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Short-term effects of forest gap size on soil enzyme activity in a *Platycladus orientalis* plantation

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Introduction: Soil enzymes play a critical role in organic matter decomposition and nutrient cycling in forest ecosystems. However, the effects of forest gaps on soil enzyme activities remain uncertain.

Methods: This study aims to investigate the short-term effects of forest gap size on soil enzyme activities in *Platycladus orientalis* plantations. We conducted a study in a 50-year *Platycladus orientalis* plantation in Xuzhou, sampling soils from three levels of forest gap size (4m radius, S; 8m radius, M and 12m radius, L) at different positions (within gap, edge, and outside the gap) and control plots (CK, no gaps) 2a after the creation of gaps. Soil peroxidase, dehydrogenase, urease, and invertase activities were measured.

Results: Specifically, we found that M and S gaps had significantly (p<0.05) higher soil peroxidase activity at the outside position in April and October, respectively, than CK. Additionally, L gaps had significantly (p<0.05) higher soil dehydrogenase activity at the outside position in April than CK. Furthermore, L and S gaps had significantly (p<0.05) higher soil urease activity at the outside position in October and July, respectively, than CK. Lastly, L and S gaps had significantly (p<0.05) higher soil urease activity at the outside position in July than CK.

Conclusion: Our findings highlight the significant impact of canopy gaps on soil enzyme activities, which has important implications for forest management and conservation.

KEYWORDS

forest soil, enzyme activity, *Platycladus orientalis* plantation, forests ecology, forest gap size

Introduction

Forest gaps have received considerable attention in recent decades as a type of disturbance and are widely recognized as a significant factor in forest dynamics (Martinez-Ramos et al., 1989; Clark, 1990). Gaps commonly arise as part of forest management activities and are thought to play a crucial role in nutrient cycling and forest regeneration (Gray et al., 2012; Yang et al., 2017; Wang et al., 2019). Due to increased irradiance, gaps are brighter and warmer, but their surface soils contain more water due to the reduction in plant transpiration (Denslow, 1987). Furthermore, gaps have a significant impact on soil microbial biomass and activity by altering microclimatic conditions and reducing litter inputs, which can lead to changes in soil biochemical properties (Denslow, 1987).

The effects of gap size on soil microbial properties remains uncertain. Although several studies conducted in conifer stands have found no significant differences in mean air temperature during the growing season between gaps of varying sizes (Gray et al., 2002; Muscolo et al., 2007a,b), many others have demonstrated that soil temperature increases with increasing gap size (Gray et al., 2002; Gugliotta et al., 2006; Muscolo et al., 2007a,b). Gap

opening has a particularly significant impact on soil moisture content, which is higher inside gaps than under the surrounding closed canopy, as observed in a wide range of forest types (Ostertag, 1998; Zhu et al., 2003; Albanesi et al., 2008; Sariyildiz, 2008).

Soil enzyme activity, as the main catalyst of many biochemical reactions in soil, is influenced by a series of physico-chemical and biological factors. Muscolo et al. (2007a) demonstrated that small gaps in pine forests, which had greater microbial biomass and larger populations of bacteria and fungi, contributed to a more rapid and balanced turnover of organic matter and nutrients, suggesting that creating small gaps is a silvicultural practice with minimal environmental impact. This study also suggested that small gaps enhance soil enzyme activity and concluded that creating small gaps was an appropriate method of forest management. Yang et al. (2017) found that approximately one year after creating gaps in the forest, small gaps promoted microbial communities and enzyme activity compared with closed canopies. They also observed that soil β-glucosidase activity and ι-leucine aminopeptidase activity were lowest in sites with large gaps and highest in those with small gaps in a Chinese pine forest. It is essential to gain a better understanding of how gap size affects soil microbial biomass and enzyme activities to develop effective forest management and conservation strategies accordingly.

Platycladus orientalis is one of the primary afforestation species in Jiangsu Province, and the creation of artificial gaps in *Platycladus orientalis* forests is a commonly employed silvicultural practice to reduce forest density. However, the relationship between gap size and soil enzyme activity in this species requires further investigation.

In this study, we investigated the effects of small gaps (4 m radius, S), medium gaps (8 m radius, M), and large gaps (12 m radius, L) on enzyme activity 1a after gap creation, in *Platycladus orientalis* plantation located in Xuzhou, eastern China. Along with characterizing soil physico-chemical and biological factors, such as soil soluble organic carbon (SOC), total carbon (TC) and total nitrogen (TN), microbial biomass carbon and nitrogen (MBC and MBN), we tested two hypotheses: (1) temperature-sensitive enzyme activity in forest gaps changes with gap size due to the variation in soil temperature, and (2) the establishment of forest gaps alters the surrounding microclimate conditions, and the impact of forest gaps on soil enzyme activity also increases with gap size. We anticipate that this study will provide valuable insights into the relationship between soil enzyme activity and forest gap size, as well as forest management practices.

Materials and methods

Study region

This study was conducted on Jiuli Hill (34°18'N, 117°14'E), located in Xuzhou City, with elevations ranging from 125 to 150 m a.s.l (Figure 1A). This region is situated in a warm-temperate zone and has a monsoon climate with a mean annual temperature of 14.0°C and a mean annual precipitation of 872 mm (2002–2013 annual average). The plant community is dominated by Oriental arborvitae (*Platycladus orientalis*) plantations at a density of 1,317 stems ha-1, along with a few coniferous-broad-leaved mixed forests. The shrub layer under the forest canopy is primarily composed of a large number of *Broussonetia papyrifera* (L.) L'Hér. ex Vent.

Experimental design and soil sampling

In January 2012, circular forest gaps of three sizes were randomly established on the southwest slope of Jiuli Hill. The size of the forest gaps was proportionate to the average crown canopy height: 0.5, 1.0, and 1.5. The gap diameters were 8 m, 16 m, and 24 m. After the trees were cut to create the gaps, plant debris was removed from the gap area, but stumps were not extracted. Three replicates were established for each gap size, as well as for control plots (CK) situated in a nearby closed forest that was at least 100 m from any canopy gap. Within each gap, 13 sampling points were arranged at the center and at 0.5, 1.0, and 1.5 times the gap radius in each of the four cardinal directions. Thus, in each direction, a point was located within the gap (I), at the gap edge (E), and outside the gap (O) in the undisturbed forest (Figure 1B).

Soil samples were collected from the nine treatment and three control plots by removing the undecomposed litter layer collecting mineral soil from a depth of 0 to 10 cm at each sampling point. Soils collected at the 4 sampling points (I, E, O, and CK) were combined to form a uniform mixture for each sample location. Soil samples were sieved (2 mm), labeled, and promptly brought back to the laboratory for analysis. The soils were sampled in October 2013, January 2014, April 2014, and July 2014.

Laboratory analysis

Soil physico-chemical property determination

Soil temperature was measured in the field using a button-type temperature sensor (DS1921-F5#, Maxim, USA) with a recording interval of 30 min. Soil moisture content was calculated by measuring weight loss after oven drying approximately 10 g of fresh soil for 24 h at 105°C. Soil total carbon (TC) and total nitrogen (TN) were measured using an elemental analyzer (Vario EL III, Elementar, Germany). Soil pH was determined using potentiometry with a water/soil ratio of 1: 2.5.

Determination of soil soluble organic carbon, microbial biomass carbon, and nitrogen content

The soil soluble organic carbon (SOC) content was quantified using a carbon analyzer (Shimadzu TOC-VCPN, Japan). Microbial biomass carbon and nitrogen (MBC and MBN) content of the soil were determined using the chloroform fumigation method (Brookes et al., 1985; Vance et al., 1987). Briefly, 20 g of fresh soil was fumigated for 24 h at 25°C with alcohol-free $CHCl_3$ in a desiccator. Following removal of the $CHCl_3$, the soil was extracted (fumigated and unfumigated) with 80 ml of 0.5 M K_2SO_4 for 30 min. Organic C in the solution was analyzed using a carbon analyzer (Shimadzu TOC-VCPN, Japan). The difference between fumigated and unfumigated samples was used to calculate MBC, using a conversion factor of $k_{EC} = 0.45$ (Joergensen and Mueller, 1996): $MBC = EC/k_{EC}$, while MBN was calculated using a conversion factor of $k_{EN} = 0.68$ (Brookes et al., 1985): $MBN = EN/k_{EN}$.

Soil enzyme activity

Soil enzyme activity was assessed using the colorimetric method with a spectrophotometer. Soil peroxidase activity was determined based on the procedure outlined by Markkola et al. (1990) and expressed as μg purple gallic acid g^{-1} soil h^{-1}. Soil dehydrogenase activity was estimated using the method described by Casida et al. (1964) and expressed as μg TPF g^{-1} soil h^{-1}. Soil urease activity was determined according to the method of Kandeler

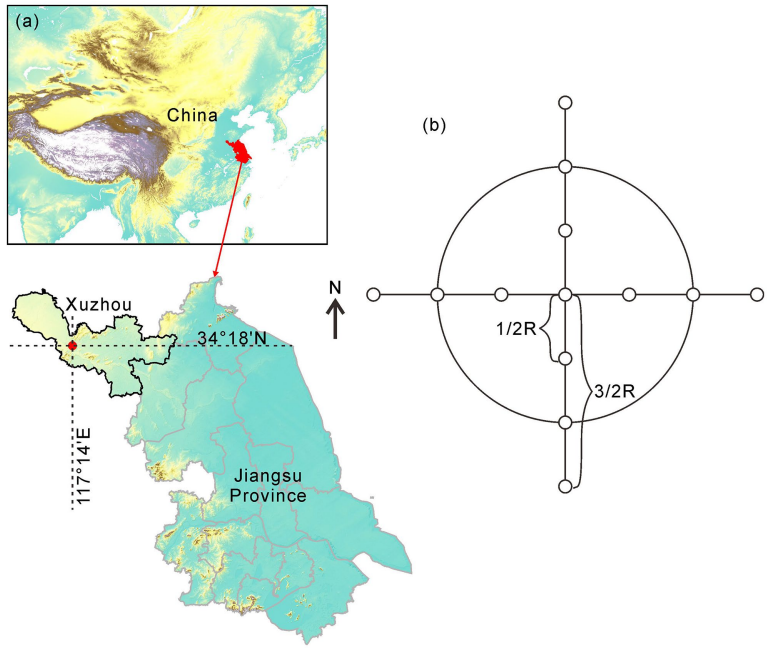

FIGURE 1
(A) Study site **(B)** Experimental design. The small circles represent sampling points.

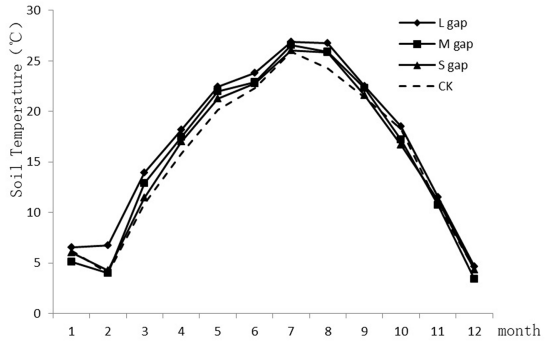

FIGURE 2
Monthly mean soil temperature in different sizes of gaps in *Platycladus orientalis* plantation.

and Gerber (1988) and expressed as mg NH_4-N g^{-1} soil d^{-1}. Soil invertase activity was estimated based on the method provided by Frankeberger and Johanson (1983) and expressed as mg glucose g^{-1} soil d^{-1}.

Statistical analysis

The differences among different gap sizes were analyzed using one-way analysis of variance (ANOVA) in SPSS 20.0 and multiple comparisons were conducted with the LSD method ($p \leq 0.05$). Pearson correlation analysis was applied to explore the relationships between soil enzyme activities and related explanatory factors.

Results

Response of soil temperature and moisture to different gap sizes

Forest gap size had greater effects on soil temperature in autumn and spring. As shown in Figure 2, the daily average temperature at a depth of 10 cm exhibited a peak in July (26.0°C) and a nadir in December (4.0°C) across all gap sizes. In October, the trend of daily average soil temperature was CK>S>L>M, whereas in January, L>CK>S>M. In April, the trend was M>L>S>CK, and in July, L>M>CK>S.

As illustrated in Figure 3, soil moisture was highest in April and July (25%), lowest in October (10%), and 15% in April. In comparison with CK, there was no significant difference in soil moisture in October, while significant increases in soil moisture were observed under M gaps in January and April as well as S gaps in July. On the other hand, a reduction in soil moisture under L gaps were observed in July.

Response of soil physico-chemical properties to different gap sizes

Compared to CK, this study found differences in SOC, TC, TN, and TC/TN among different gap sizes (Table 1). Additionally, MBC was found to increase at I and E location of M gaps in April compared to CK. Meanwhile, the S gaps resulted in a significant reduction in soil MBN ($p < 0.05$) in April at both I and O location, while the L gaps significantly increased the soil MBN in July ($p < 0.05$) at O location.

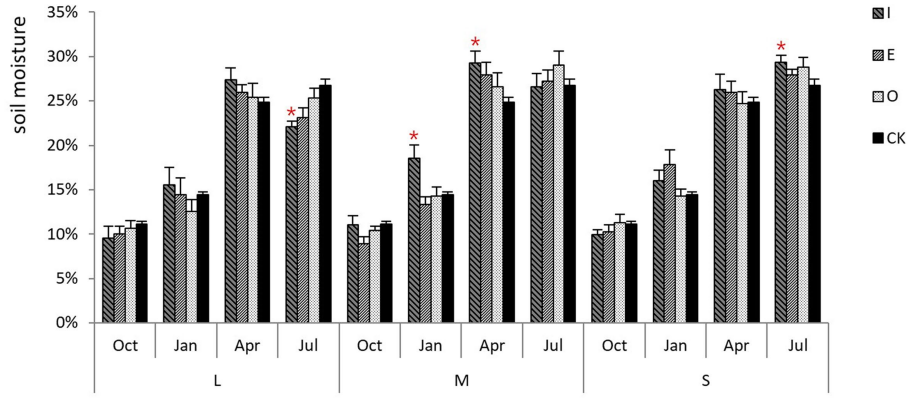

FIGURE 3
Soil moisture in different sizes of gaps in *Platycladus orientalis* plantation, the "*"signs represent significant differences.

Response of four soil enzyme activities to different locations of gaps

Compared to CK, the soil peroxidase activity was significantly ($p < 0.05$) increased by M gaps (6.42 μg purple gallic acid g^{-1} soil h^{-1}) at E location in July and significantly increased in April at O location (3.42 μg purple gallic acid g^{-1} soil h^{-1}) (Figure 4). The gaps also significantly increased the soil peroxidase activity ($p < 0.05$) in October at O location (6.29 μg purple gallic acid g^{-1} soil h^{-1}) while those significantly increased the soil peroxidase activity ($p < 0.05$) in April at E location (3.80 μg purple gallic acid g^{-1} soil h^{-1}).

Compared to CK, the L gaps significantly increased the soil dehydrogenase activity ($p < 0.05$) in January at E location (2,988.25 μg TPF g^{-1} soil h^{-1}) (Figure 5). Additionally, the L gaps significantly increased the soil dehydrogenase activity ($p < 0.05$) in April at I (2,437.51 μg TPF g^{-1} soil h^{-1}), E (2,658.04 μg TPF g^{-1} soil h^{-1}) and O (2,190.87 μg TPF g^{-1} soil h^{-1}) locations. The M gaps also increased the soil dehydrogenase activity ($p < 0.05$) in April at I (2,133.61 μg TPF g^{-1} soil h^{-1}) and E (2,342.00 μg TPF g^{-1} soil h^{-1}) locations. Meanwhile, the S gaps significantly increased the soil dehydrogenase activity ($p < 0.05$) in October at I location (2,391.81 μg TPF g^{-1} soil h^{-1}).

Compared to CK, L gaps significantly increased the soil urease activity ($p < 0.05$) at I (946.8 mg NH_4-N g^{-1} soil d^{-1}) and O location (921.3 mg NH_4-N g^{-1} soil d^{-1}) in October, while significantly increased the soil urease activity ($p < 0.05$) in April (1,893.8 mg NH_4-N g^{-1} soil d^{-1}) and July (1,110.2 mg NH_4-N g^{-1} soil d^{-1}) at E location; (Figure 6). M gaps increased the soil urease activity ($p < 0.05$) in July at I (1,036.7 mg NH_4-N g^{-1} soil d^{-1}) and E location (1,068.3 mg NH_4-N g^{-1} soil d^{-1}). S gaps significantly increased the soil urease activity ($p < 0.05$) in July at both I (1,060.0 mg NH_4-N g^{-1} soil d^{-1}) and O location (916.7 mg NH_4-N g^{-1} soil d^{-1}).

Compared to CK, L gaps significantly increased the soil invertase activity ($p < 0.05$) in January (2.93 mg glucose g^{-1} soil d^{-1}) and July (4.12 mg glucose g^{-1} soil d^{-1}) at E location and O locations, respectively (Figure 7). Similarly, M gaps significantly increased the soil invertase activity ($p < 0.05$) in April at I location (2.67 mg glucose g^{-1} soil d^{-1}), while S gaps significantly increased the soil invertase activity ($p < 0.05$) in July at both I location (4.58 mg glucose g^{-1} soil d^{-1}) and O location (3.68 mg glucose g^{-1} soil d^{-1}).

Correlation analysis of 4 soil enzyme activities, and soil physico-chemical properties and microbial biomass

Table 2 indicated that there is a significantly and positive correlation between soil peroxidase activity and soil TC ($p < 0.05$), while a significant negative correlation existed between soil peroxidase activity and soil temperature, soil moisture, TN, C/N, and MBN ($p < 0.01$). Soil dehydrogenase activity showed an extremely significant positive correlation with soil TC and MBC ($p < 0.01$), and a significant positive correlation with SOC ($p < 0.05$). Moreover, soil dehydrogenase activity was significantly and negatively correlated with soil temperature and soil moisture ($p < 0.01$) and negatively correlated with soil TN ($p < 0.05$). Soil urease activity exhibited an extremely significant positive correlation with soil TC, SOC, MBC, and MBN ($p < 0.01$) as well as an extremely significant negative correlation with soil temperature, soil TN and C/N ratio ($p < 0.01$). Soil invertase activity displayed an extremely significant positive correlation with soil temperature, soil moisture, soil TN and soil MBN ($p < 0.01$) and a significantly negative correlation with soil MBC ($p < 0.05$).

Discussion

Luo (2012) investigated the soil enzyme activity of Chinese fir plantation and found a significant correlation between peroxidase activity and soil pH value. However, in the present study, no significant correlation was found between peroxidase activity and pH value. One possible reason for this discrepancy is that the time since gap creation was relatively short, and soil pH, being a fundamental soil property, may not have been significantly influenced by the gaps in the short term. Therefore, soil pH may not be a driving factor for changes in peroxidase activity. The results of this study showed a negative correlation between soil peroxidase activity and soil temperature, possibly due to the higher solar radiation and temperature received by large forest gaps. As a temperature-sensitive enzyme, peroxidase activity was significantly increased in I and O positions of M and S gaps, indicating a promoting effect of the forest understory environment influenced by M and S gaps on peroxidase activity. These findings are consistent with previous studies by Yang et al. (2017) and

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TABLE 1 Summary of soil chemical properties, MBC and MBN of samples from large-gap, medium-gap, small-gap, and control plots.

Chemical properties	Season	L			M			S			CK
		I	E	O	I	E	O	I	E	O	
SOC/(mg/kg)	October	347.08 (22.54)c	450.55 (29.91)bc	380 (23.13)c	394.33 (30.49)bc	355.33 (19.33)c	358 (30.22)c	565.42 (63.9)a	515.25 (63.52)ab	533.42 (45.33)ab	461.83 (11.75)b
	January	292.33 (37.41)b	392.42 (54.67)ab	315.08 (29.03)b	300.5 (30.35)b	295.2 (36.76)b	403.1 (63.47)ab	589.92 (151.83)a	444.42 (59.69)a	385.18 (38.51)ab	326.41 (18.03)b
	April	649.17 (58.77)a	612.25 (46.86)ab	623.33 (27.48)a	590.08 (37.85)ab	593.17 (49)ab	586.25 (40.2)ab	454.92 (24.36)c	482.92 (19.88)c	496.5 (33.84)bc	551.02 (15.11)b
	July	276.75 (19.17)b	279.88 (30.03)ab	313.13 (33.08)ab	272.58 (19.86)b	289.92 (24.5)ab	349.17 (33.85)ab	292.42 (27.68)ab	337.75 (38.07)ab	365.33 (57.53)a	285.83 (18.25)b
TC/(g/kg)	October	70.23 (7.57)bc	77.47 (2.43)b	73.63 (6.22)bc	75.9 (2.28) b	69.77 (0.64)c	67.3 (3.65) c	86.83 (0.95)a	91 (2.71)a	93.6 (6.42) a	83.97 (4.59)ab
	January	80.17 (7.63)c	96.1 (6.35) ab	82.83 (7.23)c	87.67 (5.68)bc	88.53 (6.64)bc	83.27 (8.79)bc	101.27 (4.13)a	101.87 (5.49)a	92.5 (1.35) b	93.44 (4.12)ab
	April	87.1 (11.06)a	88.13 (2.22)a	89.03 (4.39)a	87.6 (2.1)a	90.87 (6.65)a	83 (4.5)a	81.7 (6.75) a	86.33 (1.79)a	79.43 (3.6) b	83.8 (4.03) a
	July	66.7 (8.81) a	68.2 (3.84) a	69.37 (3.22)a	72.1 (2.26) a	72.73 (2.36)a	75.77 (2.32)a	76.63 (3.91)a	70.4 (1.29) a	79.53 (7.96)a	71.17 (2.96)a
TN/(g/kg)	October	5.8 (0.36) bc	6.23 (0.19) bc	6 (0.35)bc	6.37 (0.24) b	5.9 (0.15)c	6.33 (0.24) b	7 (0.01)a	7.07 (0.2)a	7.27 (0.43) a	6.74 (0.29) ab
	January	6.53 (0.49) a	7.37 (0.41) a	6.63 (0.47) a	7.2 (0.46)a	7.23 (0.37) a	7 (0.5)a	7.87 (0.17) a	7.93 (0.38) a	7.33 (0.15) a	7.4 (0.26)a
	April	7.2 (0.55)a	7.3 (0.25)a	7.2 (0.45)a	7.3 (0.2)a	7.57 (0.43) a	7 (0.32)a	6.73 (0.33) a	7.03 (0.09) a	6.7 (0.2)a	6.89 (0.24) a
	July	5.4 (0.57)a	5.47 (0.24) a	5.8 (0.44)a	5.6 (0.15)a	5.5 (0.15)a	5.93 (0.23) a	5.73 (0.23) a	5.43 (0.09) a	6 (0.61)a	5.59 (0.17) a
TC/TN	October	12.1 (0.64) abc	12.4 (0.38) abc	12.25 (0.53)abc	11.91 (0.14)c	11.8 (0.25) c	12.07 (0.2) bc	12.41 (0.11)b	12.83 (0.17)a	12.84 (0.21)a	12.41 (0.29)ab
	January	12.23 (0.45)a	13.02 (0.4) a	12.5 (0.45) a	12.17 (0.11)a	12.18 (0.33)a	11.86 (0.37)a	12.85 (0.31)a	12.8 (0.18) a	12.6 (0.27) a	12.62 (0.23)a
	April	12 (0.62)a	12.09 (0.16)a	12.34 (0.15)a	11.99 (0.08)a	11.94 (0.21)a	11.88 (0.35)a	12.09 (0.39)a	12.32 (0.19)a	11.84 (0.31)a	12.11 (0.26)a
	July	12.27 (0.37)ab	12.46 (0.16)c	12.01 (0.36)c	12.87 (0.1) b	13.27 (0.82)ab	12.78 (0.11)b	13.36 (0.2) a	12.96 (0.23)ab	13.26 (0.03)a	12.7 (0.17) bc
MBC/(mg/kg)	October	2,083.67 (128.66)b	2,386.18 (131.61)ab	2,155.75 (157.66)b	1,957.92 (154.09)b	1,908.58 (81.57)b	1,988.33 (115.13)b	2,509 (309.34)ab	2,475.25 (269.24)ab	2,645.5 (270.72)a	2,150.3 (64.55)b
	January	2,128.58 (169.29)b	2,469.58 (190.73)ab	2,093.42 (162.98)b	2,585.6 (188.63)a	2,361.9 (169.95)ab	2,774.3 (233.35)a	2,439.83 (372.12)ab	2,764.5 (252.3)a	2,464.91 (259.66)ab	2,421.96 (80.64)ab
	April	2,485.58 (198.74) b	2,923.25 (150.9)ab	2,838.83 (217.42)ab	2,959.25 (212.35)a	3,008.83 (222.15)a	2,655.92 (171.26)ab	2,328.83 (220.05) bc	2,159.17 (90.56)c	1,955.08 (136.12)c	2,549.91 (69.38)b
	July	1,052.75 (74.69)b	1,256.13 (62.65)ab	1,376.25 (75.25)a	1,224.5 (39.12)b	1,409.75 (81.95)a	1,362 (113.9)ab	1,223.58 (50.19)b	1,044.92 (65.77)b	1,277 (118.94)ab	1,197.42 (60.62)b
MBN/(mg/kg)	October	55.92 (8.54)a	64 (8.38)a	62.33 (7.94)a	58.75 (8.57)a	55.83 (7.18)a	68.09 (9.17)a	68.6 (15.72)a	67 (18.16) a	61.42 (10.29)a	56.01 (4.09)a
	January	125.73 (18.35)a	112 (18.02)ab	113.82 (11.51)ab	135.78 (14.7)a	91.1 (12.94)b	121 (15.35)a	125.64 (21)a	147.82 (13.78)a	101 (18.63)b	109.11 (6.78)b
	April	169.55 (17.03)bc	208.17 (18.46)a	207.09 (21.95)a	189.17 (13.79)ab	207.67 (13.95)a	164.75 (20.21)bc	143.42 (12.82)c	153.08 (9.5)bc	131.33 (15.18)c	170.45 (6.07)b
	July	114.38 (8.74)b	150.38 (15.29)ab	169.5 (17.42)a	144.42 (13.82)ab	158.08 (18.6)ab	151.58 (18.7)ab	125.33 (9.32)b	106.33 (13.64)b	121 (10.63)b	130.38 (10.32)b

Data are the means (SE), $n = 3$. Different lowercase letters in each column represent significant differences ($p < 0.05$). SOC, soluble organic carbon; TC, total carbon; TN, total nitrogen; C/N, carbon/nitrogen ratio; MBC, Microbial biomass carbon; MBN, Microbial biomass nitrogen; L, sites with large gaps; M, sites with medium gaps; S, sites with small gaps; I, within; E, Edge; O, outside.

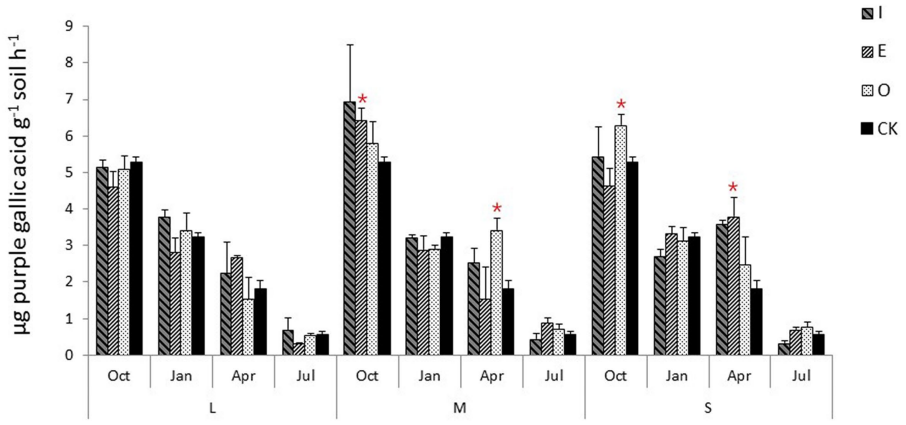

FIGURE 4
Soil peroxidase activity of different position in different sizes of gaps, the "*"signs represent significant differences.

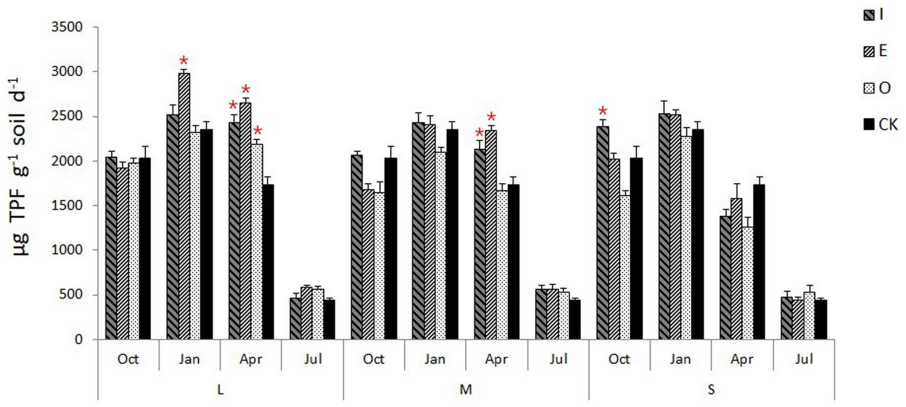

FIGURE 5
Soil dehydrogenase activity of different position in different sizes of gaps, the "*"signs represent significant differences.

Muscolo et al. (2007a) and contradict the hypothesis 1 of this study, which suggested that larger forest gaps would have a positive effect on peroxidase activity due to their higher temperature. Instead, it appears that M and S gaps have a positive effect on peroxidase activity in the surrounding soil. Sinsabaugh (2010) found that peroxidase activity is positively correlated with litter quantity. Accordingly, the smaller forest gaps had higher peroxidase activity due to their greater litter quantity compared to the larger ones.

Due to the intracellular nature of dehydrogenase, which does not accumulate extracellularly in soil (Filipović et al., 2020), and the ability of enzymatic activity to rapidly respond to even small changes in environmental conditions (Dussault et al., 2008), dehydrogenase is commonly used as an indicator of soil microbial activity (Makoi and Ndakidemi, 2008). The results of this study showed that soil dehydrogenase activity was significantly higher in all gap sizes compared to CK, and was positively correlated with MBC ($p < 0.01$), and positively correlated with SOC ($p < 0.05$), consistent with Lungmuana et al. (2017) who found a strong positive relationship between MBC and enzyme activities in the surface soil layers. Thus, it can be said that the establishment of forest gaps has led to better soil chemical conditions and higher biological activity compared to the forest under canopy, which also supported by the study of Avazpoor et al. (2019). Soil enzymes play a key role in nutrient cycling and SOM mineralization (Gianfreda, 2015).

The findings of this study indicated that soil urease activity was positively correlated with SOC, MBC and MBN ($p < 0.01$), because many bacteria, fungi, archaea and plants present in the soil produce urease (Fisher et al., 2017). Consistent with the results of this study, Wang et al. (2005) also demonstrated that the transformation of nitrogen in soil was related to urease activity. Furthermore, this study revealed significantly higher urease activity in all types of gaps in July, with larger forest gaps exhibiting higher urease activity due to the humus-urease complexes extracted from soil being highly resistant to extreme temperatures (Makoi and Ndakidemi, 2008). These findings are in line with hypothesis 1, which proposed that enzyme activity in forest gaps changes with gap size due to soil temperature variations.

The study by Yu et al. (2017) showed that invertase activity in soil can hydrolyze sucrose into glucose and fructose as available energy sources for plants and soil microorganisms. Our study found that soil invertase activity was positively correlated with soil

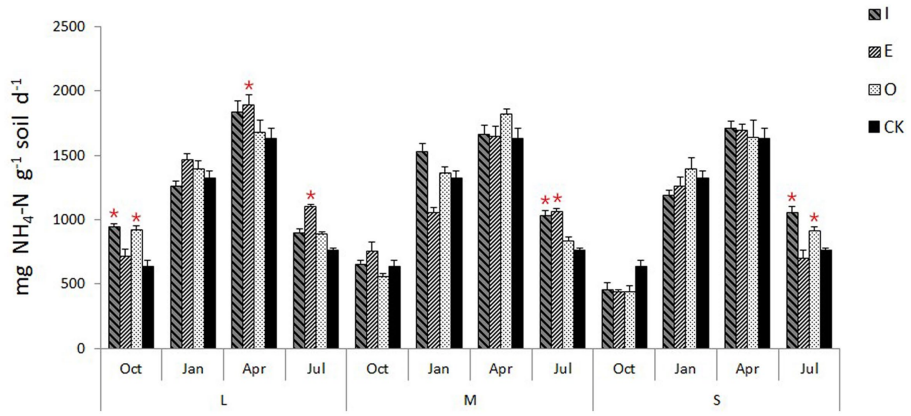

FIGURE 6
Soil urease activity of different position in different sizes of gaps, the "*"signs represent significant differences.

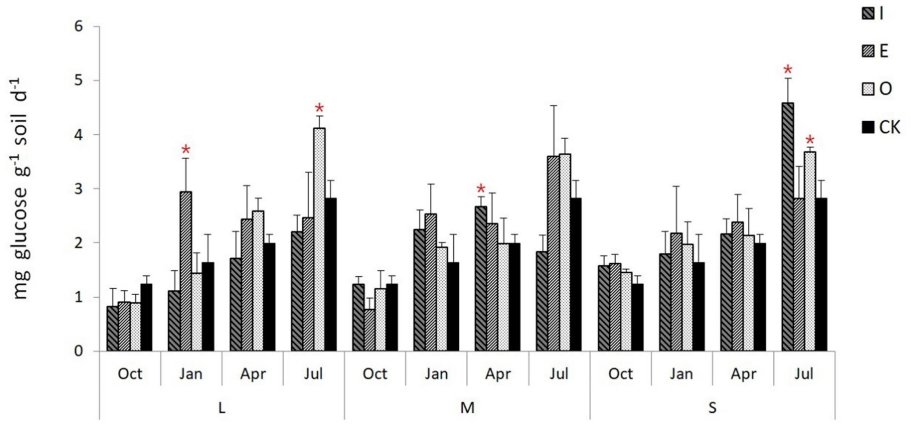

FIGURE 7
Soil invertase activity of different position in different sizes of gaps, the "*"signs represent significant differences.

TABLE 2 Correlations between soil chemical properties, MBC, MBN, and enzymatic activity.

	Soil temperature	Soil moisture	pH value	TC	TN	TC/TN	SOC	MBC	MBN
Peroxidase	−0.534**	−0.696**	ns	0.173*	−0.331**	−0.222**	ns	ns	−0.449**
Dehydrogenase	−0.741**	−0.359**	ns	0.578**	−0.208*	ns	0.165*	0.485**	ns
Urease	−0.591**	ns	ns	0.416**	−0.219**	−0.241**	0.217**	0.565**	0.375**
Invertase	0.355**	0.49**	ns	ns	0.323**	ns	ns	−0.154*	0.255**

TC, total carbon; TN, total nitrogen; TC/TN, carbon/nitrogen ratio; SOC, soluble organic carbon; MBC, microbial biomass carbon; MBN, microbial biomass nitrogen. *Significant correlations ($p < 0.05$). **Significant correlations ($p < 0.01$).

temperature, soil moisture, and MBN ($p < 0.01$), which could be attributed to the increased metabolism of soil microorganisms and the stimulation of microbial activity. In April and July, all three sizes of forest gaps had increased soil invertase activity, indicating that the establishment of forest gaps increased solar radiation and soil temperature. In particular, the soil invertase activity was significantly higher in larger forest gaps and their surroundings, consistent with hypothesis 2 that the impact of forest gaps on soil enzyme activity increases with gap size. The increase in soil invertase activity can increase the microbial population and provide energy and a favorable environment for soil enzymes, which is consistent with the results of the study by Wu et al. (2020).

Conclusion

In this study, forest gap size had different effects on different enzymes. The M and S gaps increased the activity of peroxidase, which is contrary to hypothesis 1 mentioned earlier. The L gaps and its surrounding area showed the most significant increase in

dehydrogenase activity, consistent with hypothesis 2. Urease activity increased with gap size, consistent with hypothesis 1. The impact of forest gaps on invertase activity expanded with increasing gap size, consistent with hypothesis 2.

This study explored the impact of forest gap size on soil enzyme activities. and investigates their correlation with physico-chemical properties. The creation of gaps as a silvicultural approach has significant potential to promote ecologically sustainable forest development. Nonetheless, the existing body of research on the interplay between above-and below-ground nutrient cycling in forest gaps remains insufficient, which hinders our comprehensive understanding of gap dynamics and their impact on forest ecosystems. Further research in this area is essential to fill this knowledge gap and improve our understanding of forest ecology.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

FF: conceptualization, methodology, software, data curation, and writing–original draft preparation. QG: supervision. XC: writing–reviewing and editing. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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