 0–15 cm and 15–30 cm soil layers. This phenomenon could potentially arise due to the intertwining and intermixing of the root systems from deep-rooted tree species like *M. maudiae*, *K. paniculata*, and *L. chinense* with the shallow-rooted tree species of Chinese fir. This intricate root network substantially enhances soil aeration, air and water permeability, and overall soil porosity. The increased microbial activities of the soil might cause the increase in microorganism populations, which in turn accelerates the cycle and effectiveness of nutrients in the topsoil [71–74]. On the other hand, the forest canopy was overlapping in the mixed forests, and the denser canopy and luxuriant branches could form more surface litterfall and increase organic matter content and humus to the soil systems [75]. In addition, the denser and deeper crown of canopy would alter the microclimate of the forest, leading to a decrease in the temperature and an increase in the water content in soils [76]. The microclimate in mixed forest stands can increase the decomposition rate of litter and lead to an accumulation of a large amount of organic matter in soils [77].

4.2. Screening of MDS Indicators

The MDS theory is often used to screen redundant indicators through statistical methods such as cluster analysis, correlation analysis, and principal component analysis. Thus, the MDS for soil quality evaluation has been constructed to evaluate soil quality [55,78,79]. The principal component analysis method is a widely used statistical method for constructing the smallest data set. In this study, the MDS indicators including BD, TOP, AK, TN, PH value, and CAT were screened out through principal component analysis. The Norm value of each indicator includes the soil physiological properties to evaluate soil quality changes comprehensively following the interplanting of broad-leaved tree species in Chinese fir forests [19].

Several scholars have summarized the research results of soil quality evaluation MDS [80], and the results almost covered the physical, chemical, and biological characteristics of soil quality. The SOM/SOC and soil pH were the most common indicators used for SQI evaluation, followed by the soil AP indicator. Various water content indicators, soil BD, soil texture, soil AK, and soil TN are also frequently employed for SQI evaluation. Recently, the importance of soil organisms in soil functions have been gradually recognized, leading to the incorporation of numerous biological indicators in various soil quality evaluation index systems [81,82]. The six indicators of soil BD, TOP, AK, TN, PH, and CAT were used for evaluating the SQI in this study. In fact, these six indicators have been widely employed to assess the SQI in forest ecosystems at national and international scales [19,83,84].

4.3. Soil Quality Evaluation

The overall average of the SQI at the 0–15 cm and 15–30 cm of layers of soil in the mixed forest (0.8523, 0.6636) was significantly higher than that in the pure forests (0.4477, 0.3823). This indicates that the soil quality in Chinese fir pure forest was significantly improved after interplanting broad-leaved trees such as *M. maudiae*, *K. paniculata*, and *L. chinense* in this study. The increase in soil quality could be attributed to the decomposition process of litter in Chinese fir pure forests, which contains a substantial quantity of organic substances that are resistant to decomposition (such as tannin, wax, resin, etc.). This results in a slower return rate of soil nutrients, which in turn does not promote the sustainable utilization of forest land [85–88]. However, the abundance and diversity of litter in mixed forests create favorable conditions for soil microorganisms. This accelerates the decomposition rates of litter on the forest floor, ultimately promoting the efficient return of soil nutrients [40,89]. Therefore, it is necessary to incorporate appropriate broad-leaved tree species into pure forests in order to maintain and improve soil quality. This can enhance the decomposition efficiency of litter within forests, thereby contributing to soil improvement in mixed forest ecosystems [90]. The mixed forests in the present study were in the middle age stage, and the full realization of stand functions has not been achieved; consequently, long-term monitoring and evaluation of their soil quality, growth dynamics, and stand structure are necessary for the sustainable management of fir-broad mixed forests for further studies [91].

5. Conclusions

In order to reveal the changes in soil quality after the interplanting of broad-leaved tree species into a Chinese fir pure plantation, a total of 15 physiochemical indicators were used as the MDS for evaluating the SQI. Principal component analysis combined with Norm values (BD, TOP, AK, TN, pH, CAT) was conducted. The SQI values of the Chinese fir pure forests and the broad-leaved tree species and Chinese fir mixed forests were calculated in southern China. The SQI was significantly higher in the mixed forests than in the pure forests. The correlation score further demonstrated that the SQI based on the MDS can effectively serve as a replacement for the SQI derived from the full data set. This makes it a valuable tool for the comprehensive evaluation of soil quality in forest systems. This study reveals the changes in soil quality in different soil layers following the interplanting of broad-leaved tree species into Chinese fir pure forests. Our results provide both a theoretical and practical basis for maintaining soil quality in Chinese fir forests in subtropical regions of China.

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