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The Potential Ecological Effects of Forest Harvesting on Forest Soil

Uğur Kezik* and H.Hulusi Acar
Karadeniz Technical University, Faculty of Forestry, Trabzon, Turkey

Abstract

In the last century, economic function of the forests was the main goal of forest management and wood raw material was the primary product that potentially provides the highest economic income. However, nowadays forests are considered as multipurpose resources that have ecological, economic, and social functions. Concerning this fact, ecosystem-based management plan, as a tool of sustainable forest management approach, widely implemented in both global and regional scale. The extraction stage of wood raw material may result in serious environmental impacts especially damages on forest soil if harvesting operations are not properly planned. Thus, the negative effects of forest harvesting on forest soil should be carefully considered in planning phase. In this study, the ecological impacts of forest harvesting were examined in a variety of forest ecosystems. Soil compaction and soil quality loss, as the most important indicators of soil disturbance caused by logging equipment, were assessed based on a literature review. Besides, some solutions are presented in order to minimize negative effects of forest harvesting on forest soil.

Keywords: Forest harvesting, Logging operations, Environmental impacts, Soil compaction, Soil quality loss

1. Introduction

The soil, which constitutes the most important component of the terrestrial ecosystems, houses different biomass and enormous types of living organisms. For instance, in one gram of forest soil, twenty thousands of soil organisms can be housed (Osman, 2013). Even more important, soil directly or indirectly provides nutrient and habitat for the all living organisms on the earth (Figure 1).

The soil in the forest ecosystems is crucial material for all of the existing organisms in terms of production of wood raw material and the environmental quality. Hence, the forest soils constitute the core of the whole forest ecosystem. There are long lasting complicated relationships and interactions between the trees and animals, microorganisms and microbial community in soil. Therefore, soils in forested areas have different structures and functions than that of agricultural lands (Fisher and Binkley, 2000).

Edaphic factors stand out among the factors which have their own structure and function and provide living environment for forests and constitutes the forest ecosystems simultaneously. While researching about the parameters of the soil involved in the edaphic factors, it is also important to research how the quality condition from the environmental factors and accordingly the health of the ecosystem are affected. This is required to understand the structure and component of the forest ecosystems for better analysis.

During the extraction of wood raw materials, different harvesting methods are being used in forestry. Depending on a general evaluation, the harvesting method is defined as "the whole of procedures which indicate which operations will be conducted in turn after the trees are cut and fell and which technology will be used for these operations" (Erdas et al., 2014). Commonly, there are three harvesting methods including: cut-to-length method, whole stem method, and whole tree method. In all of these production methods, processes of cutting-felling-bucking-skidding are performed and these methods have an environmental and ecological effect value. Also, methods employed for extracting the product out of the harvesting unit after cutting and felling have a significant importance on the degrees of the environmental damages. Generally, ground based methods are mainly used to transport timber after cutting and felling stages. In the ground based methods, machines, human and animal power are used separately or they are used in combination.

*Corresponding author: Tel: +90 4623774129 E-mail: kezik@ktu.edu.tr
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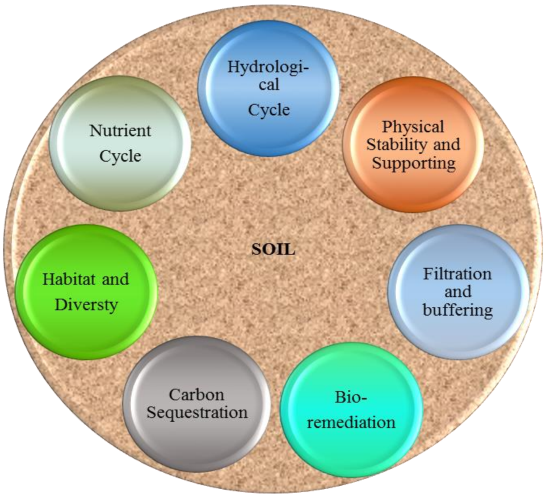

Figure 1. Fundamental soil functions in forest ecosystems

2. Soil Compaction and Soil Quality Loss

In management of forest resources, silvicultural treatments such as thinning selective cutting, etc. potentially improve the forest health and reduce the disease and fire risk together in forested areas. However, if these activities are not properly planned they may cause serious environmental damages on the soil surface and affect the soil quality which is very important for long term health of the forest ecosystem.

2.1. Soil Compaction

Compaction of the soil is defined as the increase of soil bulk density and the decrease of the total macroporosity due to being pressed of the soil particles on the surface under the pressure. In basic expression, it means the condensement of the soil depending on passing of people and animals, vehicle traffic and the weights of the skidding logs (Kimble et al., 2003).

The soil can be compacted due to the weight applied to the soil during the extraction of wood raw material. The risk of compaction of the soil increases depending on the intensity of the activities in the forest ecosystems. The areas exposed to severe amount of compaction are stabilized roads, log skidding routes, and other areas having heavy vehicle traffic. Every type of silvicultural activity and harvesting works which require continuous mechanical logging potentially cause severe amount of soil compaction. The severity of compaction due to logging can change depending on many factors (Lull, 1959):

- The type of the equipment (i.e. tracked or wheeled vehicles), attachments (i.e. cutting knife, grader knife) and tire pressure (3-10 psi or more).
- The area that negatively affected by the logging operations (10%-50% of the total area) and the depth of soil failure.
- Frequency of traffic on a particular area (it can be 10 and 20 times on some areas).
- The texture of the soil and its moisture content.

In forest ecosystems, together with the compaction of the soil, the physiological behaviors of the residual trees can change and their atmospheric CO_2 sequestration capacity can also decrease. This directly reflects the biomass productivity of the trees (Figure 2). This issue is especially important in terms of wealth, increment and annual allowable cut which are very crucial for management and planning of forest ecosystems. In fact, the event of soil compaction appears to be the most important ecosystem health indicator which regulates the relation of soil-plant-atmosphere and affects them seriously.

2.2. Soil Quality

The concept of improving the soil quality has been first suggested by Warken and Fletcher (1977) and then many studies have been conducted until today (Larson and Pierce, 1994; Allan et al., 1995; Carter et al., 1997; Karlen et al., 1997; Nortcliff, 2002). Even though the concept of the soil quality differ according to the service and product provided by the soil, in general, it is defined as "the biomass producing ability of the soil in unit area" (Ford, 1983).

From another view point, the soil quality is actually a reflection of the ideal concept of the soil for plant development. The ideal soil consists of 25% air, 25% water, 45% inorganic matter and 5% organic matter (SSS, 1975). As much as these ratios change, the physical quality indicators will change and accordingly, the chemical and biological quality indicators of the soil will also be affected. Consequently, the physiological activities in the plants (Rapport et al., 1998) are used as indicators in assessment of the forest ecosystems health.

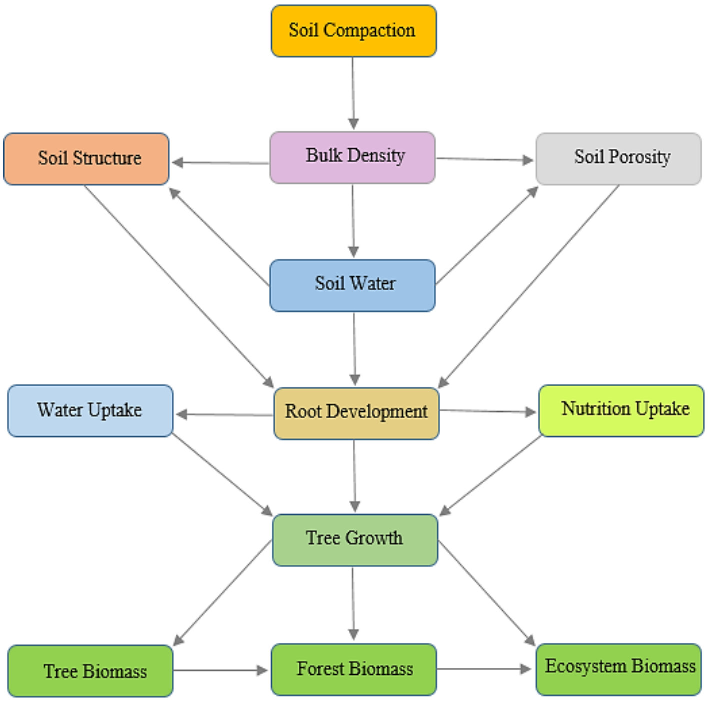

Figure 2. Soil compaction at ecosystem level (Modified from Burger et al., 2010)

In some studies, the term "site index" has been used instead of the term "soil quality" (Kimble et al., 2003). However, site index includes not only the soil parameters, but also the ecological factors such as climate, topography, hydrology and geology. Also, in assessing the site index, ecological factors including climate, land structure, soil and vegetation are definitely important factors. Furthermore, Leininger (1998) has reported that temperature and drought really significantly affect the physiological processes in plants and the fertility of the forest. These parameters are the most important functions of the soil quality;

- To ensure growth and development of plant roots,
- To allow water to pass, be retentioned and transferred to plants,
- To provide the gas change between the soil and atmosphere and allow aeration
- To increase the biodiversity in terms of the soil flora and fauna diversity and activity,
- To arrange the carbon dynamics and to increase carbon sequestration in the soil

Furthermore, the physical quality indicators of soil are given in Table 1 which indicates the effects of physical indicator on soil properties and functions. However, when there is compacted soil, the important indicators of soil quality are; texture, bulk density, soil strength, and wilting point (Da Silva et al., 1994). There is a tight relation between growing of the root and soil strength quality (Sands et al., 1979; Powers et al., 1998). Singh et al. (1992) suggested using "tilth index" which is a factor affecting the growing of the root; and they report that soil qualities affecting tilth index, bulk density, strength, aggregation, soil organic matter content and plastic index are included.

3. Forest Harvesting Effects on Forest Soil

3.1. The Physical Effects of Compaction

There are many studies conducted based on the fact that apart from the effects derived from fire and other nature events in the forest ecosystems, forestry activities such as silvicultural activities and logging operations affect the physical quality of the soil, especially by increasing the bulk density, which causes soil compaction. The primary elements among the other ones causing compaction are equipment and vehicles. In the production phase, by removing the forest products mechanically from the forest stand, the bulk density of the soil can suddenly increase, the total macro pores, which is one of the most important indicators of the physical quality of the soil decreases and its infiltration capacity drops down, and that can increase the surface runoff and erosion.

In the harvesting activities in Canada Boreal forests, it has been reported that logging operations increase the soil bulk density, decrease the infiltration capacity and accelerate erosion (Stratsev and McNabb, 2000). In South America, in pine ecosystems, on the logging route, the bulk density of the soil has increased and hydraulic conductivity and macro porosity have decreased (Aust et al., 1995). In addition, it is reported that other activities like pasturage in the forest cause the soil to be compacted. In Pinus concorto ecosystems, due to animal pasturage, the bulk density of the soil has increased by 6% (Krzic et al., 1999). Apart from logging operations, another factor causing the soil to be compacted is fire. After fires, an environment which pulls water (hydrophobic) appears on the top soil. This reduces infiltration and can suddenly change the water holding feature of the soil (Ghuman et al., 1991).

The tonnage of the equipment used in the phases of the wood production in the forest ecosystems and the degree of pressure applied on the soil by these equipment indicate the degree of the damage given to the structure of the soil. During the logging, on the area where there was vehicle traffic, especially on the top mineral soil (0-30 cm), bulk density has increased from 21% to 76% and water holding capacity together with the ratio of infiltration have significantly decreased (Cullen et al., 1991). Although operations of removing logs from the stand manually affects the soil less than mechanical way, it can cause serious damages in the soil. It has been reported that on the logging/skidding route bulk density has decreased from 15% to 20% and recovery has taken long time (Geist et. al., 1989).

Table 1. Some soil physical quality indicators (Kimble, 2003)

Soil Properties and Functions	Physical Quality Indicators of Soil
Soil Structure	Aggregation, average aggregate diameter, bulk density, resistance to compressive, porosity, pore size distribution.
Soil Water	Available water capacity, water infiltration rate, permeability.
Water Balance	The rate and amount of surface flow, subsurface flow, water retention in the soil, water deficit budget.
Soil Temperature	Energy budget, heat capacity, heat conduction, daily and seasonal changes, buffering depth.
Root Growth	Bulk density, porosity, soil depth, horizonation, wilting point.
Soil, Against the Traffic Condition	Texture, soil cohesion, water holding capacity, water infiltration rate.
Soil Erosion	Texture, structure, organic matter content of soil, water infiltration rate, surface runoff coefficient, permeability.

Akay et al. (2007) conducted a study where the soil compaction was estimated by measuring the values of soil strength and bulk density during timber extraction with a rubber-tired skidder. In order to reduce soil compaction, the effects of woody slash materials (logging residuals) and other slash treatments (chip and sawdust) was investigated by considering the numbers of vehicle trips (1, 5, and 10 trips) and two soil depth classes (10 cm and 20 cm). They reported that soil strength and bulk density markedly increased as the number of trips increased. Besides, logging residuals distributed over the skid trail generally provided better soil support capacity than that of other slash treatments.

While the change of the bulk density together with the compaction of the soil and the duration of other qualities' getting affected by this condition vary among ecosystems, we see that the most important factor is the soil structure. For instance, in natural oak forests, the negative effect of the logging route on the soil bulk density did not disappear even for 4 years (Reisinger et al., 1992). In other words, although 4 years passed, the soil structure is still damaged. Moreover, it has been reported that the physical quality of the soil is more negatively affected during the period when the soil is wet than the period it is dry (Ghuman and Lal, 1992).

On the other hand, as the soil moisture content reaches the field capacity value, it will have more potential for the compaction. Simmons and Pope (1988) have reported that as the wet soil gets compacted, the bulk density suddenly increase and in another study, it is stated that if that happens due to heavy machinery, the effect of the compaction can last for decades (Froehlich and McNabb, 1984). Light machines used surely will cause less damage in the soil. If it is required to use heavy vehicles, they must be used when the soil moisture is suitable.

3.2. The Ecophysiological Effects of Soil Compaction

The compaction of the soil caused by harvesting machinery generates important changes in the soil structure and moisture condition (Standish et al., 1988; Neruda et al., 2008). When the bulk density increases, the infiltration of the water in the soil and the soil porosity tend to decrease and all physiological features in the plant are affected negatively (Figure 3).

A high bulk density can prevent the roots from development by decreasing the porosity and water holding capacity (Gebauer and Martinková, 2005). Compaction of soil usually occurs in first 30 cm soil layer, and this is the zone where the plant root biomass is most dense (Sands and Bowen, 1978; Kozlowski, 1999). Previous study indicated that when a tractor was used in logging operations, the bulk density of the top soil increased from 41% to 52% ratio (Kozlowski, 1999). On the forwarder line, the bulk density of the top soil (0-10 cm) increases from 15% to 60% ratio while it increases from 25% to 88% when forwarder is combined with harvester (Lousier, 1990).

Although many forest tree species develop taproot, the fact that the soil bulk density and high soil dependence negatively affect biomass production potential along with root development and physiological activities (Figure 3). This is supported by the studies conducted in different regions of the world and different forest ecosystems. In Pinus radiata forests, as the soil strength increases, growing of root is affected negatively (Zou et al., 2001). In Pinus teada forests, there is a relation among bulk density and aeration and fertility (Kelting et al., 1999). In other words, in case of both increasing and decreasing of bulk density, soil compaction value be chanced and the organic matter production capacity of the trees in this ecosystem can be limited accordingly. In Duglas fir and Veymut pine forests, as the bulk density of the soil increases, root volume in compacted soil decreases (Page-Dunroese et al., 2000).

In Duglas fir, Sitka spruce, and Tsuga forests, the compaction along with the increased bulk density of the soil reduces the height growth and volume increment by 20% (Miller et al., 1996).

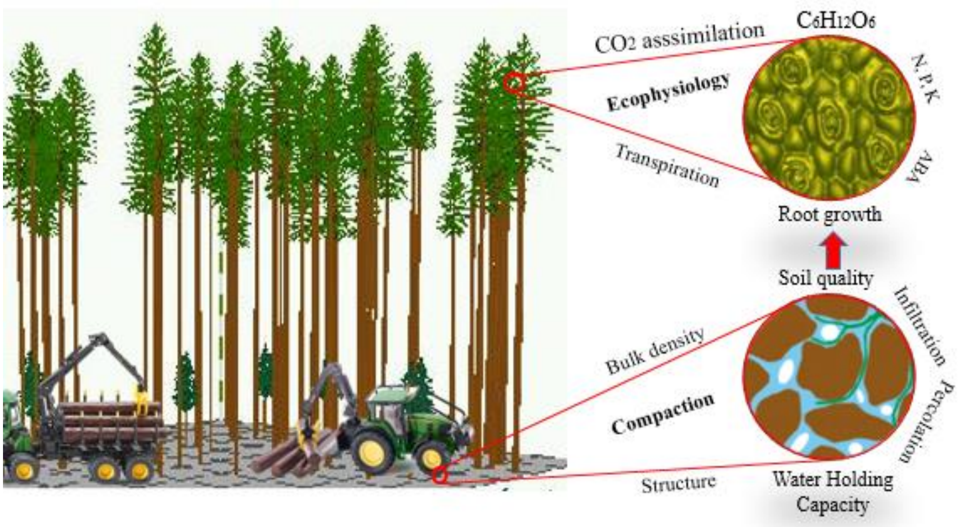

Figure 3. Soil compaction and ecophysiological relations during the forest harvesting

In Pinus elliotti forests, severe compaction reduces growth rate by reducing the soil quality (Fox, 2000). In harvesting area located in forests formed of Spruce and broadleaves as logging route and the soil quality below the road have changed, composition of species and the amount have been affected (Grigal, 2000). In Aspen stands, as the soil bulk density decreases, biomass on the soil and the number of the new shoots decrease (Stone and Elioof, 1988; Corn and Maymard, 1998). In Spruce forests in Down Boreal zone, compaction has affected soil air composition. As the compaction has increased, the amount of CO_2 increases in the soil and this decreases the nutrient uptake of the plants (Conlin and Van den Driessche, 2000). In Pine forest ecosystems, along with the rubber tired vehicles used on the logging route, the bulk density of the soil increases from 8% to 11% ratio, the soil strength increases at 69% ratio (Brais and Camire, 1998). In clear cutting area in mixed forests, soil quality and soil organic carbon are affected negatively by soil compaction (Pennock and Van Kessel, 1997). As compaction in Pinus teada stand affects bulk density, penetration resistance and CO_2 concentration, root growing decreases from 6 MPa to 8 MPa pressure of the soil (Conlin and Van den Driessche, 2000). Simmons and Pope (1988) conducted a study which demonstrated that compaction suddenly decreased root growing on the stands of Lridendron tulipifera and Liquidambar styracilue. Moreover, among many soil type and tree species, it is seen that soil bulk density is a limiting parameter. This limiting effect of bulk density is usually higher on the coarse textured or sandy soils than on fine textured and clay soils. Critical bulk density value ranges between 1.2 g/cm^3 and 1.4 g/cm^3. If these values are exceeded, root growth decreases in many soil types (Lousier, 1990).

In terms of root development, there is a strong relation between soil bulk density and soil moisture content. The negative effect of the high bulk density increases in low soil moisture (Waisel et al., 1996). However, as long as the soil moisture content is sufficient, roots grow well in a wide range of bulk density (Kozlowski, 1968; Sutton, 1991). In return, drought stress can encourage the development of deep root system in search of water under the soil (Steinbrenner and Rediske, 1964).

Compaction of soil affects carbon which is sequestrated on top of the soil and under the soil. There are not enough studies addressing this issue. Long lasting soil compaction can negatively affect both biomass and soil organic carbon pool. In the short term, as the amount of soil increases in unit area, density of soil organic carbon can increase along with compaction.

Mostly, extreme soil compaction reduces nutrition uptake, especially N, P, and K, which are taken by roots (Kozlowski and Pallardy, 1997). Soil compaction also affects the development and function of mycorrhizas by affecting the structure (Entry e. al., 2002), which can cause a change in the levels of stress hormones such as ABA and Etilen (Kozlowski, 1999). Also, it was reported that compaction significantly affects leaf water potential and photosynthesis parameters (Alameda and Villar, 2012). In another study, it was stated that compaction reduces topsoil biomass and leaf area index (Coder, 2000). By causing hypoxia, soil compaction limits the activity of aerobic microorganisms and increases their denitrification. The respiration of the plant roots is reduced by compaction and it gets harder to provide the required energy for the nutrient uptake (Kozlowski and Pallardy, 1997).

3.3. The Effects of Logging on Soil Quality Loss

Grigal (2000) defines the forest productivity as a component of the soil fertility, climate, the amount of the variety of the species and stand background. From a practical point of view, it can also be named as the total of these individual land elements which constitute the forest stands. From a wider point of view, it includes functions such as the soil quality, the maintenance of the animal health, the cycle of plant nutrient elements, the potential of carbon sequestration, percolation of rain water and the arrangement of the hydrological cycle together with acting as a buffer against acidity (Doran and Parkin, 1994; 1996; Karlen et al., 1997). Considering these points of views, the soil quality has a significant importance in a forest ecosystem.

It is reported that the logging operations in the forest directly affect many parameters in the ecosystem such as vegetation, the chemistry of the soil, the physical qualities of the soil, the soil microbial community together with ground water and main stream water (Vitousek, 1981; Hornbeck and Kropelin, 1982; Dahlgren and Driscoll, 1994). In addition, while the change of these components has negative effect on the seedling just arriving at the site, it can also badly affect the living organisms in the aquatic ecosystems which are fed from the production areas. Also, the effects of forest harvesting on the vegetation, soil, soil microbial community, relations between soil and water, chemistry of ground water, and aquatic ecosystem are commonly used as indicators of the production of a wood on the health of the ecosystem (McHale et al., 2008).

In long run, heavy harvesting machinery such as skidders, harvesters, forwarders, combined harvesting machines can change the fertility power of the habitat by affecting the physical, chemical and biological qualities of the soil in a negative way (Osman, 2013). This especially causes the top soil to be carried with its organic matter and the soil to get compacted (Hu et al., 2014). The compaction of the soil harms the soil ecosystem by changing the physical, chemical and biological qualities of the soil and it can cause ecological, physiological, and pathological problems on the seedling and residual trees (Vasiliauskas, 2001; Holdenrieder et al., 2004; Ticktin, 2004; Akay et al., 2006;Unver and Acar, 2009; Tavankari et al., 2013).

4. Results and Discussion

Forestry activities in forest ecosystems, especially the production and silvicultural activities have negative effects on the air which is the most important component of the forest soil via compaction. The bulk density of the soil appears to be one of the most important parameters which regulate most of the physical, chemical and biological processes of the soil and this directly affects the ecophysiological activities which are an indicator of the health condition of the forest ecosystems. Furthermore, as the productivity in unit area decrease, increment for forest ecosystems will decrease and annual allowable cut will also have to decrease. All of these processes will be reflected on the forest volume in unit area.

After detailed evaluations of the conducted studies, it has been concluded that equipment and vehicles used in forest ecosystems for production activities have important effects on the physical quality of the soil. A strong relation between the physical quality of the soil and forest productivity has appeared. Soil structure, especially its aggregation, is an important parameter of the physical quality of the soil. Soil structure is significantly affected by the forestry activities. Using heavy machines will increase the bulk density by causing a compressing in the soil. Nevertheless, the total macro-porosity of the soil will decrease. The total macro-porosity of the soil is the most important parameter which indicates the infiltration ratio of the soil (Kantarcı, 2000). As the total macroporosity decreases, the ratio of infiltration will decrease and surface runoff and erosion will increase. With the negative effect of compaction on the growing and development of plant roots, it will get harder for the roots to take water and nutrient. Furthermore, together with compaction, it has been reported that the chemical potential of the soil is significantly affected (Stepniewski et al., 1994). Soil compaction not only controls nutrient uptake via photosynthesis and water, but also modifies the edaphic environment.

Among the most important functions of the sustainable forest management, there are to minimize surface and subsoil soil compaction, reduce erosion, maintain the soil productivity, increase organic carbon of the soil and provide the nutrient cycle. In addition to increasing forest productivity, managing the compaction via enhancing the soil structure will also affect the dynamic of the organic carbon of the soil (Kimble et al., 2003). As the structure of the soil is enhanced, the organic carbon sequestration potential of the soil will increase. This will play an important role in reducing the atmospheric CO_2 which is the primary of the gases causing global warming and climate change.

Based on a general evaluation, the ideal bulk density of the soil for plant becomes 1.33 g/cm^3 (if 50% solid, 50% void). However, if this ratio is not achieved, plants will be negatively affected. Moreover, if such a critical point is arrived, the development of the plant roots will be limited after this point. This critical point depends on the soil structure. In clay soils, the normal bulk density varies from 1.0 g/cm^3 to 1.6 g/cm^3, whereas the critical point for the development of the root is ≥1.4 g/cm^3. In sandy soils, the normal bulk density is between 1.2 and 1.8 g/cm^3 and the critical value begins from ≥1.6 g/cm^3 (Aubertin and Kardos, 1965). Such that, in some soils, when the bulk density reaches 1.7 g/cm^3 there is no elongation of root (Andrews et. al., 1998). It was reported that the change in critical values based on soil structure depends on the ratio of total macro and micro pores (Kantarcı, 2000).

With the contemporary understanding of forestry, forest ecosystems have ecological, economic and social functions and they are tried to be managed with ecosystem-based plans in terms of sustainability principles. To fulfill the wood raw material need of the global industry, some part of the biomass constituted by the forests should be harvested annually. While there are many methods used for production in forests, we see that the most environmental damage is caused by logging and heavy vehicles used. These machines used in forestry cause the soil to be compacted and bring significant changes in the soil structure and moisture condition.

Soil is the most important parameter which regulates the water and mineral uptake for plants and temperature and most of the physiological activities in plants are controlled via this way. When the soil is compacted, the bulk density increases, porosity and infiltration of water decrease, erosion accelerates and all of these processes cause changes in the physiology of the plants and also soil microbial biomass affected by erosion (Kara et al., 2016). Therefore, photosynthesis and transpiration rate and uptake of nutrient and mycorrhiza and the change of plant hormones will be inevitable (Gebauer et al., 2012).

In most forest activities, the mineral top soil can cause significant environmental damage by being compacted. While soil compaction is affected by many factors derived from the inherent qualities of the soil (dimensions of the soil components and distribution, bulk density, pore condition, moisture content etc.), it is also heavily affected by external factors (production methods used, the density of production, land preparation etc.)

When the soil is compacted, the resistance in the soil increases, when this resistance is more than 2.0 MPa, in most plants the root elongation is limited (Gebauer et al., 2012). However, this condition may change depending on the structure of the soil. While this value may be over 4.0 MPa in coarse textured soils, in fine textured soils it can be 2.0 MPa. This can be explained by the ratio between the macro and micro pore volumes of the soil (Kantarcı, 2000).

4. Conclusions

As the need for the wood raw material increases each day, it has become mandatory to carry out timber extraction activities without damaging wood products as well as the forest ecosystem. However, unplanned logging activities potentially cause damages on forest ecosystem, especially on forest soil. Thus, negative environmental effects caused by logging activities must be minimized by implementing proper management strategies. For this purpose, the dynamics of forest soil and machine interaction must be well-known.

A ground cover (slash) layer should be used in order to reduce the impacts of ground-based logging equipment on forest soil. It has been proven that distributing the slash material on the logging trail decrease the ground pressure on the ground which leads to significant reduction on soil compaction. However, the effectiveness of slash layer can be reduced with number of trips during the machine traffic. Thus, density and quality of the slash material should be carefully determined to provide the soil with better support capacity. Besides, it should be paid strict attention to that the most forestry activities such as silvicultural and forest harvesting are to be conducted out of the vegetation period. This is very important in terms of the sustainability of forest ecosystem.

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