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Effects of Cutting Intensity on Soil Physical and Chemical Properties in a Mixed Natural Forest in Southeastern China

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Abstract: The mixed Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook.), Masson's pine (*Pinus massoniana* Lamb.), and hardwood forest is a major forest type in China and of national and international importance in terms of its provision of both timber and ecosystem services. However, over-harvesting has threatened its long-term productivity and sustainability. We examined the impacts of timber harvesting intensity on soil physical and chemical properties 10 and 15 years after cutting using the research plots established with a randomized block design. We considered five treatments, including clear cutting and low (13.0% removal of growing stock volume), medium (29.1%), high (45.8%), and extra-high (67.1) intensities of selective cutting with non-cutting as the control. The impact on overall soil properties derived from principal component analysis showed increasing with a rise in cutting intensity, and the most critical impact was on soil nutrients, P and K in particular. Soil nutrient loss associated with timber harvesting even at a low cutting intensity could lead to nutrient deficits in this forest although most of the soil physical properties could be recovered under the low and medium intensities of cutting. These results indicate that clear cutting and the selective cutting of extra-high and high intensities should be avoided in this type of forest in the region.

Keywords: selective harvesting; mixed forest; forest soil; soil nutrients; principal component analysis

1. Introduction

Soil is critical to maintaining the productivity and sustainability of forest ecosystems. On the one hand, soil physically supports trees and is a source of moisture and nutrients for tree growth. On the other hand, when trees grow a great deal of litter is generated, returning nutrients to soil to improve its fertility through decomposition. Timber harvesting impacts soil, typically decreasing soil evapotranspiration and increasing soil compaction, temperature, and its diurnal fluctuation [1,2]. If not properly executed, timber harvesting could lead to undesirable consequences including soil erosion and forest degradation [3,4].

A considerable amount of work has been done to assess the impact of timber harvesting on forest soil. Over-harvesting could have significant undesirable ecological consequences including losses in biodiversity and soil quality [5]. In recent years, much attention has been paid to understanding the impacts of timber harvesting on soil physical and chemical properties in general and on soil fertility in particular. Many studies have reported that timber harvesting deteriorates soil physical and chemical properties, including losses of organic matter, N (nitrogen), P (phosphorus), K (potassium), and minerals [6–11]; reductions in soil water holding capacity and porosity [12]; and increases in soil bulk density, soil erosion, and forest degradation [13–17]. Some others have explored the effects of forest cutting on biodiversity. Timber harvesting is a disturbance to a forest ecosystem. High-intensity disturbances can cause adverse impacts on biodiversity and soil erosion, whereas low- and medium-intensity disturbances may benefit biodiversity over a long time period [18–21]. Most of these studies, however, focus on plantation forests and short- or intermediate-term effects of timber harvesting partially because of a lack of long-term data. In addition, most of them examine the impact on individual soil properties instead of overall soil properties. Thus, there is a need to uncover the impact of timber harvest on overall soil properties in mixed forests over a longer period.

The mixed Chinese fir (*Cunninghamia lanceolata (Lamb.) Hook.*), Masson's pine (*Pinus massoniana* Lamb.), and hardwood forest is a major forest type in China, covering approximately 66 million ha [10]. This forest type is an important source of timber and various ecosystem services including carbon storage, biodiversity, and water regulation [22]. It is estimated that this forest type has supplied 40% of total timber volume harvested in China and 33 million tonnes of carbon storage [10]. Given the vital role of China in global forest products markets and forest conservation [23], maintaining the long-term productivity and sustainability of this forest is important to China and the world alike. Increases in China's domestic timber supply from its sustainably managed forests would reduce its timber imports, alleviating the pressure on global forest conservation. However, this mixed natural forest is under great pressure in a large part due to over-harvesting over the past several decades, which has caused its degradation affecting its ability to sustainably provide timber and ecosystem services. Hence, increased efforts have been made to protect this forest as part of the National Natural Forest Conservation Program in China [24]. These efforts include shifting timber harvests from natural forests to plantations [10], thus providing an opportunity to adopt less intensive timber harvesting methods in this mixed natural forest. How different timber harvesting intensities will affect forest soil and ecosystem services, however, is not well understood.

This study aims to examine the impacts of timber harvesting intensity on soil in this mixed Chinese fir, Masson's pine, and hardwood forest in the southeastern China. We focus on the impacts on both physical and chemical properties of soil 10 and 15 years after the cutting. By focusing on the impacts on a mixed forest over a longer period, we intend to enrich the existing literature that is centered on the short-term effects of timber harvest on forest plantations. Additionally, we employ principal component analysis (PCA) to assess the aggregate effects of cutting intensity on overall soil physical and chemical properties. Because timber harvesting alters several soil properties simultaneously and these properties tend to interact with one another, it is important to disclose the aggregate effects jointly. Finally, we probe the impacts across a wide spectrum of cutting intensities, ranging from non-cutting (the benchmark) to clear cutting. As such, our results can aid in determining the optimal timber harvesting intensity for this major forest type in the region. Given the geographically wide spread of this forest and other similar forests, our findings would also have implications beyond the study region.

2. Materials and Methods

2.1. Study Site

The study site was on the Dayuan Forest Farm, Jianou County, Fujian Province, southern China (117°58′45″–118°57′11″ E, 26°38′54″–27°20′26″ N). It is located between two mountains with the Wuyi Mountains on the northwest and the Jiufeng Mountains on the southeast. The research plots were established within sub-compartments 17, 18, and 19 in compartment 84 (Figure 1). The experiment site is characterized as low mountain hilly terrain. The elevation of the site ranges from 600 to 800 m with a slope of 25–34°. This area has a subtropical maritime monsoon climate. The mean annual temperature is 15 °C–17 °C, and annual precipitation is 1890 mm. According to United States Department of Agriculture (USDA) soil taxonomy, the soil on the study site is classified as oxisol.

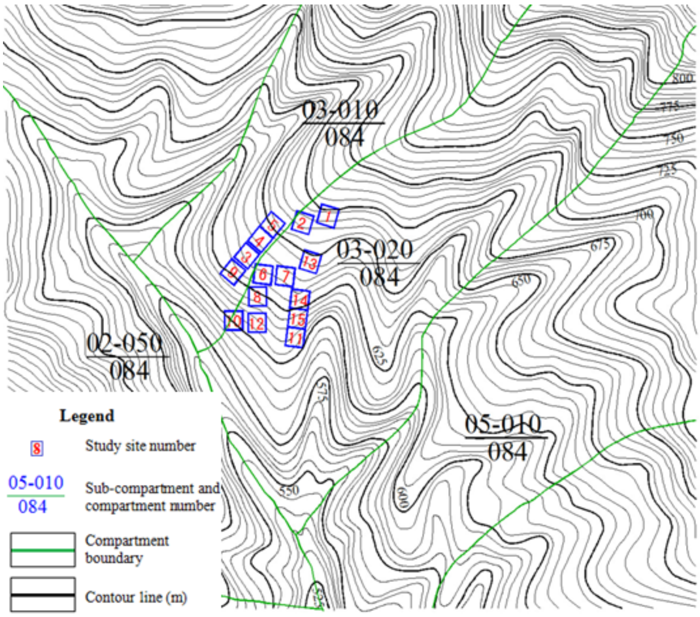

Figure 1. Study site.

Main tree species in the natural forest are *Castanopsis eyrei* (Champ. ex Benth.) Tutch., *Castanopsis carlesii* (Hemsl.) Hayata, *Daphnipyllum oldhamii* (Hemsl.) K. Rosenthal, *Schima superba* Gardner and Champ., and *Pinus massoniana* Lamb. Shrub species on the site include *Adinandra millettii* Hook. and Arn., *Lithocarpus glaber* (Thumb.) Nakai, *Engelhardtia fenzelii* Merr., *Symplocos congesta* Benth., *Eurya nitida* Korth., and *Rhaphiolepis indica* (L.) Lindl. Ex Ker Gawl. Underground herbaceous and liana species are dominated by *Dicranopteris dichotoma* (Thunb.) Bernh., *Smilax china* L., *Woodwardia japonica* (L.f.) Sm., *Hicriopteris chinensis* (Rosenst.) Ching, and *Gahnia tristis* Nees. More details about the characteristics of this forest can be found in [2].

2.2. Plot Establishment and Measurements

The experiment plots (20 m × 20 m) were established using a randomized block design. Blocking factors included topology, soil, and initial forest stand conditions. There were five treatments including four selective cutting intensities and clear cutting with non-cutting as the control. Four selective cutting intensities were low intensity (13.0% removal of growing stock volume), medium intensity (29.1%), high intensity (45.8%), and extra-high intensity (67.1%) (Table 1). The plots were established in March 1996 with three replications for each treatment.

Selective cuttings were executed in accordance with the technical requirements established by the single tree selection method [25]. Defective and inferior trees were cut out first, followed by removing over-mature and some mature trees to create a healthy and vigorous forest stand that resembled the original species composition in the forest and the target stand density under each cutting intensity. The cutting operation consisted of chainsaw cutting, on-site delimbing and bucking, skidding by human shoulder, and collecting and utilizing branches of >5 cm in diameter. This logging method is a common practice in the region. Prior to the cutting, forest stand conditions on the sites of these plots were the same with a 90% crown closure [26]. These plots were measured immediately before their establishment in March 1996 and after their establishment in November 1996. In July 2006 (10 years after the cutting) and August 2011 (15 years after the cutting), they were measured again. The characteristics of the forest stands in the treatment plots before and immediately after the cutting are shown in Table 1.

Table 1. Stand characteristics of treatment plots.

Cutting Intensity	Stand Density (No. of trees/ha)		Volume of Growing Stock (m^3/ha)		Cutting Intensity (% of Growing Stock Volume)	Mean DBH (cm)	
	Pre-Cutting	Post-Cutting	Pre-Cutting	Post-Cutting		Pre-Cutting	Post-Cutting
Low	1592	1533	258.5	224.7	13.0	17.3	16.7
Medium	2866	2275	286.6	211.8	29.1	16.0	14.4
High	1875	1617	245.5	133.7	45.8	15.7	13.5
Extra-high	2008	1350	201.3	64.8	67.1	14.7	9.6
Clear cutting	1125	0	206.3	0	100	15.9	0

2.3. Soil Sampling and Testing

Because the influence of harvesting on soil is primarily on surface soil, only the surface soil layers between 0 and 10 cm and between 10 and 20 cm were sampled. The sampling was executed according to the national standard for collecting and preparing forest soil samples [27]. Each soil sample was taken respectively from the upper, middle, and lower sections of the slope in each plot. For the purposes of testing physical properties, the soil samples were kept in their original soil shapes by putting them into aluminum boxes to prevent them from being squeezed and becoming deformed. For the purposes of analyzing soil chemical properties, the samples were put inside plastic bags, sealed and labeled. The three soil samples from the upper, middle, and lower sections of the slope in each plot were evenly mixed and air-dried; and then the mixed soil was used for lab analysis [25]. Thus, the soil testing results represented the average value from the upper, middle, and lower sections of the slop in each plot.

Soil physical properties analyzed here included soil bulk density, aggregates, porosity, and water holding capacity because they are important indicators of soil structure. Likewise, common indicators of soil chemical properties such as organic matter, nitrogen (N), phosphorus (P), and potassium (K) were considered in this study.

Analyses of soil physical and chemical properties were performed according to the national standard/protocol [28]. Soil aggregate stability was tested using the mechanical screening method (LY/T 1226-1999) [29]; water holding capacity was assessed via the cutting ring method (LY/T 1215-1999) [30]; organic matter was measured with the potassium dichromate oxidation-external heating method (LY/T 1237-1999) [31]; total phosphorus was analyzed with the perchloric acid-sulfuric acid-soluble Mo-Sb colorimetry method (LY/T 1232-1999) [32]; rapidly available phosphorus was extracted with the hydrochloric acid-ammonium fluoride extraction method (LY/T 1233-1999) [33]; total nitrogen was estimated with the perchloric acid-sulfuric acid digestion diffusion absorption method (LY/T 1228-1999) [34]; water-soluble nitrogen was quantified with the alkaline hydrolysis-diffusion absorption method (LY/T 1229-1999) [35]; total potassium was tested with the sodium hydroxide alkali fusion-flame photometry method (LY/T 1234-1999) [36]; rapidly available potassium was gauged with the ammonium acetate extraction-flame photometry method (LY/T 1236-1999) [37]. More details about the soil testing procedures can also be found in [38]. The means of these test results for a given cutting intensity were used to represent its impacts on soil physical and chemical properties.

2.4. Data Analysis

With the data derived from field measurements and laboratory analyses, we calculated the percentage change in soil physical and chemical properties under different cutting intensity relative to non-cutting. That is, we computed the R-score [7,26] as follows:

$$R = \frac{(S_{ij} - S_{i0})}{S_{i0}} \times 100\%, \tag{1}$$

where S_{ij} is the mean value of soil property i at the sites with cutting intensity j; S_{io} is the mean value of soil property i in the non-cutting plots. The percentage change (R-score) reflects the change in soil properties at a specific cutting intensity when compared to non-cutting some (10 and 15) years after the cutting. Additionally, one-way ANOVA was performed to compare the impacts of cutting intensity on overall soil properties.

We were particularly interested in the aggregate impacts of cutting intensity on overall soil properties, which called for multivariate analysis. However, possible correlations among different variables (soil properties) in the model posed statistical complications [39]. To overcome this challenge, we adopted principal component analysis.

Using the estimated principal components, we further calculated the weighted index value of impacts of cutting intensity on overall soil physical and chemical properties [40]:

$$F = \sum_{j=1}^{K} \eta_j F_j \tag{2}$$

where F is the aggregate impact score of cutting intensity on overall soil properties; η_j is the contribution rate of the jth PC (F_j) with $\sum_{j=1}^{K} \eta_j = 1$.

3. Results

3.1. Impacts on Individual Soil Physical Properties

Table 2 shows the measurements of soil physical properties at the harvest sites under different cutting intensities, 10 and 15 years after the cutting. All these indicators showed certain variation tendency over time, suggesting that soil physical properties could be at least partially restored over time. Among these physical properties, the percentage of damaged structural aggregates declined dramatically from 10 years to 15 years after the cutting. Under the low and medium intensities of selective cuttings, damaged structural aggregates 10 years after the cutting fell to 12.4% and 11.9%, respectively. However, 15 years after the cutting, the corresponding figure reduced to 3.2% and 2.7%, respectively. Soil bulk density also showed further decline from 10 to 15 years after the cutting under all cutting intensities.

Soil water holding capacity also decreased with an increase in cutting intensity (Table 2). An increase in cutting intensity led to an increase in soil bulk density and a reduction in porosity, thus reducing soil permeability and water transferring and holding capacity.

According to the R-scores (Table 3), under the low and medium cutting intensities, most of the soil physical properties were able to be restored to their levels at the non-cutting sites in 10 years; under the high cutting intensity, most of the soil physical properties could be restored in 15 years; under the extra-high cutting intensity and clear cutting, almost all the soil physical properties could not be fully recovered even 15 years after the cutting.

Table 2. Means and standard deviations of soil physical properties 10 and 15 years after cutting.

Cutting Intensity	Soil Bulk Density (g· cm^{-3})	>0.25 mm Water-Stable Aggregates (%)	Damaged Structural Aggregates (%)	Max Water Holding Capacity (%)	Min Water Holding Capacity (%)	Capillary Water Holding Capacity (%)	Total Porosity (%)	Capillary Porosity (%)	Non-Capillary Porosity (%)
10 years after cutting									
Non-cutting	1.23 (0.21) [a]	70.7 (1.7)	12.38 (0.22)	45.4 (5.1)	29.3 (0.1)	34.4 (1.9)	54.77 (1.7)	41.5 (0.3)	13.2 (1.2)
Low	1.05 (0.13)	71.9 (3.5)	11.89 (0.18)	59.2 (5.2)	39.3 (2.2)	43.0 (1.5)	62.3 (1.3)	44.9 (1.5)	19.9 (1.7)
Medium	1.18 (0.04)	73.1 (2.6)	9.62 (0.05)	51.3 (3.8)	32.8 (1.0)	38.7 (1.1)	60.0 (0.9)	45.3 (1.2)	14.8 (0.2)
High	1.24 (0.16)	68.6 (1.4)	13.51 (0.72)	43.9 (1.6)	28.4 (0.9)	34.2 (0.7)	53.6 (0.7)	41.8 (0.7)	11.8 (0.4)
Extra-high	1.28 (0.21)	67.0 (2.6)	14.05 (1.16)	41.8 (1.0)	25.0 (0.3)	34.1 (0.9)	53.2 (0.4)	43.2 (0.9)	10.0 (0.5)
Clear cutting	1.35 (0.33)	64.7 (1.4)	17.78 (1.87)	37.0 (2.3)	22.2 (1.3)	31.0 (1.0)	49.8 (0.6)	41.7 (0.4)	8.1 (0.8)
15 years after cutting									
Non-cutting	1.11 (0.06)	68.8 (1.5)	3.22 (0.01)	46.4 (4.8)	28.3 (0.1)	31.0 (1.4)	50.2 (0.9)	33.2 (0.8)	14.3 (1.0)
Low	0.99 (0.07)	69.3 (3.7)	2.71 (0.01)	51.7 (5.4)	30.5 (1.2)	36.4 (2.2)	53.6 (0.8)	38.0 (1.2)	17.1 (0.7)
Medium	1.06 (0.08)	70.5 (2.2)	2.18 (0.02)	50.2 (3.2)	30.2 (0.4)	36.1 (1.0)	52.7 (0.6)	36.8 (0.5)	15.3 (1.8)
High	1.08 (0.02)	71.7 (1.0)	2.43 (0.04)	49.3 (4.6)	29.9 (0.7)	35.8 (0.9)	52.4 (1.6)	39.5 (0.3)	14.8 (0.4)
Extra-high	1.18 (0.26)	67.1 (2.1)	4.95 (0.03)	44.8 (3.9)	25.6 (0.2)	29.6 (0.1)	48.1 (0.2)	39.2 (0.4)	13.7 (0.4)
Clear cutting	1.20 (0.35)	64.5 (0.9)	4.99 (0.06)	41.6 (4.3)	24.7 (0.6)	27.8 (0.2)	46.9 (0.8)	38.4 (0.2)	12.6 (1.7)

[a] Figures inside parentheses are standard deviations.

Table 3. Percentage changes in soil physical properties due to different cutting intensities relative to non-cutting.

Soil Property	Cutting Intensity (10 Years after Cutting)					Cutting Intensity (15 Years after Cutting)				
	Low	**Medium**	**High**	**Extra-High**	**Clear Cutting**	**Low**	**Medium**	**High**	**Extra-High**	**Clear Cutting**
Soil bulk density	−14.3	−3.6	1.1	4.4	9.9	−10.6	−5.2	−3.2	5.8	7.8
>0.25 mm water-stable aggregates	1.8	3.5	−3.0	−5.2	−8.5	0.7	2.5	4.3	−2.5	−6.3
Damaged structural aggregates	−3.9	−22.3	9.1	13.5	43.6	−15.9	−32.3	−24.3	53.5	54.9
Max water holding capacity	30.6	13.1	−3.3	−7.8	−18.4	11.4	8.2	6.2	−3.4	−10.3
Min water holding capacity	33.9	11.9	−3.2	−14.9	−24.4	7.7	6.7	5.5	−9.7	−12.9
Capillary water holding capacity	25.1	12.5	−0.6	−1.0	−9.9	17.6	16.7	15.6	−4.5	−10.2
Total porosity	13.7	9.6	−2.1	−2.9	−9.0	6.7	5.1	4.3	−4.2	−6.6
Capillary porosity	8.1	9.0	0.6	4.1	0.3	14.4	10.7	18.8	17.9	15.7
Non-capillary porosity	50.7	11.5	−10.7	−24.8	−38.5	19.7	7.0	3.9	−4.2	−11.8

Table 4. Percentage change in soil physical properties between 10 and 15 years after cutting.

Cutting Intensity	Soil Bulk Density	>0.25 mm Water-Stable Aggregates	Damaged Structural Aggregates	Max Water Holding Capacity	Min Water Holding Capacity	Capillary Water Holding Capacity	Total Porosity	Capillary Porosity	Non-Capillary Porosity
Non-cutting	−9.3	−2.7	−73.9	2.3	−3.4	−10.0	−8.3	−20.1	7.7
Low	−5.3	−3.7	−77.2	−12.8	−22.3	−15.4	−13.9	−15.5	−14.5
Medium	−10.8	−3.6	−77.3	−2.2	−8.0	−6.6	−12.2	−18.9	3.4
High	−13.2	4.7	−81.9	12.3	5.3	4.7	−2.3	−5.6	25.3
Extra-high	−8.2	0.1	−64.8	7.2	2.4	−13.2	−9.6	−9.4	37.2
Clear cutting	−11.1	−0.3	−71.9	12.4	11.3	−10.3	−5.9	−7.8	54.6

Recovery or deterioration rates of soil physical properties also displayed some difference across cutting intensities. For instance, damaged structural aggregates and >0.25 mm water-stable aggregates recovered at a slower pace under the extra-high cutting intensity and clear cutting than under non-cutting between 10 and 15 years after the cutting, whereas these two properties restored faster under the low and medium cutting intensities than under non-cutting. However, maximum and minimum soil water holding capacities deteriorated faster under the low and medium cutting intensities than under non-cutting, whereas they recovered under the extra-high cutting intensity and clear cutting between 10 and 15 years after the cutting. Similarly, non-capillary porosity deteriorated at a lower rate under the low and medium cutting intensities but recovered faster under the high and extra-high cutting intensities and clear cutting than under non-cutting (Table 4).

Hence, although soil physical properties damaged by timber harvesting showed some recovery over time, clear cutting and selective cutting of high and extra-high intensities could lead to long-term damage to some soil physical properties. The most likely long-term damage would be to water holding capacity and porosity.

3.2. Impacts on Individual Soil Chemical Properties

In general, soil chemical properties tended to deteriorate with an increase in cutting intensity (Tables 5 and 6). Soil organic matter, total N, hydrolysis N, and total P were able to be restored 10 years after the cutting under the low and medium cutting intensities and 15 years after the cutting under the high cutting intensity. It would take longer than 15 years for these chemical properties to be restored to their levels at the non-cutting sites under the extra-high cutting intensity and clear cutting if it would be possible. An increase in cutting intensity reduced canopy interception during the rainy season and caused more severe surface runoff and soil erosion, thus reducing soil fertility [41,42]. The measurements of all soil chemical properties under the extra-high intensity of selective cutting and clear cutting were lower than those at the non-cutting sites even 15 years after the cutting. This suggests that clear cutting and selective cutting of extra-high intensity could cause N deficits in this type of forest in the region.

Available P and K and total K could not be fully recovered 15 years after the cutting; even worse, they further declined from 10 years to 15 years after the cutting. The deterioration in total K and available P and K over time was partially attributable to their uptakes by trees during the time period. The reduced litterfall as trees were harvested could also contribute to soil nutrient loss [43–45]. Additionally, eluviation of K made it easier to get lost in the soil after cutting than other nutrients [46–48]. Hence, P and K deficits could be a problem in this forest even at a low cutting intensity.

Table 5. Means and standard deviations of soil chemical properties 10 and 15 years after cutting.

Cutting Intensity	Organic Matter (g· kg^{-1})	Total N (g· kg^{-1})	Hydrolysis N (mg· kg^{-1})	Total P (g· kg^{-1})	Available P (mg· kg^{-1})	Total K (g· kg^{-1})	Available K (mg· kg^{-1})
			10 years after cutting				
Non-cutting	25.1 (0.4) [a]	0.95 (0.02)	86.8 (14.5)	0.092 (0.002)	3.52 (0.02)	54.29 (0.63)	124.4 (3.7)
Low	25.6 (1.2)	0.99 (0.08)	93.9 (14.4)	0.106 (0.010)	3.23 (0.02)	53.02 (0.67)	105.3 (4.1)
Medium	25.2 (0.5)	0.97 (0.10)	93.1 (17.5)	0.108 (0.010)	3.05 (0.03)	49.70 (0.12)	86.1 (4.3)
High	22.8 (1.0)	0.84 (0.10)	78.1 (9.8)	0.091 (0.005)	2.38 (0.06)	38.60 (0.09)	74.2 (2.8)
Extra-high	20.1 (0.4)	0.77 (0.05)	75.5 (7.1)	0.090 (0.003)	1.78 (0.07)	36.18 (0.51)	63.3 (3.8)
Clear cutting	18.7 (0.7)	0.65 (0.06)	56.8 (1.7)	0.089 (0.001)	1.53 (0.03)	34.97 (0.09)	47.9 (1.9)
			15 years after cutting				
Non-cutting	23.0 (0.4)	0.97 (0.01)	80.4 (12.8)	0.080 (0.004)	1.47 (0.01)	17.37 (0.05)	81.2 (3.4)
Low	25.3 (1.0)	1.07 (0.05)	93.2 (11.7)	0.091 (0.006)	0.54 (0.05)	13.44 (0.09)	79.1 (1.7)
Medium	25.0 (0.4)	1.01 (0.11)	85.8 (10.6)	0.087 (0.003)	0.45 (0.06)	8.91 (0.03)	74.0 (3.4)
High	24.6 (0.4)	0.99 (0.07)	83.6 (13.1)	0.085 (0.007)	0.42 (0.03)	8.90 (0.08)	51.2 (2.3)
Extra-high	21.4 (0.5)	0.84 (0.05)	76.6 (12.3)	0.067 (0.008)	0.35 (0.04)	6.51 (0.08)	48.0 (2.3)
Clear cutting	18.1 (0.3)	0.72 (0.04)	74.9 (3.6)	0.060 (0.003)	0.31 (0.04)	5.80 (0.06)	37.5 (1.1)

[a] Figures inside parentheses are standard deviations.

Table 6. Percentage changes in soil chemical properties due to different cutting intensities relative to non-cutting.

Soil Property	10 Years after Cutting					15 Years after Cutting				
	Low	Medium	High	Extra-High	Clear Cutting	Low	Medium	High	Extra-High	Clear Cutting
Organic matter	1.9	0.4	−9.2	−19.9	−25.5	10.0	8.7	6.9	−6.9	−21.3
Total N	4.2	2.1	−11.6	−18.9	−31.6	10.3	4.1	2.1	−13.4	−25.8
Hydrolysis N	8.3	7.3	−10.0	−13.1	−34.6	15.9	6.7	4.0	−4.7	−6.8
Total P	15.2	17.4	−1.1	−2.2	−3.3	13.8	8.8	6.3	−16.9	−25.0
Available P	−8.2	−13.4	−32.4	−49.4	−56.5	−63.3	−69.7	−71.4	−76.2	−78.9
Total K	−2.3	−8.5	−28.9	−33.4	−35.6	−22.6	−48.7	−48.8	−62.5	−66.6
Available K	−15.3	−30.7	−40.4	−49.1	−61.5	−2.6	−8.8	−36.9	−40.8	−53.9

3.3. Impacts on Overall Soil Properties

3.3.1. Comparison of Impacts of Cutting Intensity

The descriptive statistics of impacts of cutting intensity on overall soil physical and chemical properties are shown in Table 7. According to the ANOVA results (Table 8), cutting intensity had a significant impact on overall soil properties both 10 and 15 years after the cutting at the 5% significance level.

Table 7. Descriptive statistics of impacts of cutting intensity on overall soil properties.

Cutting Intensity	**N**	**Mean**	**Std. Error**	**95% Confidence Interval for Mean**	
				Lower Bound	**Upper Bound**
10 years after cutting					
Non-cutting	16	40.50	8.82	21.70	59.30
Low	16	48.30	6.86	33.69	62.92
Medium	16	36.57	7.73	20.10	53.04
High	16	32.12	6.66	17.92	46.33
Extra-high	16	19.20	4.38	9.87	28.53
Clear cutting	16	20.89	4.37	11.58	30.19
Total	96	32.93	2.86	27.26	38.60
15 years after cutting					
Non-cutting	16	36.31	7.57	20.19	52.43
Low	16	42.31	6.65	28.13	56.49
Medium	16	30.64	7.24	15.20	46.078
High	16	29.17	6.76	14.76	43.58
Extra-high	16	16.74	4.10	8.01	25.48
Clear cutting	16	17.50	4.12	8.72	26.28
Total	96	28.78	2.65	23.51	34.05

Table 8. ANOVA results on the impacts of cutting intensity on overall soil properties.

	Sum of Squares	**df**	**Mean Square**	**F**	***p*-Value**
10 years after cutting					
Between Groups	10,257.65	5	2051.53	2.880	0.019
Within Groups	64,111.62	90	712.35		
Total	74,369.27	95			
15 years after cutting					
Between Groups	8,247.82	5	1649.56	2.650	0.028
Within Groups	56,014.02	90	622.38		
Total	64,261.84	95			

3.3.2. Principal Component Analysis

Aggregate impacts of cutting intensity on overall soil physical and chemical properties were measured with an aggregate impact score, a weighted average calculated using the first and second principal components (F_1 and F_2). Because the first and second principal components explain over 85% and 90% of total variability for 10 and 15 years after the cutting, respectively (Table 9), the aggregate impact score well reflects the effects of different cutting intensities on overall soil physical and chemical properties.

Table 9. Eigenvalue and variability explained by principal components.

Item	**10 Years after Cutting**		**15 Years after Cutting**	
	F_1 [a]	F_2	F_1	F_2
Eigenvalue	9.36	5.19	7.84	5.87
Variability explained (%)	58.50	32.41	48.97	36.71
Cumulative variability explained (%)	58.50	90.91	48.97	85.68

[a] F_1 and F_2 are the first and second principal components, respectively.

The eigenvector coefficients of soil properties for the first and second principal components are presented in Table 10. Their absolute values reflect the relative importance/contribution of each soil property to the aggregate impact score. Based on the contribution of each soil property to the aggregate impact score of cutting intensity under the first principal component (F_1), the top three properties were X_{15} (total K), X_{16} (available K), and X_{14} (available P) 10 years after the cutting, and X_{14} (available P), X_{15} (total K), and X_{16} (available K) 15 years after the cutting, respectively.

Table 10. Eigenvector coefficients for the first and second principal components.

Variable	Variable Description	10 Years after Cutting		15 Years after Cutting	
		F_1	F_2	F_1	F_2
X_1	Soil bulk density	−0.449	**0.864**	−0.371	**0.864**
X_2	>0.25 mm water-stable aggregates	0.786	0.530	0.772	0.150
X_3	Damaged structural aggregates	0.561	0.530	0.926	0.179
X_4	Max water holding capacity	−0.649	0.757	−0.477	0.785
X_5	Min water holding capacity	−0.445	**0.867**	0.671	0.720
X_6	Capillary water holding capacity	−0.824	0.555	−0.830	0.015
X_7	Total porosity	−0.721	0.642	−0.294	**0.942**
X_8	Capillary porosity	−0.875	−0.073	0.473	−0.274
X_9	Non-capillary porosity	−0.301	**0.870**	−0.556	0.814
X_{10}	Organic matter	0.878	0.427	0.428	**0.822**
X_{11}	Total N	0.852	0.521	0.599	0.792
X_{12}	Hydrolysis N	0.664	0.709	−0.740	0.619
X_{13}	Total P	−0.894	0.083	0.589	0.782
X_{14}	Available P	**0.951**	0.254	**0.994**	0.033
X_{15}	Total K	**0.990**	0.022	**0.969**	−0.097
X_{16}	Available K	**0.964**	0.196	**0.945**	0.034

Similarly, under the second principal component (F_2), the top three properties were X_9 (non-capillary porosity), X_5 (minimum water holding capacity), and X_1 (soil bulk density) 10 years after the cutting, and X_7 (total porosity), X_1 (soil bulk density), and X_{10} (organic matter) 15 years after the cutting, respectively (Table 10). Therefore, the first principal component mainly accounted for the impact of cutting intensity on soil chemical properties while the second principal component largely accounted for the impact on soil physical properties.

Table 11 shows the aggregate impacts of cutting intensity on overall soil properties. According to the aggregate impact scores, for both 10 and 15 years after the cutting the largest impact was clear cutting, followed by extra-high, high, medium, and low intensities of selective cutting. In other words, the impact on overall soil properties increased with an increase in cutting intensity.

Table 11. Aggregate impacts of cutting intensity on overall soil physical and chemical properties.

Cutting Intensity	Principle Components		Comprehensive Evaluation Score	Rank
	F_1	F_2		
10 years after cutting				
Low	−4.333	1.588	−2.021	5
Medium	−2.035	−1.383	−1.639	4
High	1.421	−2.563	0.001	3
Extra-high	1.960	−0.670	0.929	2
Clear cutting	2.990	3.023	2.729	1
15 years after cutting				
Low	−3.861	2.022	−1.148	5
Medium	−1.406	−1.072	−1.082	4
High	−0.066	−2.702	−1.024	3
Extra-high	2.333	−1.294	0.667	2
Clear cutting	3.001	3.046	2.588	1

4. Discussion

Our results showed that cutting intensity had a significant impact on overall soil physical and chemical properties. In general, soil bulk density increases, but soil organic matter, porosity, and water holding capacity decrease as cutting intensity increases, echoing the results reported in the literature [49–52]. Likewise, an increase in cutting intensity (even a low intensity of selective cutting relative to non-cutting) could cause loss in soil nutrients (N, P, and K), which is parallel to the finding of existing studies [46,51–53].

In addition to confirming existing findings, our study shed new light on the aggregate impact of cutting intensity on overall soil properties. Via PCA, we found that the first principal component was exclusively associated with soil nutrients, which explained most variation in the impact of cutting intensity, and that the second principal component was solely linked to soil physical properties. Thus, the greatest concern about high intensity cutting in this forest would be soil nutrient loss (P and K loss in particular), followed by the negative impacts on soil physical properties. Loss in soil nutrients would diminish long-term soil productivity if without nutrient replenishment such as fertilizer application, leading to forest degradation.

Moreover, the recovery of soil properties impacted by timber harvesting is a slow process. It would take longer for overall soil properties to recover as cutting intensity rises. This was not only because a higher intensity of cutting would cause greater damage to soil properties, but also because the recovery rate of soil properties would slow down more quickly or sooner with an increase in cutting intensity. As such, additional time within a cutting period may not be very helpful in restoring soil properties damaged by a high intensity of cutting, and some soil properties may not be fully restored if cutting intensity is too high.

Given the rising demand for timber, complete elimination of timber harvesting from this forest seems unrealistic. With all the above impacts in mind, if timber harvesting from this forest has to continue to some extent, cutting intensity should be maintained at a level not higher than the medium intensity. Moreover, nutrient replenishment via proper application of fertilizers may be viable in assisting forest regeneration or restoration in the region.

Our study focuses on the impact of cutting intensity on soil physical and chemical properties. Future studies can probe the effect of cutting intensity on forest growth and structure instead of soil properties, which will provide direct measurements of impacts on forest productivity, diversity, and resilience. Additionally, coordinated multiple-regional studies can help explore the impact of other forcing such as environmental conditions together with timber harvesting intensity. Finally, studies that target longer-term impacts (for example, multiple cutting periods for selective cutting and multiple rotations for clear cutting) would be invaluable in disclosing the consequences of timber harvesting on the long-term productivity and sustainability of the forest ecosystem.

5. Conclusions

We examined the impact of timber harvesting intensity on soil physical and chemical properties in a mixed coniferous and broadleaf forest (a mixed Chinese fir, Masson's pine, and broadleaf forest) in the southeastern China 10 and 15 years for the cutting. We considered five treatments—low, medium, high, and extra-high intensities of selective cutting and clear cutting—with non-cutting as the control. We analyzed the impacts of cutting intensity on both individual and overall soil properties. In terms of impacts on individual soil properties, the low and medium intensities of selective cutting did not cause a much greater impact on most soil physical properties than non-cutting while the impact on soil chemical properties augmented with an increase in cutting intensity. In terms of aggregate impacts on overall soil physical and chemical properties, an increase in cutting intensity enlarged the impact.

These findings have important implications for sustainable management of the mixed natural forest in the study region and beyond. First, most soil physical properties damaged by the low and medium intensities of selective cutting in the forest could be restored within 10 or 15 years after the cutting. However, the extra-high cutting intensity and clear cutting would cause stronger damage to soil aggregates, water holding capacity, and porosity, which could not be fully recovered even 15 years after the cutting. Second, even the low cutting intensity would cause a negative impact on soil chemical properties, and the impact would intensify with an increase in cutting intensity. The main impact would be the loss of soil nutrients, P and K in particular. Nutrient loss would become more evident over time as tree growth absorbs nutrients. Hence, timber harvesting even at a low cutting intensity could cause long-term nutrient deficits and forestland degradation in this forest in the region. Third, given the impacts of cutting intensity on both individual and overall soil properties, clear cutting and the high and extra-high intensities of selective cutting in this type of forest in the region should be avoided. These cutting intensities would cause long-term negative impacts on soil physical and chemical properties, adversely affecting the long-term productivity and sustainability of the forest.

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