Effect of Timber Harvesting Techniques and Slopes on Soil Respiration of Young and Mature Black Pine Stands in Northwestern Türkiye

Çiğdem Özer Genç [a],* Temel Sarıyıldız [b] and Burak Arıcak [b]

Releases of CO_2 from forest soils was studied relative to different timber harvesting techniques, slope classes, and stand age. Three timber harvesting techniques (suspended skidding (SS), skidding by using a skidding cone (SC), and cable-pulling (CP)) were used in young and mature black pine stands at three different slopes (0 to 20% - S1, 20% to 33% - S2, and > 33% - S3). Soil respiration measurements were carried out at five-day intervals (1^{st}, 5^{th}, and 10^{th} day) and 6 months later after the timber harvesting techniques. The soil respiration increased on the first day, decreased on the 5^{th} and 10^{th} days, and reached its lowest level on the 6th month. The SC technique in the young stands showed the highest soil respiration value on the slopes indicating that the cone placed on the head of the log during the skidding operations does not deform the soil. In the mature stands, all timber harvesting techniques and the undisturbed sites showed lower values than in the young stands on the S1. On the S2, mean value was higher in the mature stands. In contrast to the young stands, the undisturbed stands had the highest soil respiration.

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Contact information: a: Kastamonu University Faculty of Forestry Department of Forest Engineering Kastamonu, Turkiye; b: Bursa Technical University Faculty of Forestry Department of Forest Engineering Bursa, Türkiye;
**Corresponding author: cozer@kastamonu.edu.tr*

INTRODUCTION

Forests provide various ecosystem services, including wood, food, biodiversity, habitat, regulating water resources, and recreational opportunities (Duncker *et al*. 2012; Ding *et al*. 2016; Huang *et al*. 2020). Given these benefits, forest resources should be managed according to the principles of precision forestry to meet the needs of present and future generations. Precision forestry aims to achieve the optimal yield from forest resources while minimizing environmental damage. This can be achieved through modern techniques and technological tools to inform economic, environmental, and sustainable decisions in forestry studies (Akay *et al*. 2014; Gülci *et al*. 2015). While modern forest vehicles such as skidders are widely used in developed countries, they are not widely used in Türkiye yet. Skidders collect, extract, and transport wood from the stand. They load wood onto road trailers or trucks. Due to these features, they are quite practical, fast, and ergonomic. In addition, by using machine systems in the length-cut harvesting method, trees can be processed in the stand, and branches and tops can be left on the ground. In this way, soil disturbance can be seen less.

However, skidders are not suitable for use in wet areas and areas with a slope of > 30%. At this stage, in areas with higher slopes and extraction distances longer than 150 m, the use of cable will cause less damage to the environment and soil. At the same time, wood can be transported without quality and quantity losses. The production processes employed in the exploitation of forest resources can also have a detrimental impact on the sustainability of these resources, resulting in the degradation of soil properties (Bergner *et al*. 2010; Mastrolonardo *et al*. 2015; Yang *et al*. 2019). A damaged soil system can result in long-term and potentially irreversible damage to the ecosystem, affecting forest productivity. In particular, the use of heavy machinery during the production process, including the transportation, cutting, skidding, pushing, and lifting of logs, can result in significant losses of forest cover and cause notable alterations to the properties of the top and bottom soil (Enez *et al*. 2016).

Soil compaction, typically the most apparent consequence of skidding, enhances soil strength, restricts gas diffusion, and impairs root growth and microbial activity (Gomez *et al*. 2002). This, in turn, affects and delays the physiological and growth characteristics of seedlings and trees. Soil respiration, which is also a result of microbial activity, comprises the largest source of global terrestrial CO_2 efflux (Subke and Bahn 2010). In this context, it is also essential to assess the impact of interventions on forests on the change in carbon storage (IPCC 2013; Zhou *et al*. 2016). Consequently, the impact of production activities on the sustainability and stability of forest soil is significant, as they have the potential to influence physical, chemical, and biological characteristics (Decocq *et al*. 2004; Díaz-Maroto and Vila-Lameiro 2008). The extent and degree of soil deformation in production operations with skidders is variable and it is related to the number of tractors passes, harvesting technique, and the heaviness of the machinery (Cambi *et al*. 2015, 2017; Picchio *et al*. 2019), slope, tree type, soil texture, and soil moisture content (Naghdi and Solgi 2014).

Pilli *et al*. (2015) emphasized that production works provided more effective carbon management in the long term as the efficiency per unit area increased. Nevertheless, implementing harvesting, transportation, and timber harvesting operations result in the outflow of biomass from ecosystems. Furthermore, the decomposition of harvesting residues occurs faster than that of living biomass. Additionally, the management of solid waste storage contributes significantly to the carbon balance. Consequently, given that carbon sequestration is a long-term process, the time factor must also be considered when estimating the amount of carbon. In their study, Cheng *et al.* (2023) identified several factors that influenced the production of CO_2 in soil, including soil temperature and humidity, soil organic matter quality and quantity, root and microbial biomass, root nitrogen content, and soil's physical and chemical properties. Yashiro *et al*. (2008) observed no discernible distinction between production and non-production areas regarding CO_2 flux from the soil. However, soil temperature was generally higher in non-harvesting areas than in harvesting areas. Hartmann *et al*. (2014) found considerable variability in CO_2 flux depending on the level of compaction in loamy soil in a forest dominated by *Fagus sylvatica* and *Picea abies* Their findings indicated that, in contrast to severe compaction, moderate compaction increased CO_2 emissions, probably due to increased microbial mineralization of newly exposed organic matter with sufficient oxygen supply. Goutal *et al*. (2013) studied the effect of compaction resulting from heavy machinery production activities on soil respiration. As a result of their study, they found that the amount of CO_2 initially increased due to the soil compaction and then decreased. In their study, Cambi *et al*. (2015) posited that soil compaction facilitated the formation of anoxic (oxygen-free) conditions, thereby suppressing soil respiration and promoting the production and release of the potent greenhouse gas methane into the atmosphere. Magagnotti *et al*. (2012) noted that the concentration of CO_2 doubled during maintenance work on loamy, sandy soil, where Mediterranean pine plantations persisted, with values ranging from 0.4% to 0.8% by volume in machine tracks. Gaertig *et al*. (2002) found that compacted soil portions exhibited CO_2 concentrations up to three times higher than the control and that root density decreased significantly with decreased soil gas permeability. Ampoorter *et al*. (2010) observed in a Belgium skidding study that after a single skidding cycle, the CO_2 concentration was significantly higher within and between wheel tracks, in contrast to soil volume weight and compaction. They conclude that this result indicates that CO_2 concentration is a more sensitive indicator than soil compaction, as it is affected by soil water content and temperature.

Although, the effects of timber harvesting operations on soil and stand structure have been intensively investigated in Türkiye (Emir 2020; Eker 2020; Taş *et al*. 2023) the effects of timber harvesting operations on soil respiration in terms of affecting soil quality have received less attention. Therefore, we set up a study to investigate the effects of timber harvesting operations on soil respiration in skid trails located in the north of Türkiye. The soil respiration was measured as CO_2 flux from the surface soil using a LICOR 8100 gas analyzer (IRGA).

To ascertain the impact of different clearing techniques on soil respiration, the effects of three timber harvesting techniques (suspended skidding (SS), skidding by using a skidding cone (SC), and cable-pulling (CP)) were evaluated across three slope classes (0 to 20% (S1), 20% to 33% (S2), and > 33% (S3)). The temporal change of soil respiration on the first 10 days (1^{st} day, 5^{th} day, and 10^{th} day) and 6^{th} month following the clearing operations were also determined.

EXPERIMENTAL

Study Area

This study was carried out in young and mature black pine (*Pinus nigra*) stands situated on three different slopes (S1: 0 to 20%; S2: 20% to 33% and S3: > 33%) in Akkaya, Karadere, Kastamonu (Fig. 1) (41° 12' 00" - 41° 21' 29" N, 34° 01' 15" - 34° 10' 00" E). Akkaya Forest Sub-District Directorate was within the border of Kastamonu province in the Western Black Sea Region. The general size of the study area was 12693.1 ha, of which forest areas covered 9590.5 ha and the open areas were 3102.6 ha. The altitude of the study area ranged from 810 m to 1705 m. The Akkaya Forest Sub-District Directorate was within the "Western Black Sea Climate Region" as a climate region. It was located in the transition zone between the Central Anatolian continental region of Türkiye and the Black Sea humid temperate climate zone. The soil type was brown forest soil. The parent material had a schist rock type.

The study area is forests with a production function. Here, old stands are between 60 and 80 years old. Black pine stands are taken to rejuvenation at approximately 120 years old. Therefore, this area has not yet been taken to rejuvenation and no dead trees were seen. Young stands are generally are between 40 and 60 years old.

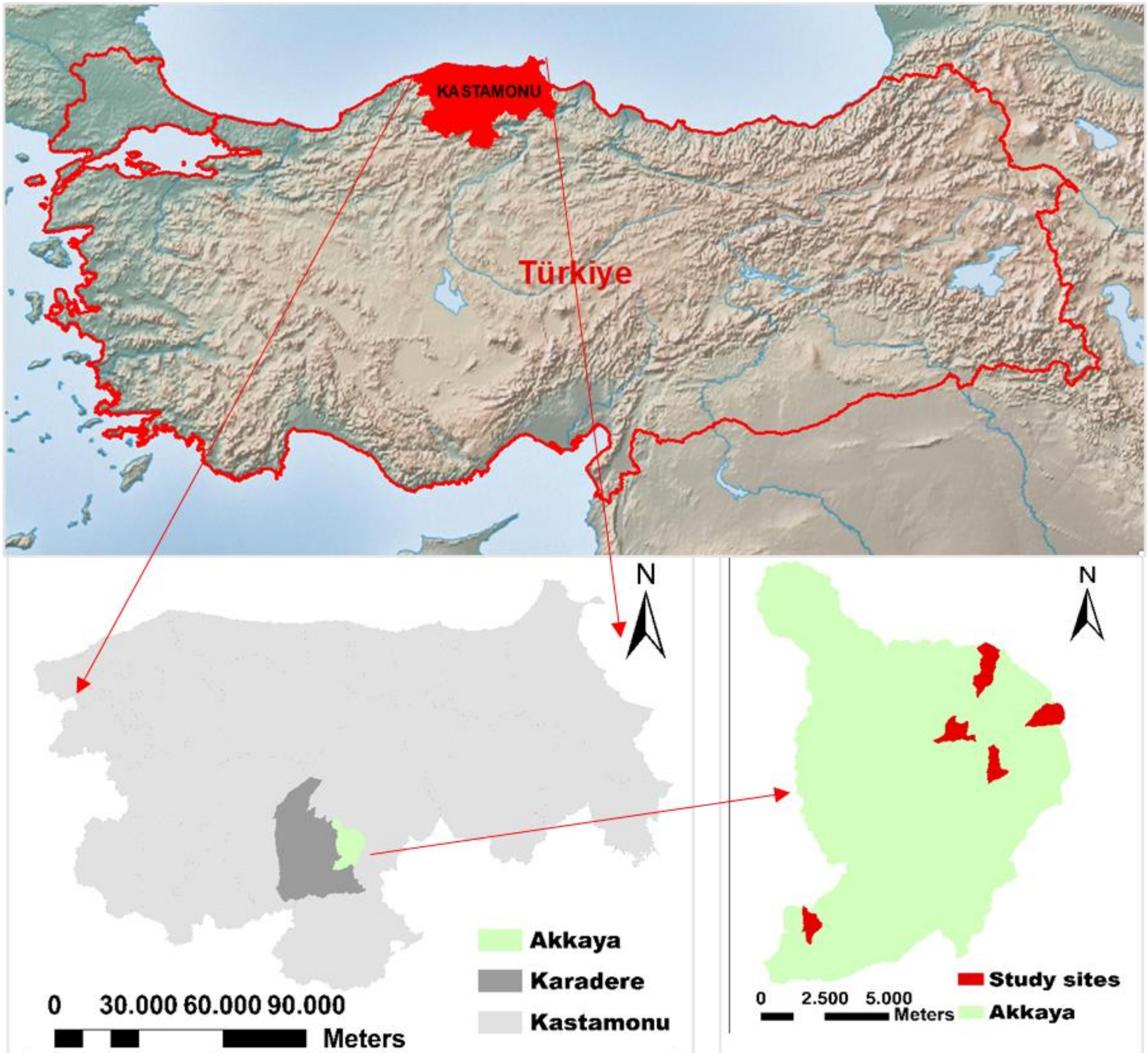

Fig. 1. Location of study area

Methods

Experimental design and soil respiration measurements

Three different timber harvesting techniques were used in the study sites as (1) suspending skidding (SS), (2) cable pulling (CP), and (3) skidding by using a skidding cone (SC) (Fig. 2). For the SS technique, the tractor entered the compartment, and the log was connected to the drum. The log was pulled approximately 50 m up the slope from where it was pulled, leaving the end of the log suspended. In the SC technique, the logs were skidded with a cable by attaching a skidding cone to the log. The tractor was positioned outside the compartment where the pulling was intended to end, and the logs were pulled with the cable from where the pulling started to where the pulling ended, with the entire log touching the ground. In the CP technique where the cable was connected to the tractor, the tractor was outside the compartment, and the whole log was skidding over the slope with the help of the rope by touching the ground without using a skidding cone (Özer Genç 2020) (Fig. 2).

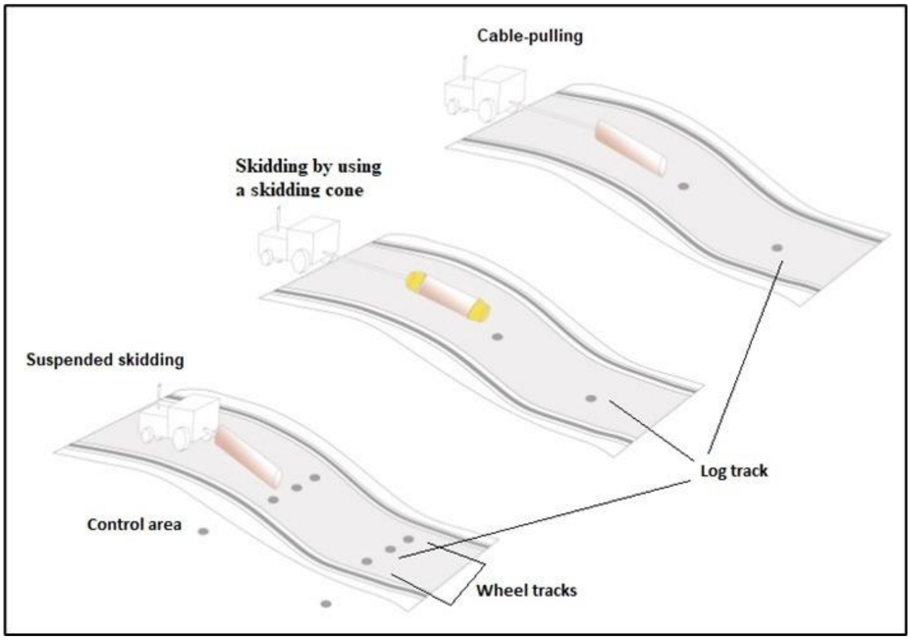

Fig. 2. Schematic representation of the three timber harvesting techniques

The techniques were used in young and mature black pine stands situated on 0 to 20% (S1), 20% to 33% (S2), and > 33% slope (S3) according to IUFRO slope classes. The characteristics of the study sites are shown in Table 1. With the SS technique, the skidding operations cannot be used over the S3 class. For that, the SS technique was only used for the S1 and S2 slope classes. The CP technique can be used over the slopes of 20%. Therefore, the CP was only used for the S2 and S3 slope classes. The SC technique can be used for slope classes, so it was used for the S1, S2, and S3 slope classes.

Table 1. Characteristics of the Study Sites

Timber Harvesting Technique	Stand Age	Slope Class (%)
No timber harvesting undisturbed sites (C)	Young Mature	S1, S2, and S3 S1, S2, and S3
Suspending skidding (SS)	Young Mature	S1, S2 S1, S2
Cable pulling (CP)	Young Mature	S2, S3 S2, S3
Skidding by using a skidding cone (SC)	Young Mature	S1, S2, and S3 S1, S2, and S3

The timber harvesting operations were applied in six lines that were parallel to each other, and there was at least one tree length among them (Fig. 2). The lengths and diameters of the logs were measured using meters and diameter gauges. At least 10 log passes were made uphill on each skidding trail in the fields. Before the timber harvesting operations were started, soil respiration, temperature, and humidity were measured at two different points in the undisturbed sites of the six different study plots. A total of 24 soil measurements (2 stand age × 3 slope classes × 2 different point × 2 replicates) were obtained for the undisturbed site (Fig. 3).

Soil respiration (CO_2), moisture content, and temperature were measured on the six lines and two different points on the post-skidding trail with two replicates on 1st, 5th, and 10th days, and after 6 months. The skidding operations were carried out in May, June (1st, 5th, and 10th day), and November (6th month).

After the timber harvesting operations, a total of 32 soil respirations were measured for the SS technique, 16 for the CP technique and 24 for the SC technique (Fig. 3). Including the undisturbed site measurements, a total of 96 soil respiration measurements were carried out in the field.

(a) (b) (c)

Fig. 3. Soil respirations were carried out in the undisturbed sites (a) and after the timber harvesting operations (b); The skid trails scarified the soil surface (c)

Fig. 4. LI-8100 LICOR was used to measure soil respiration on the skidding trail

The soil respiration was measured using the LI-8100 console (Li-Cor, Inc.; Lincoln, NE, USA) in conjunction with an 11-cm diameter and 5-cm-high CO_2 flow hood, specifically designed to be positioned directly on the soil (Fig. 4). This apparatus was used to determine soil respiration, with measurements of the CO_2 generated at soil surfaces using a portable gas analyzer (Li-Cor, Inc.; Lincoln, NE, USA). The chamber was pressed approximately 3 cm below the soil surface to prevent air leaks. The changes in CO_2 concentration were then determined in 2 min measurements. Measurements were taken between 10:00 and 15:00 in each study area. CO_2 values were expressed as µmol m^{-2} s^{-1}. At the same time as measuring soil respiration, soil temperature and moisture were also recorded using an Li-8100-201 thermo probe and a moisture probe placed at a depth of 10 cm close to the soil respiration chamber.

Statistical Analyses

A three-way ANOVA (analysis of variance) was used to determine the effects of stand age and slope classes on soil respiration, temperature, and moisture content after the timber harvesting techniques in relation to time (1st, 5th, 10th days, and 6th month). The Tukey test was utilized to identify combinations exhibiting significant discrepancies at the $P < 0.05$ significance level. Subsequently, ANOVA (one-way ANOVA) was employed to ascertain the disparity in the impact of disparate compartmentalization techniques on the time-dependent alterations on soil respiration values across areas exhibiting comparable land characteristics. The interrelationships between soil respiration, temperature, and moisture were evaluated using Pearson correlation test. All statistical computations were carried out using the SPSS version 20 software (SPSS Inc, Chicago Illinois, USA).

RESULTS

Variation in soil respiration of young and mature stands with time after the timber harvesting techniques on the S1 slope are shown in Fig. 5. In the young stands, on the 1st day measurements, the SC had the highest soil respiration (20.8 µmol m^{-2} s^{-1}), followed by SS-log track (11.1 µmol m^{-2} s^{-1}), the undisturbed site (9.7 µmol m^{-2} s^{-1}), and the SS-wheel track (9.6 µmol m^{-2} s^{-1}), which were similar to each other. In the mature stands, all timber harvesting techniques and undisturbed site showed lower soil respiration than in the young stands. The undisturbed site had the highest soil respiration (12.0 µmol m^{-2} s^{-1}), followed by the SC (10.7 µmol m^{-2} s^{-1}), SS-log track (9.6 µmol m^{-2} s^{-1}), and SS-wheel track (8.8 µmol m^{-2} s^{-1}).

On the 5th day measurements, both in the young and mature stands, the soil respiration showed a sharp decrease. In the young stands, SS-log track and SC techniques had similar soil respiration, but the undisturbed site and SS- wheel track had different; 3.94 µmol m^{-2} s^{-1} for the SS-lock track and 3.59 µmol m^{-2} s^{-1} for the SC, 2.81 µmol m^{-2} s^{-1} for the undisturbed site, and 1.47 µmol m^{-2} s^{-1} for the SS-wheel track. In the mature stands, however, the undisturbed sites had the highest (5.4 µmol m^{-2} s^{-1}) soil respiration compared to all timber harvesting techniques, which were similar to each other (about average 1.77 µmol m^{-2} s^{-1}).

On the 10th day, both in young and mature stands, soil respiration had an increase for all timber harvesting techniques and the undisturbed sites, except for the SS-log track technique in the mature stands. In the young stands, the SC had the highest soil respiration (9.04 µmol m^{-2} s^{-1}, followed by SS- log track (5.60 µmol m^{-2} s^{-1}) and undisturbed site

(3.93 µmol m^{-2} s^{-1}) and SS-wheel track (3.52 µmol m^{-2} s^{-1}), while in the mature stands, soil respiration was highest for the SS-wheel track (7 µmol m^{-2} s^{-1}), followed by undisturbed site (6.03 µmol m^{-2} s^{-1}), SC (2.77 µmol m^{-2} s^{-1}), and SS-log track (0.93 µmol m^{-2} s^{-1}).

After 6 months, there was again a sharp decrease in soil respiration both in young and mature stands for all timber harvesting techniques and undisturbed site, which were similar to each other.

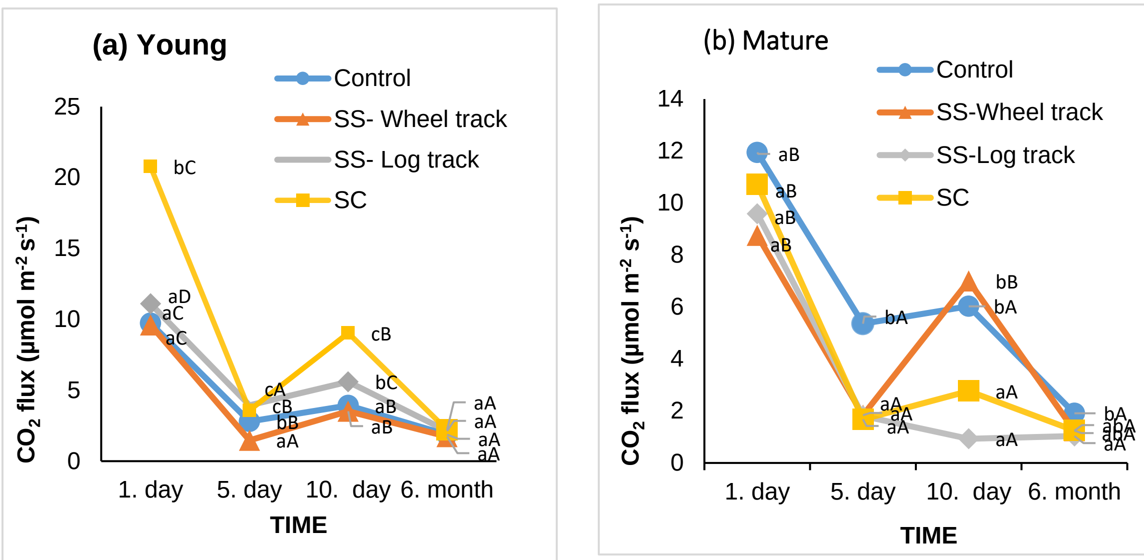

Fig. 5. Variation in soil respiration of young (a) and mature (b) stands with time after the timber harvesting techniques on the S1 slope. The different capital letters show that soil respiration varied significantly with time, while the different small letters show that soil respiration varied significantly among the timber harvesting techniques and undisturbed site on each time.

Variation in soil respiration of young and mature stands with time after the timber harvesting techniques on the S2 slope is shown in Fig. 6. In the young stands, on the 1st day measurements, the undisturbed site had the highest soil respiration (10.3 µmol m^{-2} s^{-1}), followed by the SS-wheel track (9 µmol m^{-2} s^{-1}), SC (8.23 µmol m^{-2} s^{-1}), CP (7.47 µmol m^{-2} s^{-1}), and SS-log track (6.59 µmol m^{-2} s^{-1}). In the mature stands, all timber harvesting techniques showed higher soil respiration than in the young stands. The SC had the highest soil respiration (14.3 µmol m^{-2} s^{-1}), followed by the CP (10.7 µmol m^{-2} s^{-1}), undisturbed site (10.6 µmol m^{-2} s^{-1}), SS-log track (9.75 µmol m^{-2} s^{-1}), and SS-wheel track (9.42 µmol m^{-2} s^{-1}).

On the 5th day measurements, both in the young and mature stands, the soil respiration showed a sharp decrease. In the young stands, all timber harvesting techniques and undisturbed site had similar soil respiration; 5.08 µmol m^{-2} s^{-1} for CP, 3.69 µmol m^{-2} s^{-1} for the SS-wheel track, 3.35 µmol m^{-2} s^{-1} for the SC and 2.895 µmol m^{-2} s^{-1} for the undisturbed site, and 1.75 µmol m^{-2} s^{-1} for the SS-log track. In the mature stands, however, the SS-log track had the lowest (1.02 µmol m^{-2} s^{-1}) soil respiration compared to all timber harvesting techniques, followed by undisturbed site (3.7 µmol m^{-2} s^{-1}), SC (3.24 µmol m^{-2} s^{-1}), the SS-wheel track (3.08 µmol m^{-2} s^{-1}), and CP (2.68 µmol m^{-2} s^{-1}).

On the tenth day, in young stands soil respiration had a decrease for all timber harvesting techniques with the exception of the undisturbed site (3.85 µmol m^{-2} s^{-1}), while soil respiration had an increase for all timber harvesting techniques in the mature stands.

In the young stands, the SS-log track (1.62 μmol m⁻² s⁻¹) was lower than all techniques, followed by SS-wheel track (2.92 μmol m⁻² s⁻¹), SC (2.93 μmol m⁻² s⁻¹), and CP (2.96 μmol m⁻² s⁻¹), which were similar to each other. In the mature stands, soil respiration was highest for the CP (11.8 μmol m⁻² s⁻¹). The SC (7.04 μmol m⁻² s⁻¹), SS-wheel track (5.43 μmol m⁻² s⁻¹), undisturbed site (4.03 μmol m⁻² s⁻¹), and SS-Log track (2.26 μmol m⁻² s⁻¹) were similar to each other.

After the 6 months, there were decreases in the young stands, but the undisturbed site was higher than all timber harvesting techniques. In mature stands, there was a sharp decrease in soil respiration for all timber harvesting techniques and the undisturbed sites.

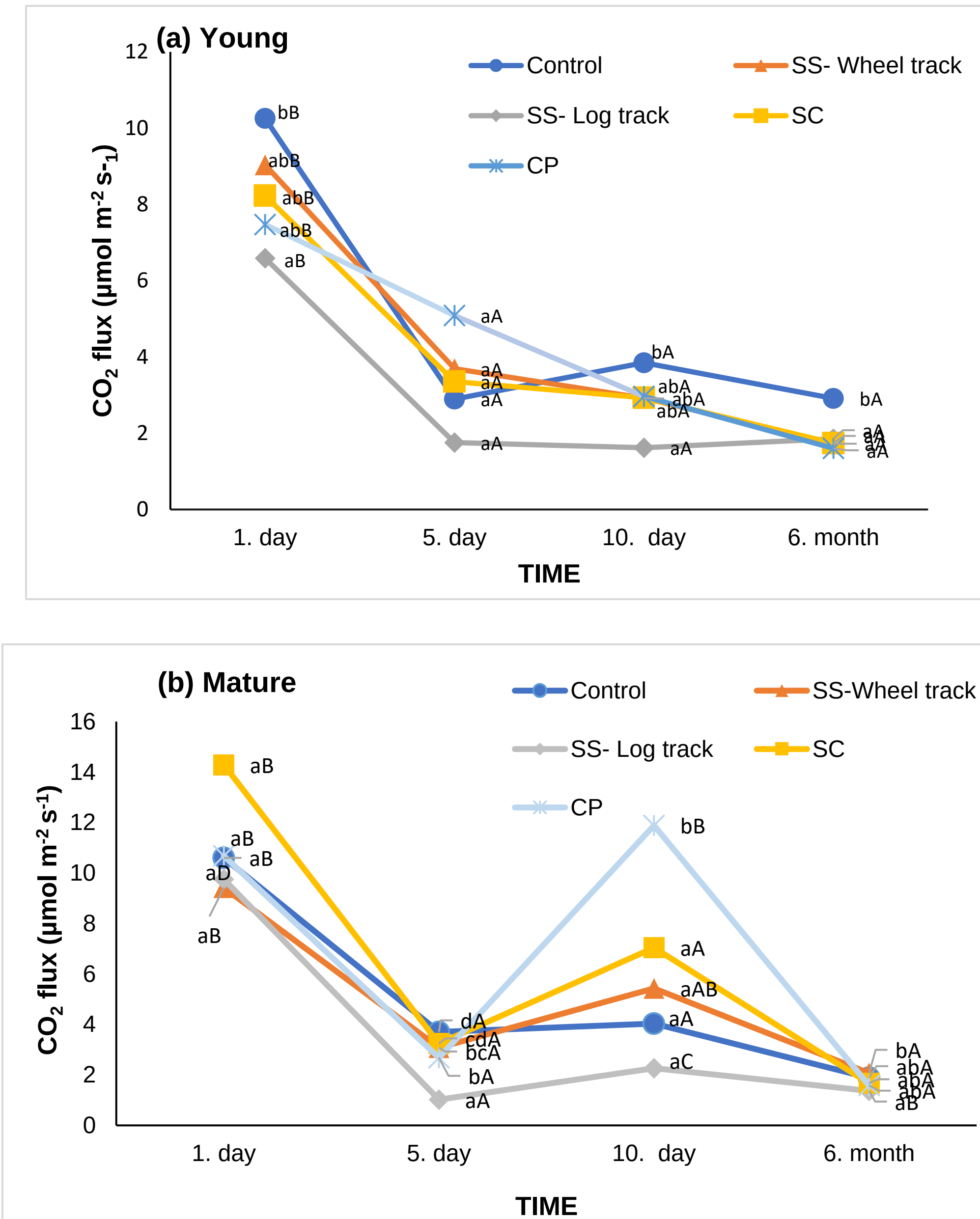

Fig. 6. Variation in soil respiration of young (a) and mature (b) stands with time after the timber harvesting techniques on the S2 slope. The different capital letters show that soil respiration varied significantly with time, while the different small letters show that soil respiration varied significantly among the timber harvesting techniques and undisturbed site on each time.

Variation in soil respiration of young and mature stands with time after the timber harvesting techniques on the S3 slope are shown in Fig. 7. In the young stands, on the first day measurements, the SC had the highest soil respiration (11.3 µmol m^{-2} s^{-1}), followed by the undisturbed site (8.53 µmol m^{-2} s^{-1}) and the CP (5.34 µmol m^{-2} s^{-1}), which was the lowest. In the mature stands, the undisturbed site showed higher soil respiration than in the young stands while both techniques had lower soil respiration than in the mature stand. The undisturbed site (9.70 µmol m^{-2} s^{-1}) and SC (8.42 µmol m^{-2} s^{-1}) had higher soil respiration than CP (5.12 µmol m^{-2} s^{-1}) for the mature stands.

On the 5^{th} day measurements, both in the young and mature stands, the soil respiration showed a decrease. In the young stands, all timber harvesting techniques and undisturbed site had similar soil respiration, 3.67 µmol m^{-2} s^{-1} for the undisturbed site, 4.39 µmol m^{-2} s^{-1} for the SC, 2.94 µmol m^{-2} s^{-1} for the CP. However, in the mature stands, the undisturbed sites had the highest soil respiration (6.64 µmol m^{-2} s^{-1}) followed by SC (3.81 µmol m^{-2} s^{-1}) and CP (1.47 µmol m^{-2} s^{-1}).

On the 10^{th} day, both in young and mature stands, CP had an increase while SC had a decrease. In the young stands, the CP (3.37 µmol m^{-2} s^{-1}) and undisturbed site (3.77 µmol m^{-2} s^{-1}) had higher soil respiration than SC (1.38 µmol m^{-2} s^{-1}), while in the mature stands, soil respiration was highest for the undisturbed site (4.68 µmol m^{-2} s^{-1}) followed by SC (3.39 µmol m^{-2} s^{-1}) and CP (3.15 µmol m^{-2} s^{-1}), which were similar to each other.

After the 6 months, there were a small decrease in soil respiration both in young and mature stands for all timber harvesting techniques and the undisturbed site, except for SC in the young stands.

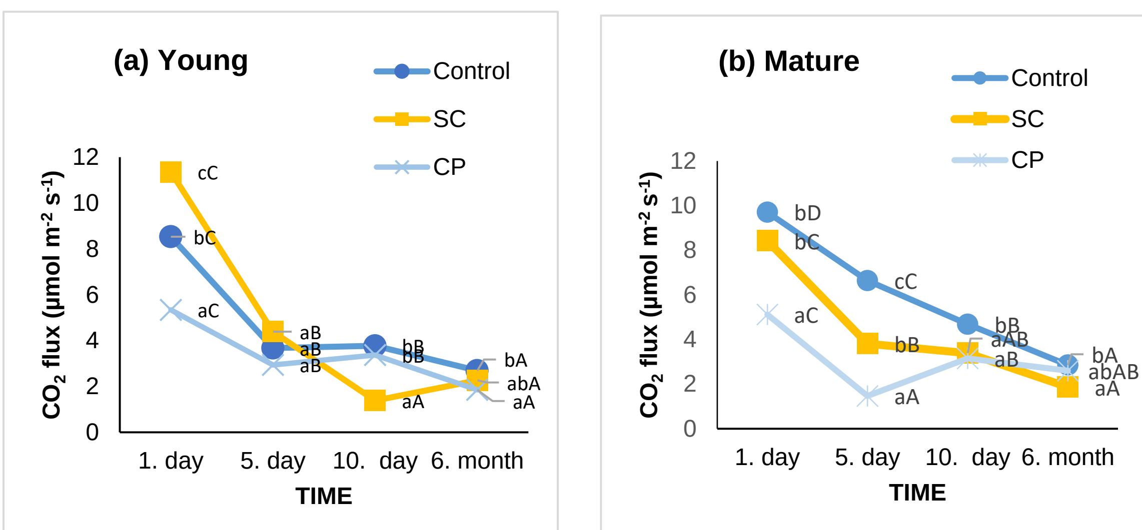

Fig. 7. Variation in soil respiration of young (a) and mature (b) stands with time after the timber harvesting techniques on the S3 slope. The different capital letters show that soil respiration varied significantly with time, while the different small letters show that soil respiration varied significantly among the timber harvesting techniques and undisturbed site on each time.

Table 2 shows the mean, F-values, and differences in soil respiration between stand ages, slopes, and timber harvesting techniques at 1^{st}, 5^{th}, and 10^{th} days, and after 6 months. Soil respiration shows statistical differences depending on time in young and mature stands. Similarly, it was determined that the difference between the techniques applied at the time of measuring soil respiration was statistically significant ($P < 0.05$) (Table 2).

Table 2. Three-way ANOVA Comparison of Soil Respiration for Stand Ages According to Timber Harvesting Techniques, Slope Class, and Measurement Time

Source of Variance	Soil Respiration					
	Young			Mature		
	df	F	P	df	MS	P
Technique	4	27,605***	0.000	4	32.896***	0.000
Slope	2	56.858***	0.000	2	30.542***	0.001
Day	3	516.214***	0.000	3	523.959***	0.000
Technique * Slope	5	33.968***	0.000	5	23.330***	0.000
Technique * Day	12	12.709***	0.000	12	18.759***	0.000
Slope * Day	6	25.043***	0.000	6	22.148***	0.000
Technique * Slope * Day	15	10.873***	0.000	15	5.704 ns	0.161
Error	142	2.297		144	4.113	

There was no significant difference between the 5th day and the 10th day of soil respirations, while there was a significant difference between the other days in young stands. In mature stands there was a significant difference between all measurement times (Table 3).

Table 3. Soil Respiration Variable According to Measurement Times

	Young			
Measurement Times	1st day	5th day	10th day	6 months
1.day	-	***	***	***
5.days	***	-	ns	***
10.days	***	ns	-	***
6.months	***	***	***	-
	Mature			
	1st day	5th day	10th day	6 months
1.day	-	***	***	***
5.days	***	-	***	*
10.days	***	***	-	***
6.months	***	*	***	-

It was determined that there was a significant difference between the slope classes with the exceptions of S2 and S3 in young stands. However, in mature stands there was only a significant difference between S2 and S3 while there was no difference between the other slope classes (Table 4).

Table 4. Soil Respiration Variable According to Slope Classes

Young			
Slope Classes	S1	S2	S3
S1	-	***	***
S2	***	-	ns
S3	***	ns	-
Mature			

Slope Classes	S1	S2	S3
S1	-	ns	ns
S2	ns	-	*
S3	ns	*	-

The influence of moisture and temperature on soil respiration was evaluated by Pearson correlation analysis (Table 5). The correlation test results indicated no significant relationship between soil respiration and temperature at the 95% confidence level for the young and mature stands ($P > 0.05$). However, a significant relationship existed between soil respiration and soil moisture for both stands at the 95% confidence level ($P < 0.05$).

Table 5. Pearson Correlation Results Showing the Relationship Between Soil Respiration, Temperature, and Humidity for Stand Ages

	Variables	Soil Respiration	Soil Temperature	Soil Moisture
Young	Soil Respiration	1	0.025	0.524**
	Soil Temperature	0.025	1	0.053
	Soil Moisture	0.524**	0.053	1
Mature	Soil Respiration	1	0.124	0.453**
	Soil Temperature	0.124	1	0.013
	Soil Moisture	0.453**	0.013	1

** The correlation is significant at the 0.01 ($P < 0.01$) significance level
* The correlation is significant at the 0.05 ($P < 0.05$) significance level

DISCUSSION

Mean soil respiration values in the current study ranged between 1.87 and 12 µmol m^{-2} s^{-1} in the undisturbed sites. After the timber harvesting, mean soil respiration values differed between 0.93 and 20.8 µmol m^{-2} s^{-1} during a 6-month period. These results indicated that the values in the young *Pinus nigra* stands were higher than in the mature *Pinus nigra* stands, both in the undisturbed sites and after the timber harvesting. The highest respiration value was seen with the SC method in the young stands, while the lowest respiration value was found with the CP and SS methods in the mature stands.

Shabaga *et al*. (2015) found that carbon emission was between 1.1 and 1.9 µmol m^{-2} s^{-1} at the undisturbed sites in mixed coniferous forests and ranged from 1.5 to 3.5 µmol m^{-2} s^{-1} after the timber harvesting. A similar study conducted by Čater and Simončič (2021) for beech, spruce, and fir forests showed that soil CO_2 flux in the undisturbed sites ranged between 4.9 and 8.6 µmol m^{-2} s^{-1}. They noted that mean soil respiration on the harvested area was in all cases higher than the undisturbed site during the whole period. However, they found that the differences between the harvested area and the undisturbed sites gradually decreased over time. When the stands were compared among the different dominant species, the highest soil respiration values were seen in beech stands.

Bereczki *et al*. (2024) compared the soil respiration values between young and middle-aged oak stands, and they concluded that respiration values varied between 0.6 and 1.0 µmol m^{-2} s^{-1} in the young stands, and between 0.58 and 1.31 µmol m^{-2} s^{-1} in the middle-aged stands. They stated that the middle-aged oak stands had higher respiration values than young oak stands.

It is concluded that the differences between the results of soil respiration values could be attributed to the differences in tree species, slope classes, stand age, timber harvesting methods, measurement time, and climate variability.

In this study, generally, mean soil respiration values decreased over time in all timber harvesting techniques applied in the young and mature stands. The lowest respiration values were seen on the 6th month. The SC technique in the young stands showed the highest soil respiration value on the slope classes indicating that the cone placed on the head of the log during the skidding operations with a cone does not deform the soil and instead results in a softer drift by ventilating the soil. Xu *et al*. (2011) noted that soil respiration declined post-harvest but showed signs of recovery in areas with less intensive harvesting methods over a five-year period.

In the mature stands, all timber harvesting techniques and undisturbed showed lower soil respiration than in the young stands on the S1 slope, whereas on the S2 slope, mean soil respiration was higher in the mature stands and no differences between the young and mature stands on the S3 slope. In contrast to the young stands, the undisturbed stands had the highest soil respiration. Similarly, Allman *et al*. (2016) found that CO_2 concentration was high in the undisturbed stand.

Babur and Dindaroğlu (2020) found a significant decrease in microbial biomass with the loss of organic carbon in the soils of the skidded areas. They attributed this decrease to the loss of organic matter and moisture in the soil, which are the most critical parameters for the life of soil microorganisms. It is shown that microbial respiration can directly influence the growth and development of all plants in terrestrial ecosystems, as it affects all soil organic matter and other microbial parameters (Winding *et al.* 2005; Riutta *et al*. 2021; Mahmoodi *et al*. 2023). Similarly, Naghdi *et al*. (2015) emphasized that equipment type, traffic intensity, and slope gradient had strong effects on the physical properties of the soil. In the S1 and S3 slope class, the SC technique increased soil respiration compared to the undisturbed group on 1st day. However, when the soil respiration values after the 6 months were analyzed, it is evident that there was no significant difference between the undisturbed group and the techniques. In the S2 slope class, all techniques exhibited a reduction in soil respiration values compared to the undisturbed group. It was noted that respiratory values tended to increase towards the 10th day, but again decreased and reached the lowest level on the 6th month.

It was seen that the soil respiration values of the undisturbed group were higher than those of the other techniques after removing the S1 and S3 slope classes in the mature stand age. This indicated that the soil respiration decreased due to the interventions, with the decrease continuing for the 1st and 5th day. Towards the 10th day, the soil respiration slightly increased, yet soil respiration values reached their lowest point after the 6th month. While there was no difference between the respiration values on the 1st and 10th days in all of the techniques, the homogeneous group exhibited the lowest respiration values on the 5th day and 6th month. In the S2 slope class, while the SC technique demonstrated an increase in soil respiration values on the 1st day of the removal process, no significant difference was found between the undisturbed and other techniques. A decline in soil respiration values was seen from the 5th day onwards in all removal techniques, with an increase in respiration values observed from the 10th day onwards. At the end of the 6th month, the soil respiration values decreased and reached the lowest level compared to the 1st day. After 6 months, it was noted that there was no statistically significant difference between the undisturbed group and the timber harvesting technique groups. Similarly, Yashiro *et al*. (2008) reported no change in the amount of CO_2 after one year the harvesting operation.

Among the various environmental factors, soil moisture has been shown to influence soil biological activity (Setälä *et al*. 2023). As evidenced by production studies, Nilsen and Strand (2008) showed that soil compaction influenced soil respiration by directly affecting soil moisture, temperature, biomass, and stand cover. Makineci *et al*. (2007) found that the moisture content values were 21.2% in the skidding road and 27.2% in the undisturbed site. Similar to the current results, previous studies indicated that soil compaction increased and soil moisture values decreased when samples from skidding trails were compared with those from undisturbed sites (Croke *et al*. 2001; Demir *et al*. 2007; Kiumarsi *et al*. 2024). The current study demonstrated that the variations in soil moisture resulting from timber harvesting operations impact soil respiration values. In a study conducted in a beech forest by Coletta *et al*. (2017), soil respiration rates were measured under different harvesting methods. The innovative method resulted in a soil respiration rate of approximately 5.62 μmol m^{-2} s^{-1} immediately after harvesting, while traditional methods showed a rate of 4.53 μmol m^{-2} s^{-1}. This suggests that innovative techniques may temporarily enhance soil respiration compared to traditional methods.

It is considered that the results of this study will enable correct decisions to be made in determining the timber harvesting technique suitable for the technical structure of the land and it can make great contributions to the popularization of the use of the appropriate technique in skidding operations for Turkish forestry. It will be an exemplary application for sensitive forestry studies by determining area-appropriate techniques that will reduce the damage to the ecosystem due to timber harvesting works.

This study, which is considered to be an exemplary application for sensitive forestry studies, can contribute to many scientific studies in the field of forestry within the scope of environmental sensitivities by revealing the effect on soil respiration by applying different skidding operations. Considering these precisions, the use of skidding cones in skidding operations will be beneficial for the implementation of environmentally friendly forestry operations.

CONCLUSIONS

1. In forestry, the harvesting of timber was found to profoundly impact soil quality. The effect appeared to be mainly related to compaction. Thus, soil respiration (CO_2 flux), which is sensitive to compaction, can be employed as a crucial criterion for assessing soil quality. On the other hand, it was possible to observe some variations in soil respiration values with the measurement time, as daily changes in air or soil temperature and moisture can have a significant impact on CO_2 emissions from soil microorganisms and roots. Daily variations in temperature and moisture during the measurement periods may cause significant fluctuations in soil respiration.
2. Based on 6^{th} month respiration values, the use of skidding cones (SC) in areas has a positive effect by increasing the soil respiration, so the SC technique is generally the recommended technique. However, the suspended skidding (SS) and cable-pulling (CP) without cones techniques increase soil compaction and result in a decrease in soil respiration. Therefore, it is concluded that they are not suitable for the timber harvesting in the black pine stands as the resulting deformation causes the soil quality to decrease.

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