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Physicochemical Soil Properties Following Selective Cutting of Large-Diameter Trees in a Lowland Dry Evergreen Forest in Cambodia

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Abstract

Forest degradation often leads to soil degradation. To clarify the impacts of large-diameter tree cutting and *in situ* sawing operations on forest site characteristics, we investigated forest floor characteristics and soil physicochemical properties at sites where logging had already been performed of a lowland dry evergreen forest on sandy acrisol soil in central Cambodia. Transects were staked along the direction where individual trees had fallen after being felled approximately 10 years prior, and each transect was divided into five subplots (control, stump, timber, unused trunk, and crown) representing different sections of the fallen tree. A temporary supply of organic matter associated with cutting activity mitigated soil degradation; however, this effect was limited. Differences in soil physicochemical properties between the control subplots and the logging-affected subplots were particularly pronounced in the reduction of the concentrations of exchangeable bases (Ex·Ca^{2+} and Ex·Mg^{2+}) and corresponding pH(H_2O), although some soil properties were conserved (Ex·K^+ and total N stock). These results suggested that a continuous supply of litter from standing trees was effective in mitigating soil degradation and that the preservation of pre-existing juvenile trees at cutting was essential for sustainable forest use. Our findings also indicated that sandy acrisol soils are vulnerable to disturbance from logging. Future research on forest restoration in degraded soils is needed.

Discipline: Forestry
Additional keywords: Acrisols, *Anisoptera costata*, *Dipterocarpus costatus*, forest degradation, soil degradation

Introduction

Human activities have resulted in the pan-tropical decline of tropical forests and the expansion of degraded land (Lewis et al. 2015). Soil degradation is strongly related to the failure of forest restoration (Chazdon 2008), and it is necessary to investigate soil degradation processes and take appropriate measures (McGarry 2011). Research on soil degradation resulting from predatory selective logging (i.e., the overcutting of trees suitable for timber) is limited (Edwards et al. 2014). Illegal logging has severe impacts because environmentally sound and sustainable practices are not considered at the time of harvesting (Judd et al. 2004).

Selective cutting (note: unauthorized logging is generally referred to as “cutting” in Cambodia) of large-diameter trees occurs in lowland dry evergreen forests of Cambodia. The area impacted by cutting a single large-diameter tree is about 10 m × 30 m. Cutting sites have characteristic forest floor conditions (Fig. 1). The canopies of felled trees provide a large supply of fresh leaves, twigs, and vines to the forest floor (Fig. 1a), which readily decomposed and supply organic matter rich in nutrients such as nitrogen (N). The large branches that formed the canopy remained at the time of the survey. The unused portions of trunks are left between the fallen canopy trees and milled section described below (Fig. 1b) and provide no immediate organic matter supply at the time of harvesting; disturbance to the forest floor is limited to the area directly under the trunks, with

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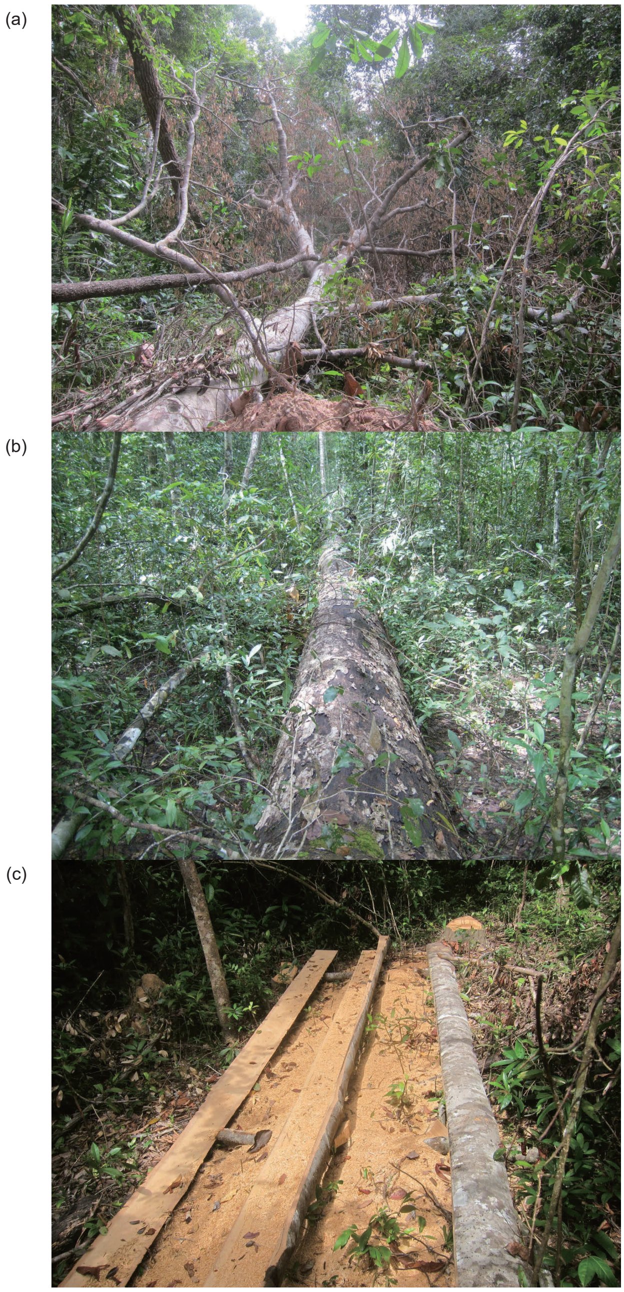


Fig. 1. Typical forest floor conditions associated with selective logging in Kampong Thom Province, central Cambodia

(a) Felled tree canopy at a recent cutting site (26 June 2018). (b) Unused tree trunk (4 November 2008). (c) Sawdust on the forest floor at a recent cutting site (26 June 2018)

minimal mowing or trampling by loggers. The felled trees are milled on site and then removed as timber posts or planks, which generates a large supply of sawdust and bark on the forest floor where the trunks have fallen (Fig. 1c). Such woody residues are persistent organic material containing high levels of lignin and covers the ground surface immediately after cutting. Finally, near the stump, there is a small supply of sawdust from felling, and the surrounding area is trampled by loggers and mowed. Overall, the litter resulting from logging is often scattered. Understanding the qualitative and quantitative variations in organic matter supply during cutting is necessary to identify the dynamic changes in soil degradation in lowland dry evergreen forests.

The objective of this study was to clarify whether qualitative and quantitative variations in organic matter supply resulting from selective cutting affected the subsequent soil degradation. We investigated spatial variation in forest floor characteristics and soil physicochemical properties in large-diameter tree logging sites approximately 10 years after felling in a lowland dry evergreen forest in central Cambodia.

Methods

1. Study site

This study was conducted in Kampong Thom Province in central Cambodia (12°76′ N, 105°48′ E, Fig. 2). The site is located within the Stung Chinit River catchment, where the Stung Chinit River runs through the Cambodian Central Plain into Tonlé Sap Lake. The mean monthly temperature ranged from 23°C to 29°C during 2004-2007 (Chann et al. 2011), and the average annual rainfall was 1625.8 mm during 2007-2016 (Kabeya et al. 2021). The seasonal tropical climate is governed by monsoons, and November through April are dry (Kabeya et al. 2021). The study site is a lowland forested area on a flat, gently rolling alluvial plain at an elevation of 80 m-100 m a.s.l. The geology of the region is characterized by extensive quaternary sedimentary rock (Wakita et al. 2004), and the topsoil is generally slightly coarser than deeper layers (Toriyama et al. 2007a). Soils in the dry evergreen forest are typically sandy acrisol soils, which are characterized by acidity, low base saturation, clay translocation, and low cation exchange capacity; these are classified as haplic acrisols (alumic, profondic) and kanhaplic haplustult according to the World Reference Base system and US Soil Taxonomy System, respectively (Toriyama et al. 2007b, 2008). The site properties and spatial distribution of the study site are described in greater detail elsewhere (Ito et al. 2021).

The forest type of the study area is lowland dry evergreen forest, a subtype of evergreen forest according to the classification system of the Cambodian Forestry Administration (Forestry Administration 2011, Brun 2013). The dominant species in lowland dry evergreen forests is typically Dipterocarpaceae (Rundel 1999). Two tall Dipterocarpaceae tree species are present in the study area: *Dipterocarpus costatus* C. F. Gaertn and *Anisoptera*

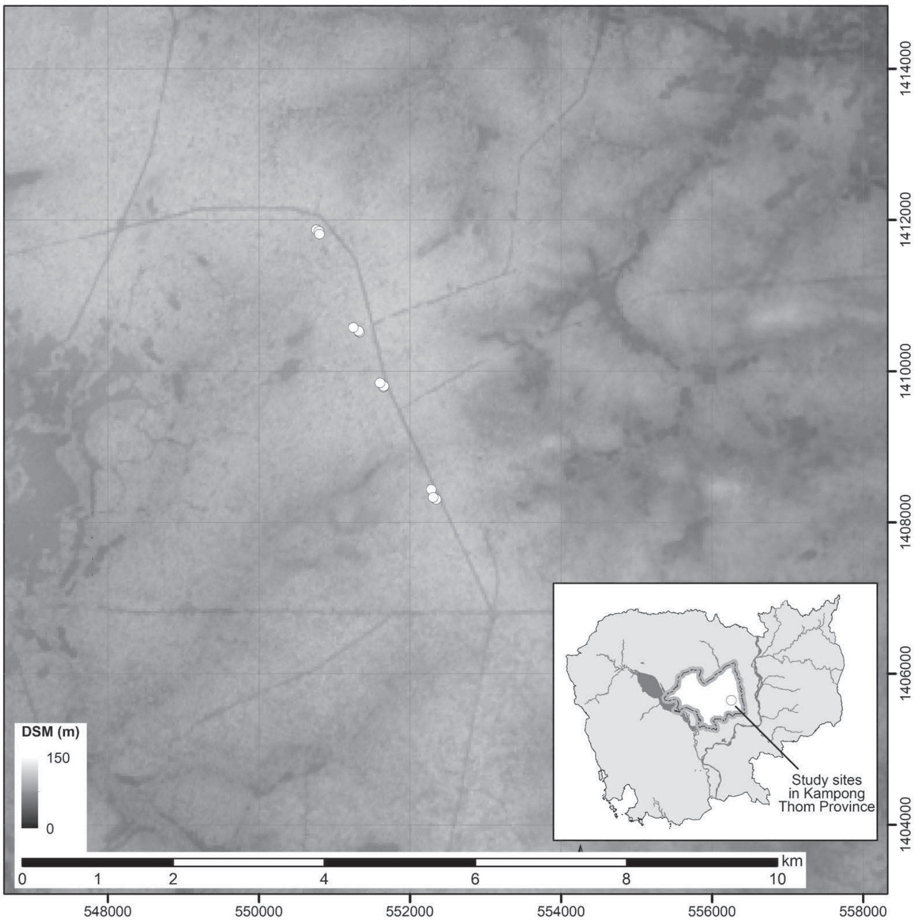


Fig. 2. Digital surface model of the study site in Kampong Thom Province, Cambodia. White circles indicate the 12 experimental plots

The background gradient is a digital surface model (DSM) provided by JAXA (ALOS World 3D-30 m, https://www.eorc.jaxa.jp/ALOS/en/dataset/aw3d30/aw3d30_e.htm). DSM is a three-dimensional representation of the heights of the Earth's surface, including natural (e.g., tree) or artificial objects.

costata Korth. (Pooma 2002, Tani et al. 2007), which are primary target species for logging (Kim Phat et al. 2002). These species commonly reach 30 m-35 m in height (Toyama et al. 2013), dominating the upper canopy layer of the forest (Tani et al. 2007), and can reach maximum stem diameters of 130 cm (*D. costatus*) or 150 cm (*A. costata*) in this study area (Ito et al. 2023a). A permanent sampling plot (0.24 ha in area) located in the study area had a basal area of 42.2 m^2 ha^{-1} and tree density of 1,816 trees (diameter at breast height > 5 cm) ha^{-1} before selective cutting (Ito et al. 2023b).

2. Experimental plots

The surveys were conducted in 12 plots located within an area of approximately 2 km (east-west) × 4 km (north-south) (Fig. 2). The location of each plot was chosen from among 88 cutting locations identified by comparing ALOS/PRISM satellite images from two time periods (Ito et al. 2023a). A field survey conducted in 2008-2009 confirmed that the study area was logged for dipterocarp during the 2007-2008 dry season (Ito et al. 2023a). The plots were set up in June 2018, approximately 10 years after cutting had occurred. Transects were staked along the direction where individual trees had fallen after being felled. Each plot along a transect comprised five subplots: control, stump, timber, unused trunk, and crown (Fig. 3). The latter four subplots are collectively referred to hereafter as logging-affected subplots. The mean (± standard deviation [SD]) and range of distance from the center of the stump to the crown tip were 35.8 ± 3.0 m and from 30.0 to 40.0 m, respectively. Each control subplot was established opposite the direction in which the tree fell, with little human disturbance. The mean (± SD) and range of distance from

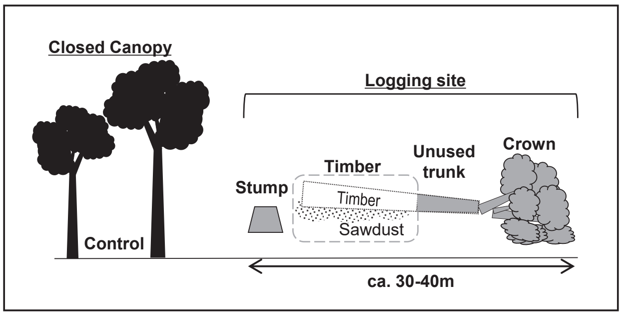


Fig. 3. Schematic diagram of the five subplots: control, stump, timber, unused trunk, and crown
Timber and sawdust may have been deposited in the timber plots during logging operations but were not present during the survey.

the center of the stump to the control subplot was 7.3 ± 2.5 m and from 3.5 to 13.0 m, respectively. In the stump and timber subplots, milling operations were conducted after felling. The lumber was removed from the forest, leaving a large amount of sawdust and wood blocks at the site. The sawdust had disappeared from the forest by the time of the survey; however, decaying wood blocks remained from the milling operations (Ito & Tith 2023). Logging roads for lumber removal often passed near the stump and timber subplots. The mean (± SD) distance from the stump end to the lower end of the unused trunk was 13.7 ± 4.2 m. Canopy openness (%) was estimated for each subplot from March 2 to 3, 2019. The hemispherical photograph estimation method is described in detail elsewhere (Tani et al. 2011).

3. Forest floor survey

Organic matter and juvenile trees were surveyed from December 6 to 13, 2018, and from December 7 to 10, 2019, just after the end of the rainy season. Forest floor litter was surveyed in each subplot. Organic matter on the forest floor was sampled from within a 50 cm × 50 cm frame in each subplot and divided into leaves, branches and bark, and other material (e.g., hard seeds). These types of organic matter were weighed after oven-drying (70°C, 48 h). The total carbon (TC) and nitrogen (TN) contents of the organic matter samples were determined using an elemental analyzer (vario MAX; Elementar, Hanau, Germany).

The number and height of juvenile trees (including vines) were recorded in each subplot using the same 50 cm × 50 cm frames used in the litter survey. Circumference was measured in individuals with a diameter greater than 5 cm at 1.3 m height. For tree species, we recorded whether the tree was a dipterocarp species (*D. costatus* or *A. costata*), i.e., a logging target, and whether the tree was a vine.

4. Soil survey

Mineral soil samples for physical and chemical analyses were collected from soil depths of 0 cm - 5 cm, 5 cm - 15 cm, and 15 cm - 30 cm. Soil samples for physical analysis were collected using a 100-cm^3 steel cylinder from the middle of the samples taken from each depth. At soil collection, the volumetric soil moisture content was measured using a time domain reflectometer sensor, equipped with 12-cm sensor rods (HydroSense; Campbell Scientific, Inc. Logan, UT, USA). Root density (number 100 cm^{-2}) was recorded by counting the number of roots in an area of 100 cm^{-2} of the soil profile of each layer for fine roots (diameter < 2 mm), medium roots (diameter 2 mm - 20 mm), and coarse roots (diameter > 20 mm). Both chemical and physical analysis samples were taken in triplicate at each soil depth from the five subplots of each plot (n = 540). Each soil sample core was weighed, spread out, and dried in the open air. After air-drying, each soil core sample was sieved through a 2-mm sieve and divided into fine mineral soil (diameter < 2 mm), stones, roots, and organic particles (mostly charcoal), and weighed. Charcoal was identified by visual inspection (approx. > 1 mm). Soil samples were then oven-dried (105°C, 24 h) and weighed. The bulk density of each soil core sample was calculated as the oven-dried weight of fine soil material per volume (100 cm^3). Charcoal content was calculated as the air-dried weight of charcoal per volume (100 cm^3).

Soil samples for chemical analysis were collected evenly from each soil layer. The TC and TN contents of mineral soil samples were determined (vario MAX; Elementar, Germany). The pH(H_2O) of the mineral soil was measured potentiometrically in suspension with a 1:2.5 ratio of fresh soil to water. Exchangeable (Ex·) cation concentrations were then determined. Fine fractions (< 2 mm) of air-dried soil (2.5 g) were mixed with 50 mL of 1 M ammonium acetate at pH 7, shaken for 1 h, and filtered through a 0.45 µm filter. The cation (Na^+, Ca^{2+}, Mg^{2+}, and K^+) concentrations of extracts were analyzed using inductively coupled plasma optical emission spectroscopy (Optima 8300; PerkinElmer, Waltham, MA, USA).

5. Statistical analysis

Forest floor properties, canopy openness, and the chemical and physical characteristics of the forest floor litter and mineral soil were compared among subplots (or soil layers) using a linear mixed model incorporating each site as a random effect. The linear mixed model estimated the parameters for each subplot. The hypothesis that each parameter had a value of zero was evaluated using a *t* test. Significant differences among subplots were evaluated using the post hoc Tukey-Kramer HSD test. For the forest floor vegetation analysis, the numbers of juvenile trees were compared among subplots using a linear mixed model, incorporating each site as a random effect. In addition, an ordinal logistic model was used to compare forest floor vegetation richness across subplots, considering the size of juvenile trees. All individual trees found in the study frame were ranked in order of height. Vines were treated as the lowest-ranked tree regardless of stem length. These ranks were used as an objective variable in the ordinal logistic model, and ranks were compared among the subplots. Rank predictions will be smaller when there is a relative abundance of larger-sized juveniles (and vice versa). All statistical analyses were conducted using JMP statistical software (ver. 10.0; SAS Institute Inc., Cary, NC, USA).

Results

1. Forest canopy and forest floor

Forest canopy openness was significantly greater in the stump and crown subplots than in the control subplots (Fig. 4a). Canopy openness (%) in the stump and crown subplots was more than double that in the control subplots.

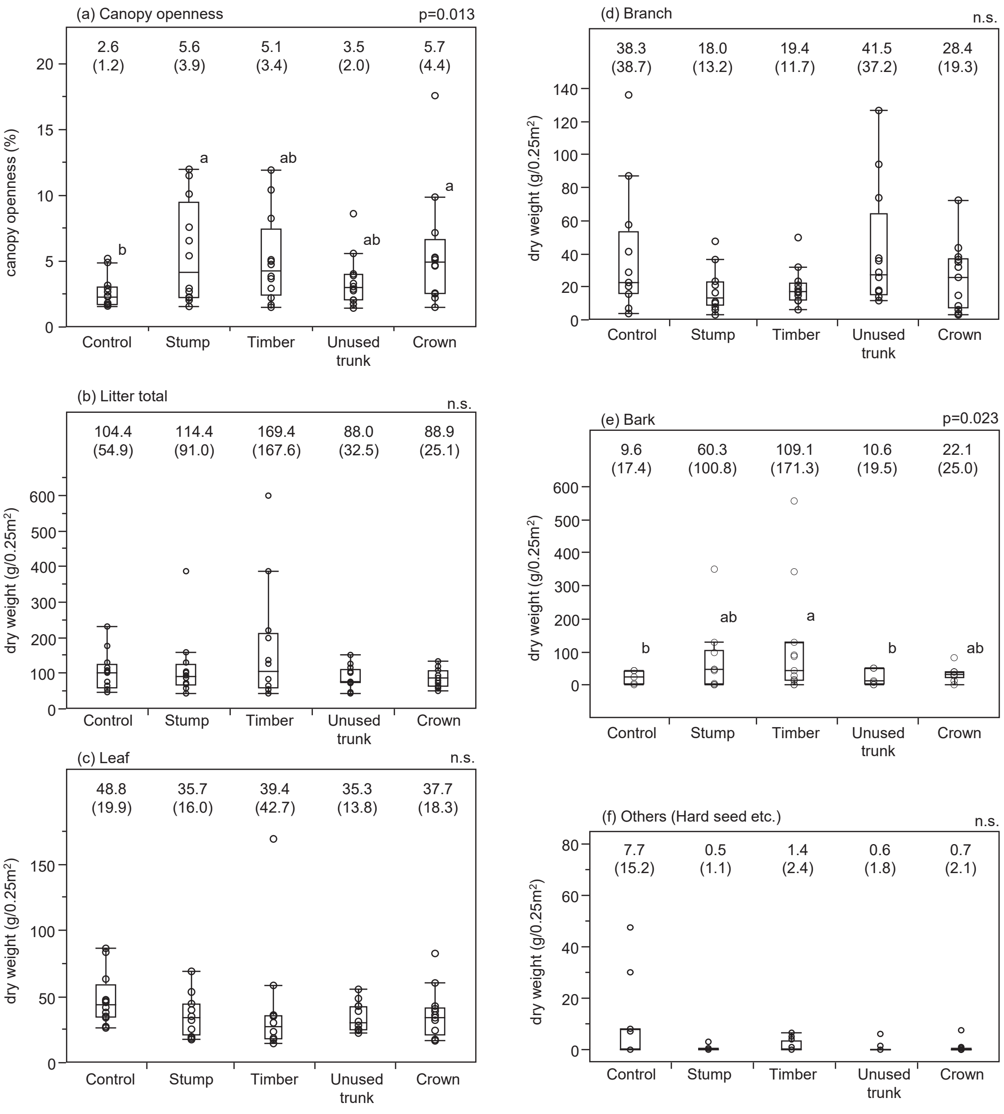


Fig. 4. Forest canopy openness and litter biomass by subplot

(a) Canopy openness (%), (b) Litter total, (c) Leaf litter, (d) Branches, (e) Bark, (f) Others. Values at the top of the columns are averages for each subplot (± standard deviation [SD]) n = 12). Box and whisker plots show the median, 25% and 75% quartiles, and range of the data. Different letters among columns indicate significant differences according to analysis of variance (ANOVA; $P < 0.05$). Data points beyond the range of the plots were identified as outliers when the value exceeded the upper or lower limit of 1.5 times the height of the box.

Canopy openness in the timber subplots was nearly double that in the control subplots; however, this difference was insignificant due to high variability. Canopy openness in the unused trunk subplots showed less variation and was not significantly different from that in any of the other subplots.

Total litter biomass, leaf, and branch litter biomass did not differ significantly among the subplots (Fig. 4b, c, d). For each component of litter biomass, only the amount of bark differed significantly among subplots (Fig. 4e). The amount of bark was significantly greater in the timber subplots than in the control and unused trunk subplots but did not differ from those of the stump and crown subplots.

There were almost no differences in the C and N contents and stocks of the litter components among the subplots (Appendix 1, 2). The exception was the N content of leaf litter in the unused trunk subplots, which was larger than that in the crown subplots. There was no significant relationship between the amount of forest litter and forest canopy openness (data not shown).

A total of 594 juvenile trees (excluding vines) were found within a total survey area of 15 m^2. Of these, two were identified in crown and unused trunk subplots as *D. costatus*, and one was identified in an unused trunk subplot as *A. costata*, a species targeted for harvesting. The number of juvenile trees and vines growing on the forest floor did not differ significantly among the subplots (Table 1). However, the stump and timber subplots showed significantly larger ranks than the control subplots. Larger rank values indicate a relative abundance of small juvenile trees, which suggests lesser forest floor vegetation development. In contrast, the crown and unused trunk subplots were not significantly different from the control subplots in ranks. Additionally, some juvenile trees in the crown subplots had broken trunks and branches, which were presumed to have been damaged during the felling of large trees.

2. Soil physicochemical properties

The volumetric soil moisture content was low and increased with depth, with average contents of 4.8%, 6.5%, and 7.5% in the 0 cm - 5 cm, 5 cm - 15 cm, and 15 cm - 30 cm layers, respectively. The soil moisture differed significantly among subplots, with relatively low values found in the stump subplots (Fig. 5a). Soil moisture values in the 0 cm - 5 cm layer of the crown subplots and the 0 cm - 5 cm and 5 cm - 15 cm layers of the stump subplots were lower than those in the control subplots.

The bulk density increased with soil depth for all subplots (Fig. 5b). The trends among the subplots varied with soil layers, and no consistent trend was observed. The crown subplots had the lowest bulk density in the 0 cm - 5 cm layer while also having the greatest bulk density in the 15 cm - 30 cm layer.

Among the chemical properties, pH(H_2O) showed the most significant differences between the control and other logging-affected subplots (Fig. 5c). The pH(H_2O) in the 0 cm - 5 cm soil layer was significantly lower in the four logging-affected subplots than in the control subplots; the same pattern was observed in the 5 cm - 15 cm and 15 cm - 30 cm soil layers.

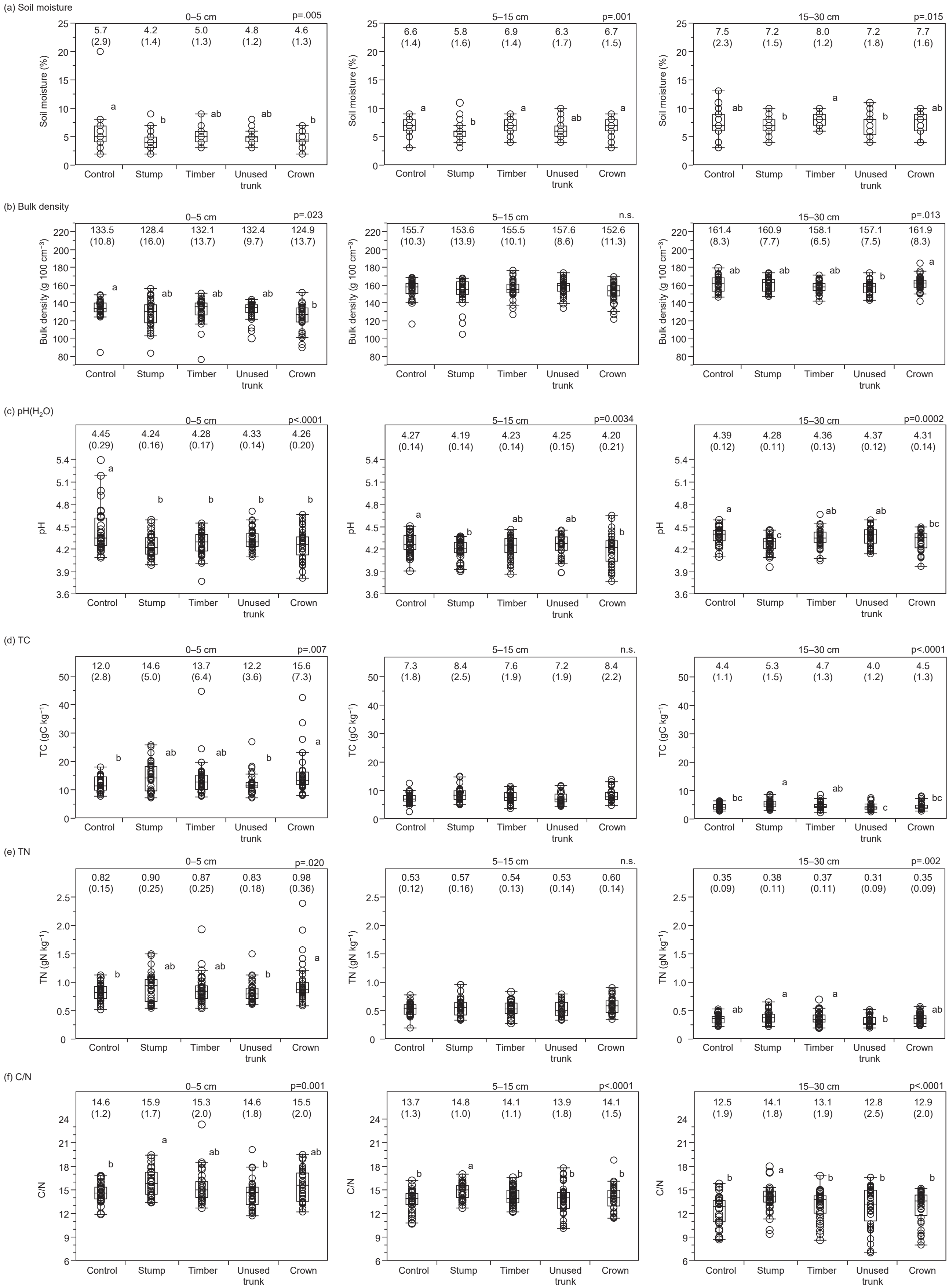
There were differences in TC and TN contents among the subplots, although different trends were observed in each soil layer (Fig. 5d, e). The TC and TN contents were greater in the 0 cm - 5 cm layer of the crown subplots than in the 0 cm - 5 cm layer of the control subplots.

The C/N ratio (C/N) decreased with depth across all subplots, with a range (95% confidence interval) of 7.0-23.3 (9.4-18.0) for all soil samples. The C/N of the control subplots was lower across all soil layers, but only

Table 1. Forest floor vegetation by subplot (n = 12): average (± standard deviation) (range) of stem density of all free-standing individuals (Standing trees, number of stems 0.25 m^{-2}); stem density of vines (Vines, number of stems 0.25 m^{-2}); and least squares means (± SE) of the rank score by plant size

Subplot	Standing trees		Vines		Rank#
	average ± SD	range	average ± SD	range	average ± SE
Control	9.2 ± 5.3	(0-21)	1.2 ± 1.3	(0-3)	68.0 ± 2.2 ^{a}
Stump	8.2 ± 4.6	(3-16)	1.2 ± 1.3	(0-4)	79.8 ± 2.3 ^{b}
Timber	9.8 ± 5.8	(0-19)	0.9 ± 1.2	(0-3)	77.5 ± 2.2 ^{b}
Unused trunk	9.3 ± 5.1	(2-20)	1.0 ± 1.6	(0-5)	73.7 ± 2.2 ^{ab}
Crown	13.2 ± 9.5	(5-33)	0.8 ± 1.4	(0-4)	72.6 ± 2.0 ^{ab}

The larger the size of an individual tree, the smaller the rank score was set to be. Thus, subplots with smaller average ranks indicate more developed forest floor vegetation. Values that do not share a common superscript letter are significantly different at $P < 0.05$ based on Tukey's HSD test (Rank, $P = 0.001$).



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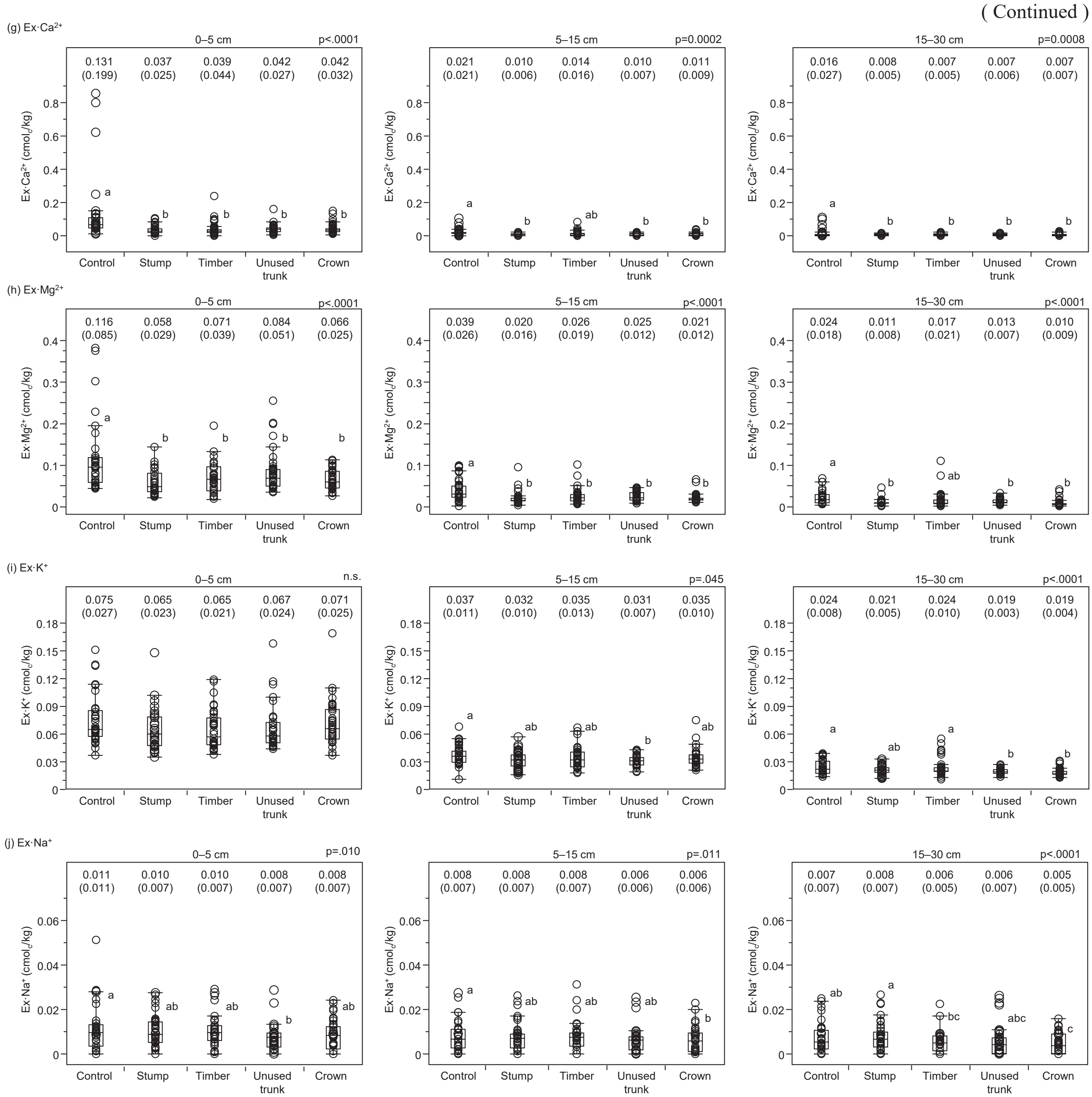

Fig. 5. Soil chemical properties in the 0 cm - 5 cm (left), 5 cm - 15 cm (middle), and 15 cm - 30 cm (right) soil layers of the different subplots

(a) Volumetric soil moisture content (%), (b) Bulk density (g 100 cm^{-3}), (c) pH(H_2O) (dimensionless), (d) Total carbon content (TC, g kg^{-1}), (e) Total nitrogen content (TN, g kg^{-1}), and (f) C/N ratio (dimensionless). Ex-cation concentrations (cmol$_c$ kg^{-1}) include (g) calcium (Ex·Ca^{2+}) (h) magnesium (Ex·Mg^{2+}), (i) potassium (Ex·K^+), and (j) sodium (Ex·Na^+). Values at the top of the columns are averages for each subplot (± SD; n = 12). Different letters among columns indicate significant differences (ANOVA; $P < 0.05$). Box and whisker plots are as described in Figure 4.

the stump subplots showed significantly higher C/N ratios than the control (Fig. 5f). Across all three soil layers, the unused trunk subplots had lower C/N ratios among the logging-affected-subplots and were closest to the control subplots.

Soil Ex·Ca^{2+} and Ex·Mg^{2+} concentrations were markedly higher in the control subplots than in the other logging-affected subplots (Fig. 5g, h). The trend was more evident in the surface layer, but significant differences were also observed across all soil layers. In the 0 cm - 5 cm soil layer, the Ex·Ca^{2+} and Ex·Mg^{2+} contents were significantly higher in the control than in the other subplots, although extremely high outliers were often observed. Conversely, trends were not readily apparent for Ex·K^+ (Fig. 5i) and Ex·Na^+ (Fig. 5j). There were no significant differences among the subplots for Ex·K^+ in the 0 cm - 5 cm soil layer (Fig. 5i).

There were significant differences in the total C and Ex·cation stocks within the 0 cm - 30 cm soil layer between the control and some of the other logging-affected subplots, but the differences in the N stock were not significant (Appendix 3).

3. Root and charcoal contents

The root content decreased significantly with depth, with average (and upper and lower 95% confidence intervals) of 1.00 (0.91-1.09), 0.37 (0.28-0.46), and 0.16 (0.07-0.25) g 100 cm^{-3} in the 0 cm - 5 cm, 5 cm - 15 cm, and 15 cm - 30 cm layers, respectively. Differences in the root content in the 0 cm - 5 cm soil layer were found only between the unused trunk subplots and the timber subplots (Fig. 6a). When the root contents were combined over the full soil depth of 0 cm - 30 cm, significant differences were eliminated among the subplots, but the least squares means were in the order of control > unused trunk > crown > stump > timber (Fig. 6b). The density of roots in the soil profile is presented in detail in Appendix 4.

Charcoal was occasionally found in the soil samples (8.9% in a total of 540 soil core samples), with appearance rates of charcoal visible to the naked eye in soil samples of 8.9%, 6.7%, and 11.1% in the 0 cm - 5 cm, 5 cm - 15 cm, and 15 cm - 30 cm layers, respectively. Of the 12 plots, charcoal in the 0 cm - 5 cm surface layer was found in 5 plots. Of these, it was found in 3 plots in the crown and timber subplots, 2 plots in the stump subplot, 1 plot in the control subplot, and none in the unused trunk subplot. On the other hand, charcoal in either the 5 cm - 15 cm or 15 cm - 30 cm layer was found in 9 of the 12 plots, respectively. The charcoal content in soil for all subplots averaged (± SD) 0.074 ± 0.362, 0.030 ± 0.288, and 0.025 ± 0.152 g 100 cm^{-3} in the 0 cm - 5 cm, 5 cm - 15 cm, and 15 cm - 30 cm layers, respectively.

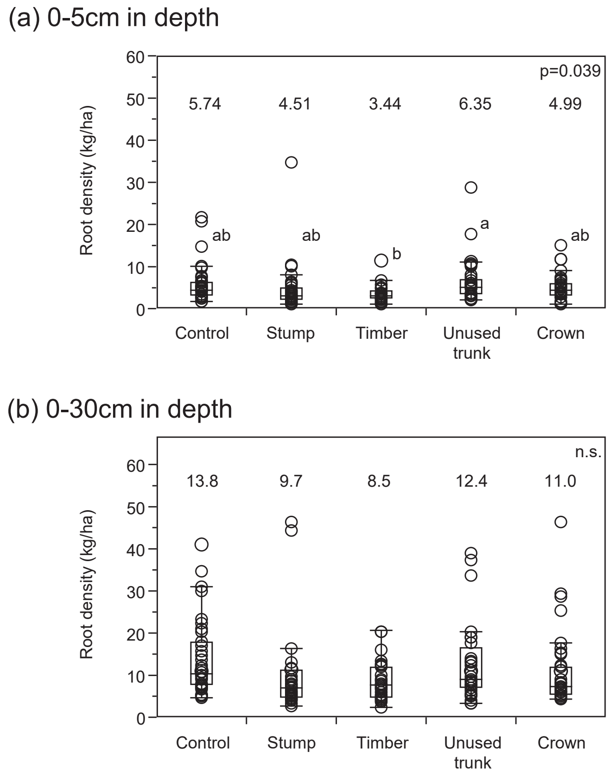

Fig. 6. Root density (air-dry weight per area) in surface soils of the different subplots
(a) Topsoil layer (0 cm - 5 cm) and (b) all soil layers (0 cm - 30 cm). Values at the top of the columns are averages for each subplot (n = 12). Box and whisker plots are as described in Figure 4.

Discussion

1. Determination of forest site disturbance

Disturbances in the canopy layer at the time of felling, as indicated by canopy openness, were found to remain even approximately 10 years after felling (Fig. 4a). The stump subplots, from which the logged canopy that was once directly above the subplot had disappeared, and crown subplots, into which the canopy had fallen, had the same degree of canopy openness. The lower soil moisture in the 0 cm - 5 cm soil layer in the crown and stump subplots may reflect more direct sunlight exposure (Fig. 5a). The small variation in the unused trunk subplots may be due to the fact that the unused trunk subplots were disturbed only by the trunk width of straight trunks, with no additional human disturbance during post-felling sawing or transporting operations. Alternatively, the high variability and often observed greater openness in the timber subplots may be due to the greater or lesser influence of anthropogenic disturbance after felling.

The amount of bark deposited on the forest floor reflects post-felling disturbances. The amount of bark deposited in the unused trunk subplots was similar to that in the control subplots (Fig. 4e), indicating that the unused trunk subplots were the least disturbed microsites in the selective logging area. This finding was consistent with the observed trend in canopy layer disturbance among the subplots, as indicated by canopy openness. The average amounts of bark were 5-10 times higher in the stump and timber subplots than in the control subplots (Fig. 4e). This was due to bark-scraping operations after felling. The bark deposited in the crown subplots was twice that of the control subplots on average (but not significantly different, Fig. 4e). This bark was likely supplied by large canopy branches that fell during logging.

In contrast to the differences in the amount of bark deposited among subplots, there were no significant differences in the accumulation of more decomposable organic matter, such as leaves and branches, among subplots (Fig. 4c, d). Less difference in the amount of leaf litter indicated that litterfall was spatially uniformly supplied in the forest floor at about 10 years after selective logging occurred (Fig. 4c). Although there was significant spatial variation in canopy openness among subplots (Fig. 4a), spatial heterogeneity was likely attenuated by considerable horizontal leaf movement as they fell from the canopy to the forest floor. The amount of branch litter varied widely within subplots, with no significant differences between subplots (Fig. 4d). However, considerably larger outliers were found in the control and unused trunk subplots (Fig. 4d), indicating that dead branches are occasionally supplied to subplots with a closed upper canopy (Fig. 4a). In response to the spatially uniform forest floor litter biomass, there were no differences among the subplots in C and N stocks for litter of any type on the forest floor (Appendix 1). These findings suggest that spatial variation in organic matter due to selective logging is minor on the forest floor, which is the base of the material cycle and related to organic matter decomposition.

Charcoal in the soil samples likely represented past and present anthropogenic disturbances. Although the cutting sites were not all burned by the logging teams, we often found traces of what appeared to be logging team bonfires near logging roads and timber subplots (unpublished). Charcoal found in the 0 cm - 5 cm soil layer may have been partially dispersed (e.g., by surface flow during the rainy season) from such bonfire sites. Charcoal was found in the crown subplot with the same frequency as in the timber subplot, but the reason for this is unknown. Charcoal in the deeper soil layers may be the result of wildfires or human-caused fires that occurred before the forests had been established. The frequent presence of charcoal in the deep soil layers (9 of 12 plots) suggests that the current lowland evergreen forest area was broadly affected by fire in the past.

2. Regeneration of trees

The rankings revealed spatial heterogeneity in the degree of forest floor vegetation development (Table 1). The condition of regenerated vegetation likely differed between the unused trunk and crown subplots, which included pre-existing juvenile trees, and the stump and timber subplots, where most juvenile trees were < 10 years old and had been established after the end of logging activities. Spatial heterogeneity in the degree of forest floor vegetation development can be attributed to differences in damage to juvenile trees caused by disturbances during logging.

In the crown subplots, some juvenile trees were crushed by felled large-diameter trees. However, juvenile trees that survived after the felling of large-diameter trees were subsequently able to grow, even with some damage. This subsequent growth may have been better in the crown than in the control subplots because of the open sky and better light conditions (Fig. 4a).

In the stump and timber subplots, the forest floor was severely disturbed due to post-felling milling and transportation. These sites were open spaces (Ito, unpublished) when we visited for field verification 1-2 years after cutting (Ito et al. 2023a). At least some plots still showed a greater degree of canopy openness in this study about 10 years after cutting (Fig. 4a). This was presumed to be because any juvenile trees present before logging were considered obstacles to the logging work and removed. The period between the removal of pre-existing juvenile trees and the establishment of new seedlings may have accelerated soil degradation in the stump and timber subplots.

Successional trees of the two target dipterocarp species have been reported to be scarce in the vicinity of the mother tree in this area (Ito et al. 2023b). In this study site, no successional individuals of the two logged dipterocarp species were found in the stump and timber subplots; thus, it is unlikely that these subplots will recover the same tree species composition as before logging due to the loss of mother trees and pre-existing juvenile trees. Both target dipterocarp species are endangered (Nguyen et al. 2019, Nguyen et al. 2021), and conservation efforts may be warranted.

3. Spatial heterogeneity of soil degradation

(1) Non-degraded properties

A study of soil degradation from a litter removal experiment conducted in the same forest type and same area as this study found a trend toward greater bulk density, lower TC and TN content, and a more conservative but lower C/N in plots where litter was continuously removed (Ito et al. 2014). Contrary to expectations, no trend consistent with this previous study was identified in any of the subplots in this study. No greater bulk density was observed in the logging-affected subplots than in the control subplots (Fig. 5b). The range of bulk density in this study is similar to the range recorded in soil surveys in an undisturbed forest in the same area (130 to 160 g 100 cm^{-3}; Toriyama et al. 2007a, Toriyama et al. 2007b). This corresponds to the degree that prevented further compaction (Ito et al. 2014). No reduction in TC and TN contents was observed in the logging-affected subplots (Fig. 5d, e). Contrary to the trend obtained with the litter removal treatment, lower bulk density and higher TC and TN contents than the control were found in the 0 cm - 5 cm layer of the crown subplot (Fig. 5b, d, e). This result suggests the influence of the large amount of organic material that fell during logging. It is consistent with earlier observations in the context of conservation agriculture, which showed that high biomass-C inputs promoted soil organic carbon recovery in the topsoil (0 cm - 5 cm) layer in Cambodian ferralsols (Hok et al. 2015). C/N was significantly higher in the stump subplots than in the control subplots for all three soil layers (Fig. 5f). It is likely that the TC content increased in the soil below the stump subplots due to root decay in the felled trees, as suggested by the increase in TC content in the deepest soil layers (15 cm - 30 cm; Fig. 5d). Although this study focused on the supply of organic matter to the forest floor during logging, the supply of organic matter due to logging also occurred underground.

Significantly lower C/N than the control was not observed in any of the logging-affected subplots (Fig. 5f). However, whether selective logging mitigated soil degradation deserves careful consideration. The C/N values from the 2003 survey, a period when the forests in the study area were well preserved, were quite large (values for soil layers up to 30 cm in depth, 23.0-31.2) (Toriyama et al. 2007b). However, the range of C/N ratios for the soil samples in this study was 9.4-18.0 (95% of the total); despite large C/N ratios in the logging-affected subplots, the C/N values in the 2003 survey were sufficiently large not to overlap with the range of this study at all. Furthermore, the mean ± SD of C/N in the top 0 cm - 5 cm soils collected in a 2009 survey was 17.0 ± 3.1 (control plot; Ito et al. 2014), which was higher than the 14.6 ± 1.2 of this study, based on data collected in 2018 and 2019 surveys. The 2009 survey corresponds to the period when large-diameter tree-cutting was underway in the study area (Ito et al. 2023a). Stronger decomposition in tropical forest ecosystems leads to lower C/N ratios (Guillaume et al. 2015). The reduction in aboveground biomass over time (i.e., forest degradation) would have resulted in a decrease in organic matter supply to forest soils, which may be responsible for the chronological decline in C/N throughout the study area.

(2) Degraded properties

Among soil properties, the pH(H_2O) showed the most significant differences between the control and logging-affected subplots (Fig. 5c). The pH(H_2O) was lower in the logging-affected subplots; this trend was more pronounced in the surface layer. We expected pH(H_2O) to increase in at least the crown subplots by returning base cations from readily degradable plant litter to soil, increasing base cations, and raising soil pH. However, contrary to our expectations, pH(H_2O) was also degraded in crown subplots. The above-mentioned soil survey in 2003, when the forest was well preserved, reported pH(H_2O) values of 4.44-4.81 at depths up to 30 cm below the surface in sandy acrisols under dry evergreen forests (Toriyama et al. 2007b). This value was slightly higher than the control subplot (4.27-4.45) and the logging-affected subplots (4.19-4.37) in this study. Forest degradation throughout the study area may have caused soil degradation even in the control subplots.

The differences in pH(H_2O) were most pronounced in the 0 cm - 5 cm soil layer (Fig. 5c). The same trend was observed for the Ex·cation concentrations (Fig. 5g-j), suggesting that the decrease in pH(H_2O) at the surface may be due to a decrease in base saturation. Markedly lower Ex·Ca^{2+} and Ex·Mg^{2+} concentrations were observed in the logging-affected subplots in this study (Fig. 5g, h). Clay content explained a significant proportion of the variation in Ex·Ca^{2+}, Ex·Mg^{2+}, and Ex·cations (Yamashita et al. 2008). The soils in the study area are very sandy, with a sand content of 79.4%-88.5% in the 30 cm soil layer (Toriyama et al. 2007b); Ex·Ca^{2+} and Ex·Mg^{2+} concentrations are very low even in non-degraded forest (Toriyama et al. 2007b), comparable to other sandy acrisols in deep sands in Cambodia (Bell et al. 2022) and the Congo (Bouillet et al. 1999), and less than those of chromic acrisols in northeastern Thailand (Obara et al. 2006). These concentrations are only approximately 1/10th of the more loamy or clayey acrisols (ultisol per the USDA soil classification system), e.g., in Thailand (Sakurai et al. 1998, Noble et al. 2000, Soisungwan 2005, Bruun et al. 2017), the Philippines (Ohta 1990), and Sumatra (Yamashita et al. 2008, Allen et al. 2016). In Thailand, acrisols converted to agricultural land, Ex·Ca^{2+} decreased at 0 cm - 30 cm and increased at 30 cm - 60 cm of soil depth compared with adjacent undisturbed forest, suggesting downward infiltration and accumulation (Noble et al. 2000). However, soil profiles over 200 cm were investigated in our study area. There was no evident accumulation of Ex·Ca^{2+} within that depth range (Toriyama et al. 2007b). Sandy soils in lowland areas of Cambodia have been identified as vulnerable to physicochemical degradation (Bell et al. 2022). Low-activity clay soils containing acrisols experience greater leaching of basic cations under deforestation (Veldkamp et al. 2020). Our study site is characterized by sandy soils with large seasonal fluctuations in groundwater levels due to the alternation of wet and dry seasons (Kabeya et al. 2021). Calcium has been reviewed as having greater leaching losses even in disturbances within small areas (Bruijnzeel 1998). Therefore, calcium was identified as a potential limiting nutrient in regenerating forests on highly weathered ferralsols in lowland Central Africa (Bauters et al. 2022) and on orthic acrisols or podzols in Sabah, Malaysia (Nykvist 1998). These findings suggest that lowland evergreen forests are vulnerable to soil degradation, where Ex·cations are more prone to loss through downward leaching, possibly out of the watershed.

Depletion of potassium, an essential nutrient for plant growth, was of particular concern to us in soil degradation because of its significant impact on forest regeneration. However, in contrast to Ex·Ca^{2+} and Ex·Mg^{2+} concentrations, there were no significant differences among the subplots for Ex·K^+ in the 0 cm - 5 cm soil layer (Fig. 5i). Studies of acrisols and ferralsols, which have similar low nutrient characteristics (Kauffman 1998), have also reported that K leaching/depletion rates after logging and/or cultivation without fertilization are lower than those of Ca and Mg in Guyana (Brouwer & Riezebos 1998), in Peninsular Malaysia (Shariff et al. 1989) and in several sites in northeastern Thailand (Ota et al. 1996). However, the opposite trend was observed in northeast Puerto Rico (Schaefer et al. 2000) and Peninsular Malaysia (Yusop & Suki 1994). The lack of differences in the key nutrient Ex·K^+ may be due to its high mobility in soil-plant systems (Yamashita et al. 2008). Its rapid absorption and accumulation in plant biomass through efficient soluble K^+ uptake have been suggested in other tropical acrisol studies (Noble et al. 2000, van Langenhove et al. 2020). Moreover, atmospheric K^+ supply may partially mitigate nutrient loss due to logging. Leaching losses of basic cations after tropical forest cutting can be replenished by nutrient inputs from rainfall within a few years (Bruijnzeel 1998). However, the atmospheric supply of various cations and the quantitative relationships of each cation exhibit considerable regional variation, even within tropical forests (Bruijnzeel 1991, Suksawang et al. 1996). In urban areas of Cambodia, wet deposition concentrations are greater for Ex·Ca^{2+} and approximately 7-fold greater than for Ex·K^+ and Ex·Mg^{2+} (EANET 2011). Future research should examine the atmospheric supply to the study site and determine whether the inputs can consistently explain why Ex·K^+ losses are mitigated, and Ex·Ca^{2+} and Ex·Mg^{2+} losses are not.

4. Selective cutting and subsequent soil degradation

The most common recommendations for mitigating soil degradation caused by selective logging include reducing the intensity of harvesting (Edwards et al. 2014), excluding some trees from harvesting (Pereira et al. 2002), and reducing soil compaction by heavy equipment along logging roads (Pinard et al. 2000). Measures to mitigate the effects of uncontrolled illegal logging after it has occurred also require consideration. Soil organic matter can mitigate soil degradation via enhancing nutrient retention capacity (Vityakon 2001, Yamashita et al. 2008). Selective logging and the resulting large supply of organic matter to the forest floor may provide a means of mitigating soil degradation. Based on this expectation, it was perhaps that soil physicochemical properties would be retained in the timber subplots, which have a thick cover of persistent sawdust; however, contrary to this expectation, soil physicochemical properties were as or more severely degraded in the timber subplots than in the other logging-affected subplots. The sawdust had disappeared from the forest by the time the survey was performed, 10 years after felling. Leaf litter decomposition experiments at the same study site reported that forest floor organic matter was rapidly eaten by termites (Isoptera), and to a greater extent in the timber subplots, which had once been covered with sawdust, implying that a large supply of temporary organic matter may have increased the biomass of the termite population (Ito & Tith 2023). In a forest ecosystem where termites, as ecosystem engineers, quickly consume forest floor litter, the mitigation effects of a large supply of temporary organic matter will not continue. This study suggests that the continuous supply of litter by standing trees may be essential for mitigating soil degradation due to forest floor cover.

The soil properties of the crown subplots, which were thought to have received a large supply of easily decomposable and nutrient-rich litter at the time of felling, did not show many significant differences from the other subplots 10 years after felling. Thus, there was also no evidence of the conservation of soil physicochemical properties in the crown subplots. In the crown subplots, the site environment was conducive to subsequent juvenile tree growth due to the favorable light conditions of the open canopy. This was supported by the second lowest rank of juvenile tree analysis in the crown subplot (Table 1). Soil degradation in these subplots indicated that even if juvenile trees that survived logging grew well after the area was logged, their growth was insufficient to compensate for the damage to other pre-existing juveniles in terms of organic matter supply to the forest floor.

One possible effective reforestation strategy is preventing damage to pre-existing juvenile trees; however, this is not a feasible remedy for uncontrolled illegal logging. Furthermore, this study revealed the effectiveness of reforestation strategies, as well as their limitations. Seedlings established before logging that were undamaged by logging covered the forest floor in the unused trunk subplots. Despite relatively less degradation of soil physicochemical properties in these subplots, significant differences from the control subplots were still evident (e.g., pH, C/N, Ex·Ca^{2+}, Ex·Mg^{2+}, Fig. 5). The cessation of the litter supply that was once continuously supplied to the surrounding area by felled large trees due to logging may have contributed to the changes in the soil chemical properties observed in the unused trunk subplots.

Conclusion

Forest and soil properties at a forest site disturbed by selective logging activities 10 years ago were classified into three categories (Fig. 7): (1) uniform across all subplots (left panels), (2) heterogeneous (i.e., differences among logging-affected subplots) (right panels), and (3) different between the control and logging-affected subplots (i.e., uniform across logging-affected subplots) (center panels). The first category (1) included characteristics related to leaf and branch litter and root (0 cm - 30 cm) mass, as well as soil properties such as Ex·K^+ and total N stock. Spatial heterogeneity due to logging disturbance was mitigated for these properties. Trends in the second category of properties (2) could be explained by disturbance caused by logging activities and organic matter supply. Temporary organic matter supply appears to have mitigated soil degradation to some extent, but the effect was not pronounced. The third category (3) included soil properties such as pH, Ex·Ca^{2+}, and Ex·Mg^{2+}. These soil properties were the most sensitive to soil degradation due to selective logging in sandy acrisol soils (i.e., low-activity clay soils). Even in the less-disturbed unused trunk subplots, lower Ex·cation and pH levels were observed. The uniform degradation of logging-affected subplots, regardless of organic matter supply or the presence of juvenile trees, suggested that the soils in our study site are extremely vulnerable to selective logging disturbance. It remains to be seen how such soil degradation will affect future reforestation, and further research is needed on the basic knowledge and key practices to facilitate both reforestation and soil restoration.

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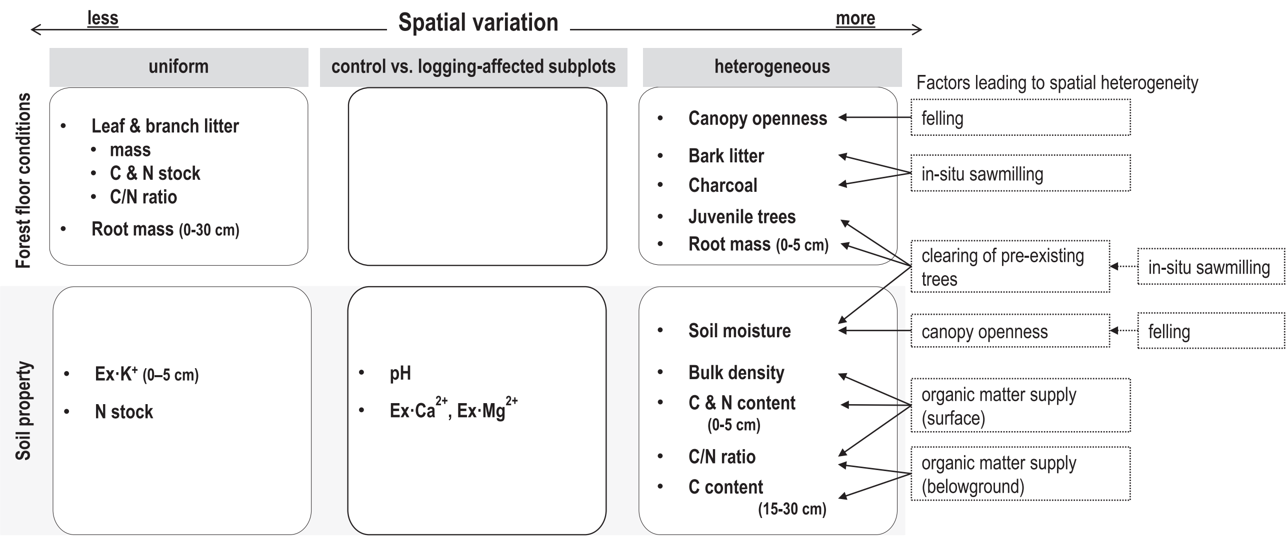

Fig. 7. Schematic figure of classification based on forest floor and soil property spatial heterogeneity caused by disturbance due to selective cutting activities

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Appendix 1. Forest floor litter properties by subplot: average (± standard deviation) and (range) of carbon (C) and nitrogen (N) stock properties in each 50 cm × 50 cm frame within each subplot (n = 12)

Item	Subplot	C stock (g C 0.25 m^{-2})		N stock (g N 0.25 m^{-2})	
		average ± SD	range	average ± SD	range
Litter total	Control	47.4 ± 25.5	(21.0-106.3)	0.86 ± 0.38	(0.44-1.56)
	Stump	54.3 ± 42.8	(20.1-179.2)	0.79 ± 0.39	(0.42-1.96)
	Timber	80.0 ± 81.0	(18.7-288.9)	1.11 ± 0.99	(0.38-3.83)
	Unused trunk	40.9 ± 16.1	(20.6-71.3)	0.80 ± 0.25	(0.47-1.35)
	Crown	44.9 ± 14.7	(22.8-65.4)	0.83 ± 0.30	(0.47-1.28)
Leaves	Control	22.3 ± 10.8	(12.3-42.7)	0.51 ± 0.21	(0.29-0.96)
	Stump	16.6 ± 8.2	(8.6-36.4)	0.38 ± 0.17	(0.18-0.62)
	Timber	19.3 ± 22.5	(6.7-87.9)	0.40 ± 0.35	(0.15-1.43)
	Unused trunk	16.1 ± 5.7	(9.7-27.4)	0.41 ± 0.14	(0.28-0.66)
	Crown	17.1 ± 9.5	(8.1-41.6)	0.41 ± 0.20	(0.21-0.93)
Branches	Control	17.9 ± 17.1	(2.0-59.4)	0.29 ± 0.27	(0.03-0.82)
	Stump	8.7 ± 6.3	(1.7-21.5)	0.14 ± 0.08	(0.03-0.29)
	Timber	9.2 ± 5.5	(3.1-23.5)	0.14 ± 0.07	(0.05-0.30)
	Unused trunk	19.7 ± 17.8	(5.5-60.6)	0.33 ± 0.29	(0.10-1.07)
	Crown	12.6 ± 9.5	(1.4-35.3)	0.21 ± 0.17	(0.02-0.53)
Bark	Control	10.9 ± 10.2	(0-21.7)	0.12 ± 0.15	(0-0.37)
	Stump	34.9 ± 50.8	(0-165.7)	0.33 ± 0.49	(0-1.64)
	Timber	56.1 ± 84.0	(0.2-268.1)	0.62 ± 1.06	(0.01-3.53)
	Unused trunk	10.1 ± 11.4	(0-26.5)	0.13 ± 0.17	(0-0.43)
	Crown	17.0 ± 12.9	(0-46.9)	0.20 ± 0.14	(0-0.51)
Others	Control	3.4 ± 6.7	(0-20.8)	0.02 ± 0.03	(0-0.10)
(e.g., hard seeds)	Stump	0.2 ± 0.5	(0-1.2)	0.00 ± 0.00	(0-0.01)
	Timber	0.6 ± 1.0	(0-2.9)	0.00 ± 0.01	(0-0.01)
	Unused trunk	0.3 ± 0.8	(0-2.7)	0.00 ± 0.00	(0-0.01)
	Crown	0.3 ± 0.9	(0-3.3)	0.00 ± 0.01	(0-0.02)

No significant differences were detected among the subplots for any of the properties based on Tukey's HSD test (P < 0.05).

Appendix 2. Forest floor litter properties by subplot: average (± standard deviation) of litter carbon (C) and nitrogen (N) content properties (n = 12)

Item	Subplot	C content (%)	N content (%)	C/N (dimensionless)
		average ± SD	average ± SD	average ± SD
Leaves	Control	46.0 ± 4.5	1.07 ± 0.16 [b]	43.7 ± 5.9
	Stump	46.5 ± 4.3	1.08 ± 0.21 [ab]	44.8 ± 11.3
	Timber	47.8 ± 2.9	1.07 ± 0.19 [b]	46.1 ± 10.5
	Unused trunk	47.3 ± 2.3	1.22 ± 0.08 [a]	38.9 ± 3.4
	Crown	47.4 ± 3.0	1.17 ± 0.13 [ab]	41.2 ± 6.3
Branches	Control	48.1 ± 2.7	0.77 ± 0.15	64.3 ± 10.2
	Stump	48.3 ± 2.0	0.83 ± 0.19	61.1 ± 13.9
	Timber	47.6 ± 2.2	0.76 ± 0.22	67.8 ± 20.8
	Unused trunk	47.5 ± 1.4	0.84 ± 0.23	60.0 ± 15.9
	Crown	47.5 ± 2.1	0.80 ± 0.21	63.2 ± 16.7
Bark	Control	44.9 ± 6.2	0.55 ± 0.23	97.9 ± 57.2
	Stump	48.6 ± 3.8	0.54 ± 0.15	95.4 ± 23.9
	Timber	47.0 ± 3.8	0.59 ± 0.27	92.4 ± 34.5
	Unused trunk	46.9 ± 5.5	0.53 ± 0.21	101.9 ± 47.0
	Crown	48.7 ± 4.2	0.66 ± 0.29	88.9 ± 48.2
Hard seeds*		44.0 ± 9.2	0.22 ±0.11	246.0 ± 163.8

Values that do not share a common superscript letter are significantly different at $P < 0.05$ based on Tukey's HSD test (N content in leaves, $P = 0.013$). *Values were composited and taken from all subplots.

Appendix 3. Stocks of chemical elements in mineral soils by subplot: average (± standard deviation) and (range) of carbon stock (C, Mg C ha^{-1}), nitrogen stock (N, Mg N ha^{-1}), and cation stocks (Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+}, kg ha^{-1}) for the 0 cm-30 cm soil layer (n = 12)

Subplot	C (Mg C ha^{-1})		N (Mg N ha^{-1})		Ca^{2+} (kg ha^{-1})	
	average ± SD	range	average ± SD	range	average ± SD	range
Control	29.8 ± 5.2 [bc]	(21.4-42.0)	2.2 ± 0.4	(1.6-2.9)	62.5 ± 75.1 [a]	(5.0-328)
Stump	34.6 ± 7.9 [a]	(22.2-54.2)	2.3 ± 0.5	(1.5-3.7)	22.3 ± 10.4 [b]	(1.4-41.0)
Timber	31.6 ± 6.5 [abc]	(17.7-43.9)	2.3 ± 0.4	(1.4-3.2)	24.8 ± 17.3 [b]	(0.0-66.5)
Unused trunk	28.8 ± 7.2 [c]	(17.2-50.1)	2.1 ± 0.5	(1.5-3.3)	24.0 ± 13.5 [b]	(1.8-56.0)
Crown	32.8 ± 7.3 [ab]	(24.2-48.0)	2.4 ± 0.4	(1.7-3.2)	23.8 ± 18.3 [b]	(3.4-75.5)

Values that do not share a common superscript letter are significantly different among subplots at $P < 0.05$ based on Tukey's HSD test (C, $P = 0.0007$; Ca^{2+}, $P < 0.0001$).

Appendix 3 (cont.).

Subplot	Mg^{2+} (kg ha^{-1})		K^{+} (kg ha^{-1})		Na^{+} (kg ha^{-1})	
	average ± SD	range	average ± SD	range	average ± SD	range
Control	47.6 ± 31.0 [a]	(17.0-136.1)	64.8 ± 17.9 [a]	(40.5-103.5)	8.6 ± 7.9 [a]	(0.1-28.8)
Stump	23.1 ± 13.6 [b]	(7.8-70.2)	55.1 ± 12.6 [b]	(33.7-81.7)	8.4 ± 6.7 [ab]	(0.0-28.5)
Timber	30.0 ± 18.3 [b]	(7.4-103.4)	59.6 ± 19.0 [ab]	(34.6-106.2)	7.3 ± 6.2 [abc]	(0.0-25.1)
Unused trunk	30.5 ± 14.4 [b]	(13.0-57.1)	53.9 ± 9.1 [b]	(36.5-77.5)	6.7 ± 6.8 [bc]	(0.0-26.3)
Crown	23.5 ± 10.5 [b]	(11.0-57.0)	55.8 ± 12.7 [b]	(33.3-92.8)	6.1 ± 5.3 [c]	(0.0-18.5)

Values that do not share a common superscript letter are significantly different among subplots at $P < 0.05$ based on Tukey's HSD test (Ma^{2+}, $P < 0.0001$; K^{+}, $P = 0.0007$; Na^{+}, $P = 0.0007$).

Appendix 4. Root density in the soil profile for three soil layers by subplot: average (± standard deviation) (range) number of fine roots (diameter < 2 mm), medium roots (diameter 2 mm - 20 mm), and coarse roots (diameter > 20 mm) within a 10 cm × 10 cm area (n = 12)

Item	Subplot	0-5 cm		5-15 cm		15-30 cm	
		average ± SD	range	average ± SD	range	average ± SD	range
Fine	Control	18.6 ± 14.3	(6-60)	7.3 ± 3.8	(3-15)	3.8 ± 4.1	(1-16)
	Stump	10.4 ± 6.2	(3-24)	6.8 ± 4.2	(1-17)	2.2 ± 1.5	(0-5)
	Timber	9.6 ± 6.7	(4-26)	4.8 ± 3.5	(1-11)	2.6 ± 2.4	(0-9)
	Unused trunk	16.1 ± 10.4	(3-43)	5.8 ± 5.5	(1-21)	2.4 ± 2.1	(0-8)
	Crown	17.3 ± 8.7	(6-30)	6.1 ± 4.5	(2-15)	2.2 ± 1.1	(1-4)
Medium	Control	1.9 ± 2.3	(0-6)	1.0 ± 0.9	(0-3)	0.3 ± 0.5	(0-1)
	Stump	1.0 ± 1.3	(0-4)	0.7 ± 0.8	(0-2)	0.3 ± 0.5	(0-1)
	Timber	0.8 ± 0.9	(0-3)	0.4 ± 0.7	(0-2)	0.4 ± 0.7	(0-2)
	Unused trunk	0.8 ± 0.8	(0-2)	0.9 ± 1.2	(0-4)	0.3 ± 0.5	(0-1)
	Crown	1.4 ± 2.2	(0-7)	0.8 ± 0.8	(0-2)	0.3 ± 0.5	(0-1)
Coarse	Control	0.1 ± 0.3	(0-1)	0.1 ± 0.3	(0-1)	0 ± 0	(0-0)
	Stump	0.1 ± 0.3	(0-1)	0 ± 0	(0-0)	0 ± 0	(0-0)
	Timber	0 ± 0	(0-0)	0 ± 0	(0-0)	0.1 ± 0.3	(0-1)
	Unused trunk	0.1 ± 0.3	(0-1)	0 ± 0	(0-0)	0.2 ± 0.6	(0-2)
	Crown	0 ± 0	(0-0)	0 ± 0	(0-0)	0.1 ± 0.3	(0-1)

A linear mixed model analysis with soil depth and subplots as explanatory variables incorporating each plot as a random effect showed that the fine root density of the timber subplots was significantly smaller than in the control subplots based on Tukey's HSD test ($P = 0.025$).