Revista Pădurilor 137(4) (2022) 001-048

Revista Pădurilor

available online at: www.revistapadurilor.com

IMPACT OF SKIDDING OPERATIONS ON FOREST SOILS: A NARRATIVE REVIEW

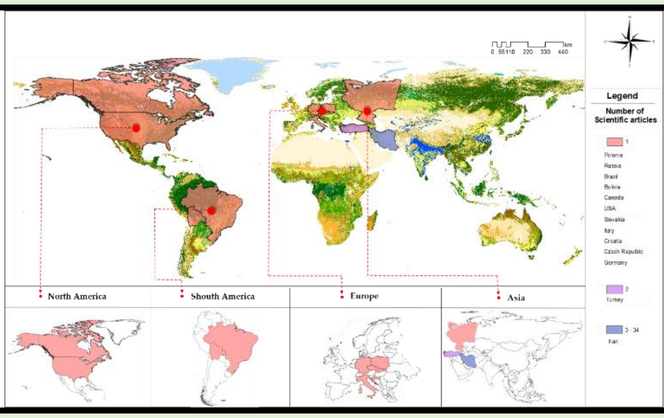
Monica Cecilia Zurita Vintimilla [a,*]

[a]**Department of Forest Engineering, Forest Management Planning and Terrestrial Measurements, Faculty of Silviculture and Forest Engineering, Transilvania University of Brașov, Şirul Beethoven 1, Brasov 500123, Romania, monica.zurita@unitbv.ro**

HIGHLIGHTS

- Machine traffic has a negative effect on soil's physical properties;
- Skidding operations contribute significantly to increased soil compaction and erosion;
- The study gives a synthesis of available knowledge on skidding operations and their impact on forest soils.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Manuscript received: 1 December 2022
Received in revised form: 16 December 2018
Accepted: 16 December 2022
Page count: 24 pages.

Article type:
Review

Editor: Stelian Alexandru Borz

Keywords:
Soil disturbance
Forest operations
Skidding
Soil
Impact
Review

ABSTRACT

Skidding operations contribute significantly to increased soil erosion which depends on the intensity of extraction. The purpose of this review was to identify the most significant information published by specialists in recent years, as well as to synthesize the available knowledge on skidding operations and their impact on the soil. The study was conducted based on available information for countries and locations around the world over a 35-year period (1986-2021). The literature review was based on the search for articles related to skidding operations. The bibliography and information were obtained from online sources and published research papers. The main terms used for the search were "skidding", "forest operation" and "soil disturbance". 22 variables characterizing the description, the study area, the structural parameters of the stand and the experimental variables, were frequently identified in the analyzed articles. Four variables were recorded in a range of 7 to 7.8%, such as type of machine, precipitation, disturbed bulk density, and soil texture. Future studies should consider variables related to the training, experience and expertise of equipment operators, which may be important. As most of the studies on soil impact focused on the physical properties of the soil, further studies should consider more the changes in biological and chemical composition of the soils.

* Corresponding author. Tel.: +40 720 671 052
E-mail address: monica.zurita@unitbv.ro

INTRODUCTION

Soil is a thin layer of material on the Earth's surface that governs mass and energy flow between the lithosphere, biosphere, hydrosphere, and atmosphere [1]. According to the Food and Agriculture Organization, soils hold approximately 70% of global biodiversity and the second largest carbon reservoir on the planet behind the oceans [2-3]. In forest ecosystems, soils are an important part of the natural environment and a key substrate for a variety of flora and fauna biological processes [4]. Soil degrades quickly as a nonrenewable resource, and its formation and regeneration are extremely slow [5]. Pervious research suggested that in forest ecosystems, soil degradation causes fauna and flora to be more vulnerable [6-7]. Soil disturbance is defined as the changes in the physical, chemical, and biological processes of the soil which are often interconnected [8].

Forest operations are the discipline of planning, implementation, management and continuous improvement of forest management systems [9-10]. It focuses on the rational use of forests with the aim of improving their regeneration, composition and development, as well as adapting their benefits to the societal needs [11]. When managed responsibly, logging has the potential to support local livelihoods, economic development, biodiversity conservation, and other vital services that forests provide such as protecting soils from erosion, regulating groundwater, protecting the soil from the effects of wind and frost, among others [12]. Unfortunately, in practice, most of the logging operations remain unplanned and cause impact to the forest soils [13].

For more than 70 years, several authors have studied how mechanized forestry operations affect the forest floor, as well as ways to mitigate these impacts and promote soil recovery after the operations [14-17]. Skidding operations contribute significantly to increasing the soil erosion [12], which mainly depends on the intensity of extraction and the degree of damage caused by harvesting techniques [18]. Among the negative impacts that directly affect the soil, the following are considered: sedimentation from erosion, excessive soil heating, reduction in structural stability, gradual decline in slope stability [19-21] and mainly the disturbance [12]. Soils with high organic matter content, low bulk density, low strength, and high porosity are prone to compaction [22-26]. Compaction reduces root penetration into the soil [27], growth and plant yield [28, 29]. Vehicle tracks have a negative effect on soil aeration, which makes it impossible for microorganisms to develop [30], resulting in decreased absorption of nutrients and water [31]. Soil's bulk density and porosity are the most direct quantitative measures of compaction and are widely used to indicate changes due to heavy mechanical traffic [26, 28, 32]. The quantification of damages to the soils produced by forest operations is essential to account for production parameters (economic aspects) and negative environmental impacts [16, 33]. Minimizing soil disturbance is currently one of the most important challenges for the forestry sector [34]. Soil disturbances occur when equipment and logs are moved on the ground or skid trails, causing changes in its structural characteristics [35-36] and productivity [37]. One of the main disturbances identified is soil compaction that affects long-term forest productivity [38]. The effects of compaction can persist in a forest for several decades [28, 37, 39], and problems related to soil disturbance have become a challenge faced by foresters, especially in mountainous forested regions [38].

The purpose of this review was to identify the most significant information published by specialists in recent years, as well as to synthesize the available knowledge on skidding operations and their impact on forest soils. The findings of this study may be useful in gaining a better understanding of the field's scientific achievements.

2. MATERIALS AND METHODS

This study is based mainly on the review of the literature on skidding operations, which allowed to know the current state on the subject in the research area and the advances made to date. The study was conducted based on information available for countries and locations all over the world covering a 35-year period (1986-2021). The literature review was based on searching papers that were related to the performance of skidding operations. This work used a narrative review approach that was developed based on a bibliographic review. The literature and information were obtained from online sources and research papers published in English and Spanish languages, such as Google Scholar, Web of Science, Scopus, and CABI, by using keywords and various combinations of them defined to search for articles relevant from the perspective of skidding operations **(Figure 1)**. The main terms used for the search were "skidding", "forest operation" and "soil disturbance".

3. RESULTS AND DISCUSSION

The use of keywords mentioned above, returned a total of 155 articles of which 67 in Google Scholar, 44 in Web of Science, 31 in Scopus, and 13 in CABI (as of December 20, 2021) (**Figure 1**). The articles were categorized into different topics: soil disturbance (with 43 articles), productivity (31), modeling (20), machinery (18), time consumption (14), ergonomics (7), roads (7), forest disturbance (4), skidding with animals (3), review (6), GHG emissions (1) and hydrology (1). Some articles were not included in this study for reasons related to downloading charges, registration of university users, etc., and also, when establishing the elimination criteria, presentations at conferences and duplicate articles were not taken into consideration. From the total of 155 articles collected, 34 articles were chosen that clearly fitted the review topic and met the selection criteria. The review focuses on the issues of soil disturbance, which were identified as the most studied topic and with the largest number of articles, in relation to skidding operations. The study focuses on identifying the effects that skidding operations produce on the morphology of the soil.

The information was organized in a Microsoft Excel ® sheet, by considering the reference, authors, article title, year, journal, country, month of study, study area in hectares, skidding distance, type of machine and harvesting system. Each skidding system has its own specific characteristics, depending on the natural and production conditions, the technology used and the proportion of manual operations in the general process [40]. A large number of factors influence the extent and severity of soil compaction [41]. In this bibliographic review, variables have been identified and collected for each study. To organize these variables, they were arranged into 4 groups:

1. Descriptive variables: study area, skidding distance, type of machine, method and harvesting system [42, 37];
2. Local variables: elevation, temperature, precipitation [43], slope [37], soil moisture, undisturbed bulk density, undisturbed porosity, disturbed bulk density, disturbed porosity and soil texture [37];
3. Stand structural parameters: stand density, forest age, tree diameter, tree height, species [44];
4. Experimental variables: number of plots and machine passes [37].

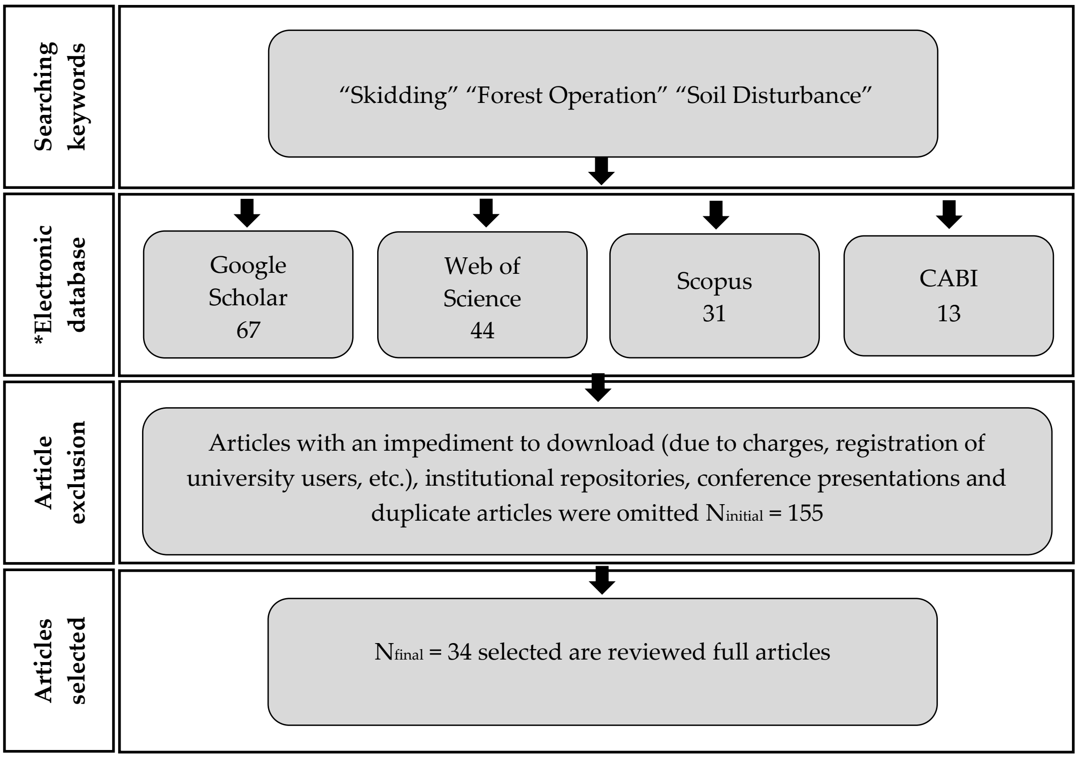


Figure 1. Flowchart of stages in the literature review process. Note: * The order of the databases presented is based on the number of publications.

The total number of articles taken into study was 34. However, in several articles it was found that various comparisons were made; some studies presented a number experimental circumstances giving in many cases more than one result which was considered a group in the analyzed data. As such, the results were considered by an individual analysis, which yielded 105 data groups with their specific variables. All data analyzes were done separately, regardless of the dependent and independent variables used. For example, some used soil disturbance in relation to soil type, slope, sample collection depending on the depth that was taken, number of passes the machine made along the trail, type of machine used etc. Also, due to reporting data standards, some of the results required conversions to provide a common point of comparison. Imperial to metric, as well as time and coordinate conversions, were among the necessary transformations.

The majority of the articles were published in peer-reviewed journals (155 references). There were also 15 oral presentations and three university publications. From all of them, 8.38% were published in Spanish and 96.61% in English. The journals with the highest number of publications were the *Croatian Journal of Forest Engineering* (29), *Journal of Forest Science* (16), *Forests* (6), *Northern Journal of Applied Forestry* (4) and *Journal of Forest Engineering* (4). In presenting the findings of the literature research, according to a simple chronology of the publications gathered, in line with the broad focus of the review, peer reviewed publications on skidding operations have steadily risen over the past two decades (**Figure 2**), in particular since 2007. The identification process returned a number of 155 studies for the period of 1986-2021. The average number of publications per year was 5.50, when calculated for the entire period.

It was found that studies related to skidding operations were on the rise in recent years. In relation to the subject, the first topic studied was focused on productivity and dates back to 1986, in which the time study methodology was applied to calculate production rates and the costs of thinning operations [44]. Productivity studies were more frequent in the period 1986-1999 [45-48]. In that period, currently active Journal of Forest Engineering and Northern Journal of Applied Forestry were the main publishing journals, with a total of 4 and 2 publications respectively. In 1990, the first article that analyzed soil disturbances was identified; this study evaluated the changes in the dry apparent density of the soil (dry unit weight) and evaluated the soil disturbance associated with the traffic of forest tractors with wide tires in five forest soils [49]. In the 2000-2005 period, the most studied topics were "time consumption" corresponding to 4 articles, "productivity" (2) and "soil disturbance" (3 references).

As shown in **Figure 2**, there was a growing trend in publications after the year 2006, with the highest number of articles in the year 2015. The research approaches were extended with topics such as ergonomics [50], roads [51], forest disturbance [52], GHG emissions [53], and hydrology [54]. This reflects the growing attention given to skidding operations and their impacts. However, in the period of 2006-2021, productivity, soil disturbances, modeling, machinery, and time composition remained the main research topics.

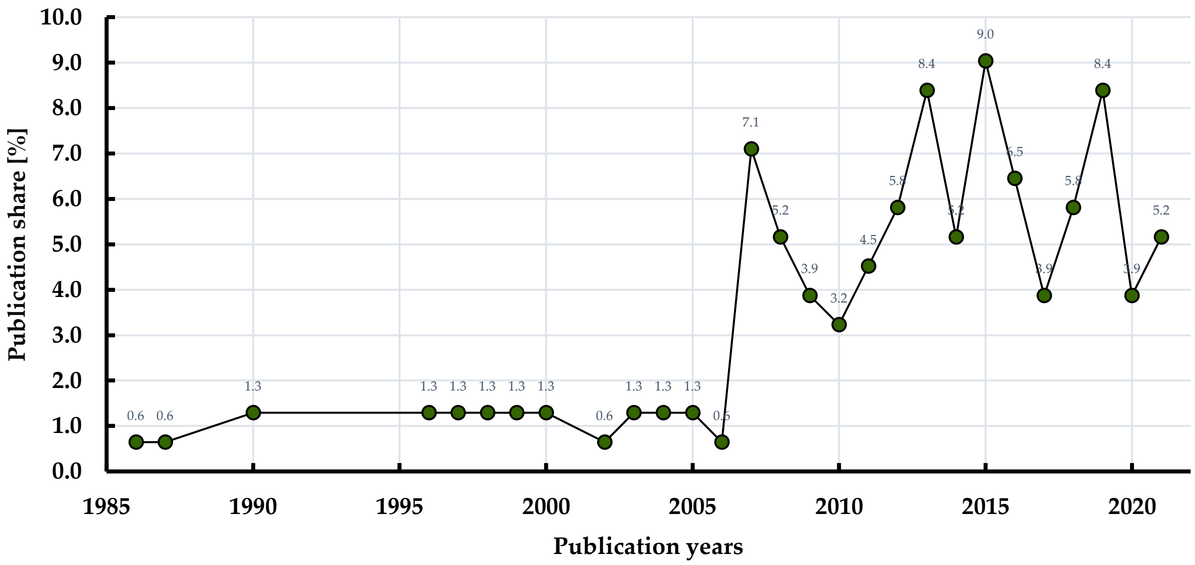


Figure 2. Peer-reviewed publications on skidding operations during the period 1986-2021, gathered from Google Scholar, Web of Science, Scopus and CABI.

Another important topic was the comparison between machines and animals (buffalo, oxen, mules, and horses) that carry out skidding operations. Most of the studies on this topic were found in Spanish-speaking countries: Mexico (2), Cuba (2), Costa Rica (1), Argentina (1) and Spain (1), representing 5.8% of the articles [55-60].

Figure 3 shows that in the period 2000-2005 there were 3 publications that referred to soil disturbances; it was the period with the least number of publications referring to the subject. From 2006, the number of publications begun to be constant at an average rate of 1.8 publications, and in the period of 2012-2015, there was the highest number of publications about the soil disturbances topic; 2015, for instance, with 5 articles, was the year with the highest number of articles published.

In relation to soil disturbance, a study was identified in 2000, in which Startsev & McNabb analyzed the effects of skidding on the infiltration properties of the surface soil. Common topics discussed relate to the effects of operations on soil properties by accounting for different slope levels and traffic frequency [29, 35, 37, 39, 42, 61-66]. Various research has looked at the relationship between soil disturbance and the number of loaded machine passes [67], as well as at comparisons between the effects of traditional (animals) and mechanical equipment [68, 32].

In terms of geographical origin, the articles came from four continents. More than half of the total were mainly concentrated in Asia with 68.06%, but although the Asian continent has a greater number of publications, only three countries contributed to this count (Iran, Turkey, and Russia), with Iran standing out with 21 studies. Europe accounted for 17.6% of the studies which were more diverse in terms of contributing countries (examples: Italy, Croatia, Poland, Slovakia, Germany, and the Czech Republic).

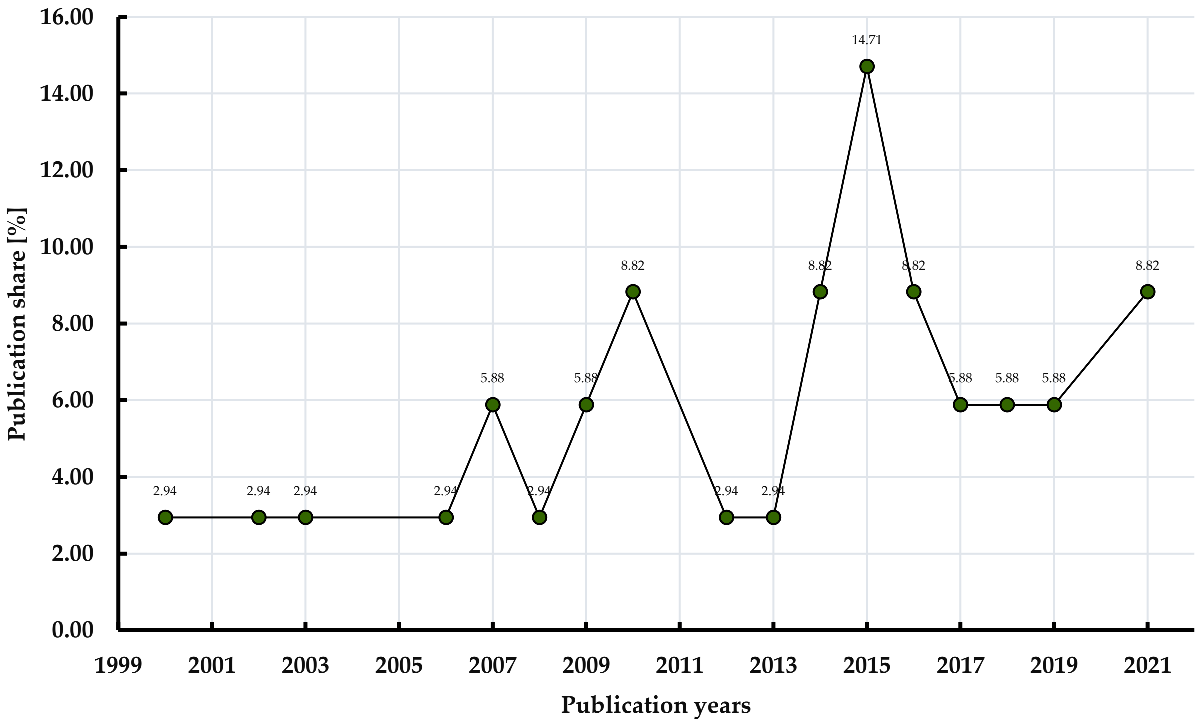


Figure 3. Peer-reviewed publications on soil disturbance during the period 1986-2021, collected from Google Scholar, Web of Science, Scopus and CABI.

In this bibliographic review, 34 scientific articles were analyzed, and in several of them, the authors made comparisons by considering various scenarios related to the type of soil, type of machinery and slope, among others; these factors were also considered in the present study. Having this in mind, 105 data groups were generated and taken into analysis, based on their study characteristics. As a result (**Figure 4**), it was identified that 55% of the data records relate to the variables in the study area, 19% to stand structural parameters, 17% to descriptive variables and 9.1% to experimental variables. In the study area, elevation, temperature, precipitation, slope, soil moisture, undisturbed bulk density, undisturbed porosity, disturbed bulk density, disturbed porosity, and soil texture were analyzed. They were the variables with the highest percentage due to the focus of the articles that analyze the soil disturbances.

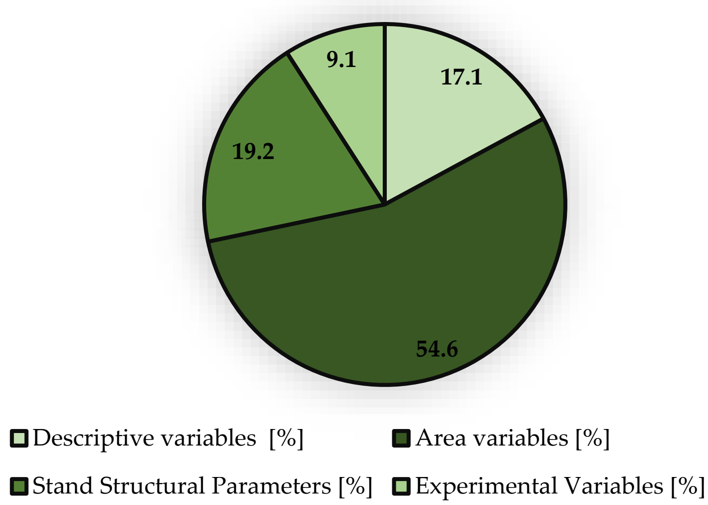


Figure 4. Share of the types of variables analyzed in the articles.

In fact, 22 variables characterizing the description, study area, stand structural parameters and experimental designs, were frequently identified in the articles taken into analysis. Four variables were recorded in a range of 7 to 7.8%, such as the type of machine, precipitation, disturbed bulk density, and soil texture. Considering the variables mostly recorded by the authors, these were the slope, species and number of machine passes (6 to 6.9%). Two variables that were also recorded with higher shares in the analyzed papers were the temperature and undisturbed bulk density, 5.4% and 5.2% respectively. The other variables accounted for shares of less than 5%.

The articles with the highest number of variables recorded were "*Effects of rubber-tired skidder and farm tractor on physical properties of soil in plantation areas in the north of Iran*" [69], "*Soil disturbance caused by different skidding methods in mountainous forests of Northern Iran*" [70] with a total of 18 variables identified per article, followed by articles that recorded 17 variables such as "*Effects of skidder passes and slope on soil disturbance in two soil water contents*" [65], "*Effects of ground-based skidding on soil physical properties in skid trail switchback*" [71], and 16 variables - "*Impact assessment of skidding extraction: effects on physical and chemical properties of forest soils and on maple seedling growing along the skid trail*" [72] and "*Soil compaction and porosity changes caused during the operation of Timberjack 450C skidder in northern Iran*" [73] (**Table A1**).

Study area represents the area in which the research was done and the data collection was carried out. Approximately 43% of the publications described the study area variable quantified in hectares, accounting for a total of ca. 128545 hectares. The maximum area taken into study was of approximately 54442 hectares.

Skidding trail (distance) is an important element of forest management, allowing harvested wood to be extracted [74-75]. A skid trail is defined as a strip of land within a stand, devoid of woody vegetation and undergrowth, with certain technical parameters; in some cases, its parameters were described to include slope lengths, cross slope, area, and radii of horizontal and vertical curves [66]. In forest stands, there is commonly a network of paths with a certain density resulting from the distance between them, which in turn is influenced by the way the forest is managed [74, 76-77]. It was identified that 11.4% of the articles taken into study recorded the distance on which the skidding was done; the minimum distance was 30 and the maximum 1300 m.

The use of machines was found to be the main cause of the soil compaction [78]. Skidders are widely used in mechanized harvesting operations generating impact on the soil's physical properties [65, 73]. However, each skidder model has different mechanical characteristics such as its mass [79]. Harvesters, skidders, and forwarders, which the modern forestry industry uses for mechanized harvesting operations, reach up to 45 tons and, when loaded, up to a maximum of 60 tons [80]. Machines for logging operations are almost constantly increasing in size and in terms of power and load capacity [81]. 93.3% of the papers taken into study recorded the type of machines used: Timberjack 450C was found in 47 data groups with a share of 48%, being followed by HSM 904 in 18 data groups, representing 18.4%. European studies considered machines such as HSM 805 HD (2 data groups), Timberjack 1110 8WD, SLKT 81, John Deere 548H and ECOTRAC 120 V. A North American paper analyzed the use of machines such as John Deere 648E, 748E, Timberjack 480B, 450C, Valmet 540, Timberjack 520A. In South America (Brazil) the use of a Caterpillar 525 machine was described in an article. Several Timberjack models were described as the studied machines: 450C, 1110 8WD, 460D, 480B, and 520A, which represented 55.1% of machines, followed by HSM 904 and 805 HD which represented 20.4%. Other machines with lower numbers of studies were TAF with 7.1%, John Deere 548H and 648E (6.1%), LTT 100A and 55A (5.1%), ECOTRAC 120 V (3.1%), Caterpillar 525 (2%) and SLKT 81 (1%) (**Figure 5**).

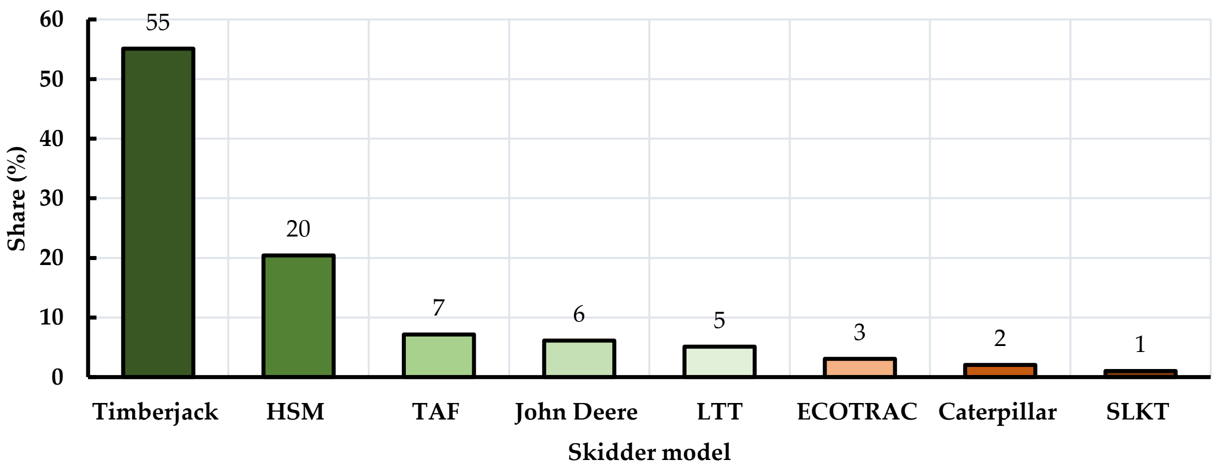


Figure 5. Models of skidders described by the papers taken into study.

Each skidder model has different mechanical characteristics [82], and several authors mention that these characteristics of the machines contribute to the generation of soil compaction [83-85]. However, in the analyzed articles, no information was recorded to specify other parameters such as acceleration, tire radius, length dimensions, width dimensions, height dimensions, operating weight, loaded travel speed, unloaded travel speed, load capacity, work schedule per day, and fuel consumption. Only two articles were identified that recorded information concerning the acceleration of machines.

In terms of harvesting systems, commercial forestry uses increased mechanization with heavy machines and high operational capacity for the extraction and transport of wood. In recent years, these vehicles have been improved [86] and became more powerful and cheaper [26]. A wide range of wheeled and tracked vehicles, such as harvesters, forwarders, skidders, were taken into study [16, 87, 88] and the dominant harvesting systems were described as fully mechanized (**Figure 6**). 28.6% of the articles recorded information on mechanized systems, 23 data groups recorded the use of semi-mechanized systems, which represents 79.3%, and there were 6 studies on fully mechanized systems, which represented 20.7%. Most of the harvesting operations were semi-mechanized, as chainsaws were used in several experimental studies, followed by mechanized extraction with different types tractors. Highly mechanized systems were not recorded in many cases because some studies were carried out in forests located in mountainous sites with steep slopes or in lowlands on clay soils [68].

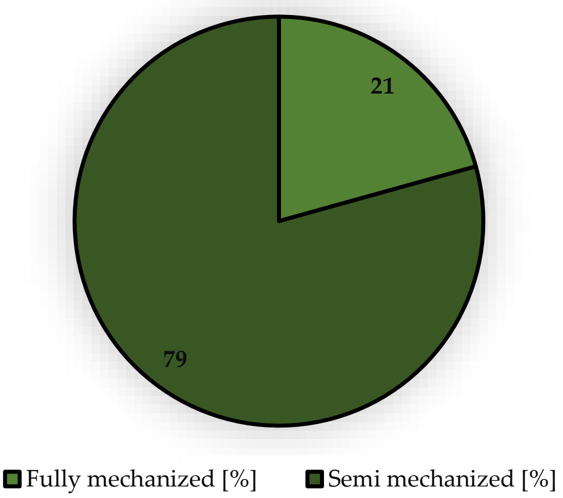


Figure 6. Share of papers taken into study by the described degree of mechanization.

Modern techniques have a major negative impact on forest ecosystems [16, 89-90]. The larger the cutting area, the greater its consequences for surrounding forest communities [91], and it can cause changes in the microclimate, composition, abundance and ecology of plants and animals [91]. The effect of selective logging is known to be much weaker than that of clearcutting [92]. There were two systems commonly described in forest utilization: individual selective logging, group selective logging, and in some cases the two can be combined in the same area [93]. Each system has its own specific characteristics, which depend on natural and production conditions, technology, and the proportion of manual operations in the overall process [40]. This study found that 27.6% of the articles collected information on the silvicultural system, where 16 data groups recorded that simple selective cutting was carried out and 13 group selective cutting.

The elevation of a geographic location represents the height above or below a fixed reference point, most commonly a reference geoid, which is a mathematical model of the Earth's sea level as an equipotential surface [94]. By this study, the minimum elevation was identified at 140, and the maximum at 1500 meters above sea level; 41.9% of the data used in this study described the elevation.

By the studied conditions, forest operations were more common in summer and autumn [68]. However, the fastest rate of soil recovery occurs in areas with cold winters and high rainfall, under humid conditions, where freeze-thaw cycles can loosen soil pores [95]. By this study, it was found that 64.8% of the publications collected information regarding temperature with a minimum of -5.4° and the maximum of 25°C. The studies were carried out mainly in the months of September, October, and November, in the Asian continent; in Iran, 7 studies collected information in this period, 5 studies collected information in the months of June, July and August, while in the case of Europe most of the studies collected data in the months of September, October, and November that belong to the autumn season (3 studies). Studies were found also in the winter, summer and spring seasons in Europe. In the articles from North and South America, no information was identified on the months in which the data collection was carried out.

Precipitation is used in meteorology to refer to all the phenomena of falling water from the sky in any form: rain, hail, snow, etc. Soil moisture content depends on the amount of precipitation. Increased amounts of precipitation can cause a significant decrease in resistance to soil penetration. Water weakens the bonds between particles and reduces internal friction by lubricating the particles, allowing the particles to slide together and compact by expelling air [67]. In the analysis of the articles it was observed that the use of tractors in the first thinning or the skidding of wood after heavy rains usually cause damage to the surface and properties of the soil [67]. The precipitation variable was recorded in 89.5% of the data groups; the lowest precipitation recorded was 10 mm and the highest 2070 mm.

Slope is the inclination of a linear, natural or constructive element with respect to the horizontal (0° or 180°) [96]. Identification and consideration of slope in planning forest operations and skid trails, in particular, can be an important measure in protecting soil resources [68]. The slope affects the physical properties of the soil [35]. Most soil damage occurs after few passes of a tractor, and particularly on steep slopes, the highest level of soil deterioration occurs [63-64, 97]. When a skidder passes more slowly due to slope steepness, the topsoil vibrates more and consequently becomes more compact compared to trails on gentler slopes [43]. Every effort should be made to avoid slopes more than 20% on skidding pathways [38]. According to this study, 75% of the examined articles described the slope variable, which had a range of values between -20 and 70%.

Soil moisture content is a value that characterizes the amount of water in the soil; it can be expressed as a percentage, water by weight or volume, or inches of water per foot of soil [98]. The movement of forest machinery on the soil surface causes changes in the chemical and physical composition of the soil [67]. Examination of the moisture content in soil is important to establish the limits for the use of harvesting and transport machinery in unfavorable conditions [67]. Studies have indicated that erosion damage is intensified if skidding operations take place when soil moisture is high [84, 99]. When the soil moisture content reaches or exceeds the critical value, it is advisable to prohibit all machinery traffic in forest stands [67]. In 47.6% of the papers, data on soil moisture were reported; the minimum and maximum values were 16 and 38%, respectively.

Soil compaction results in the increase in bulk density [37, 39]. The increase in apparent density is mainly due to soil slippage [78], and in the case of forest operations it happens when a machine passes only once on the skid trails [84]. In this study, it was identified that bulk density was one of the variables with the highest share reported in the reviewed papers; data was collected in undisturbed soils (before the operations) and disturbed soils (after the operations); the data with reference to undisturbed soils were lower compared to the disturbed ones, in the case of bulk density (g/cm^3) - 61.9% of the studies; the lowest value identified in the apparent density was 0.1 and the maximum value was 1.6 g/cm^3. For disturbed soils, the minimum bulk density was 0.1 and the maximum was 2.7 g/cm^3. It was one of the main variables analyzed in the studies, because they focused on the morphological change of the soil after the operations. A soil bulk density value between 1.40 and 1.55 g/cm^3 is considered to be at the critical level, where plant roots cannot penetrate light and medium textured soils [28]. Through this review, it was identified that 53 data groups presented a lower value compared to the aforementioned range, 27 data groups remained between these values but they represented a critical level for the soil, and a total of 11 data groups exceeded these values, with a gradual increase from 1.60 to 2.65 g/cm^3. Consequently, the bulk density exceeded the critical level, but not in most cases. Soil pore space refers to the percentage of the soil volume not occupied by solids; the soil volume is made up of 50% solid materials (45% minerals and 5% organic matter) and 50% pore space [100]. After skidding operations, soil compaction occurs, causing an increase in soil bulk density and a decrease in total porosity [87, 101]. Porosity is significantly affected by traffic intensity and slope gradient [35]. In the case of porosity of undisturbed soils, the minimum and maximum values reported were of approximately 37 and 95%, respectively; for soils with disturbances, the reported porosity was in the range of approximately 1-66%.

The soil is body formed by the interaction of five main elements: parent rock, climate, relief, living beings and time [102]. Soils can be divided into three types according to the predominance of the textural fraction they present, which can be: sandy soils, loamy soils, and clay soils [103]. Soil texture determines the susceptibility of a soil to erosion, since erosion rates can differ between various soil types under the same conditions of rainfall intensity, slope gradients, and amount of vegetation cover [71, 104]. Soil variations, related to timber harvesting operations, can generate changes in biogeochemical cycles that affect soil ecosystems [16]. The physical and also morphological properties of soils are severely altered at skid trails and loading sites [92]. 90.5% of the studies collected information regarding the soil texture; 61.7% of them identified clay-loams, 18.1% silt-loams, 5.3% loam-sands, 5.3% sand-loams soils, while 8.5% of the studies reported more than one type of soil (**Table 1**).

Stand density, represents the number of trees per area [105]. Density is a reliable indicator of the degree of occupation of trees in a specific place and time, and it is also one of the few variables that represent, in a simple and objective way, the structure of forests [106]. 41.9% of data records reported information related to stand density, with a minimum of 140 and a maximum of 169 trees per hectare. Within forest operations, the age of the forest is rather an unpredictable variable [38].

21% of the data records provided information related to the age of the stand, with a minimum of 17 and the maximum of 130 years. Tree diameter is the unit of measure that is calculated from a straight line that joins two points on a circumference, a closed curve or the surface of a sphere passing through its center [107]. Diameter at breast height, or DBH, is a standard measure of expressing the diameter of the trunk or bole of a standing tree [108]. DBH is one of the most common dendrometric measurements [109]. 43.8% of the data records contained information related to the diameter of the trees, with a minimum of 23.1 and a maximum of 135 cm. Tree height is a geometric variable that is used to determine the height of a tree [110]. This study identified that 43.8% of the data records contained information related to tree height, with a minimum of 22 and a maximum of 30.7 meters. 82.9% of the studies identified the species that were part of the skidding operations. 83 data groups described deciduous forests, 4 coniferous forests and 3 data groups recorded data from mixed forests. The main tree species that were identified in the data groups are given in **Figure 7**.

Table 1. Types of soils identified in the studies by the texture.

Soil texture	Number of studies	Share (%)
Silt loam	7	**18.1**
Sandy loam	6	**6.4**
Clay loam	8	**61.7**
Loamy sand	5	**5.3**
More than one soil type	8	**8.5**
Total	**34**	**100**

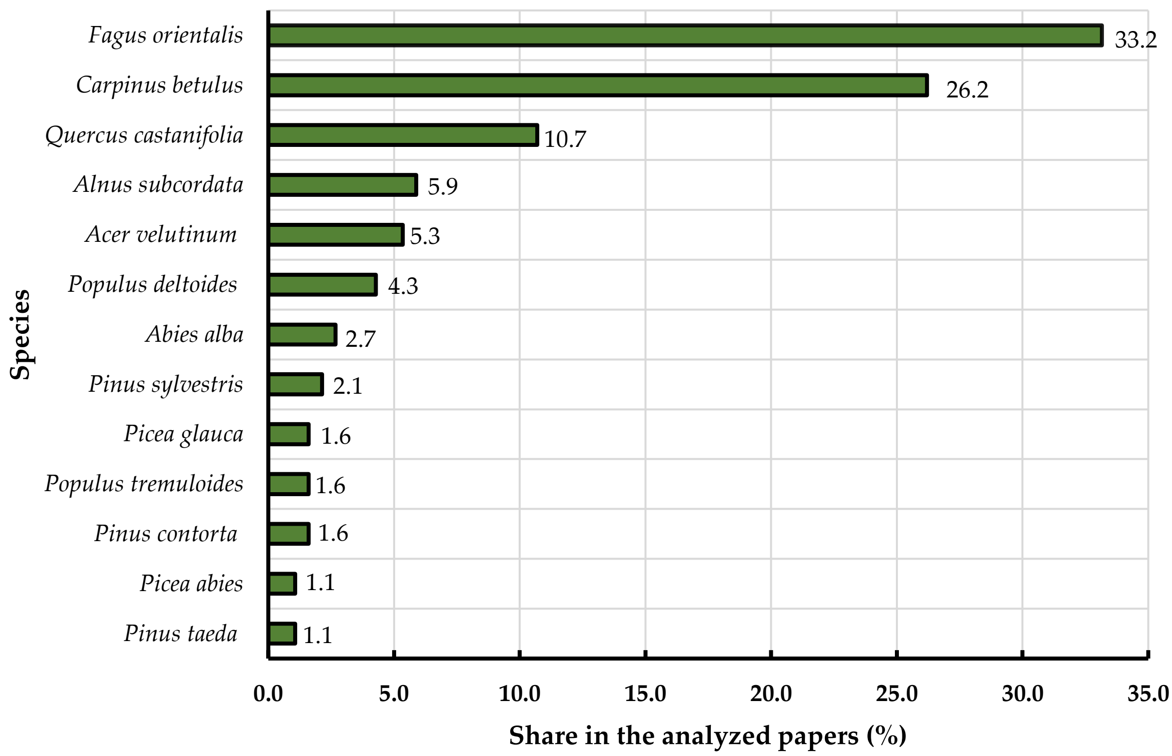


Figure 7. Tree species described by the analysed papers.

35% of the data described the variable on number of plots, with a minimum of 2 and a maximum of 94 plots. Number of machine passes represents the number of passes over the same ground [111]. The machine passes have an important influence on the structural characteristics of the soil, aeration and water balance and, therefore, can considerably affect the organisms, the development of the roots [65], and the increase of soil compaction [112]. The first pass of heavy forest machines over the forest floor surface causes significant structural changes in its upper layers. This can reach damaging levels with a detrimental effect that can last 30 years or more after extraction [8, 35, 113-114]. 73.3% of the studies recorded data related to the number of passes that machine had in a day/work cycle, since it is relevant when analyzing the compaction that occurs in the soil after skidding operations. The number of passes made by the machines and recorded by the analyzed papers reached to 40. In some studies data comparisons were made against noncompacted soil after each pass or at the end of the activity, to analyze the level of compaction produced.

The analysis of papers allowed to identify that precipitation and disturbed bulk density were the variables analyzed to a large extent which accounted for 89.5 and 86.7%, respectively. However, it is important to acknowledge that all the variables interact as well as they were analyzed according to the need of each study. Although the existing studies analyzed some variables more frequently, such as slope, number of machine passes, undisturbed bulk density, undisturbed porosity, disturbed bulk density, altered porosity, machinery, soil texture, etc., in some regions the applicability of their results is limited.

5. CONCLUSIONS

It is concluded that in the studies on soil disturbance in skidding operations, 4 types of variables were analyzed (descriptive, local, structural and experimental parameters), where the location variables were the most represented as a group (54.7%); however, the type of machinery, precipitation, disturbed bulk density and soil texture were the most collected data in the studies. It is recommended in future studies to consider variables related to the training, experience and expertise of equipment operators, which may be important factors to consider. It is also necessary to identify variables such as the number of cycles, the speed with which the machines are operated, the number of work cycles that are done per day and the time they take, the production per working day, which are also variables that would provide relevant information for soil disturbance studies. Most studies on soil compaction focused on the physical properties of the soil, therefore, further studies should consider more the changes in biological and chemical composition of the soils.

FUNDING

This work received no external funding.

CONFLICT OF INTEREST

The author declares no conflict of interest.

APPENDIX

Table A1. Scientific publications taken into study.

Paper No.	Authors	Year	Country	* Number of case studies	Variable type - Description	Variable type - Study Area	Variable type - Stand Structural Parameters	Variable type - Experimental	Number of variables recorded
1	Agherkakli et al.	2010	Iran	1	3	5	2	0	10
				2	3	5	2	0	10
2	Allman et al.	2015	Slovakia	3	3	8	2	0	13
				4	3	8	2	0	13
3	Borchert et al.	2015	Germany	5	3	7	4	1	15
				6	3	7	4	1	15
				7	3	7	4	1	15
				8	3	7	4	1	15
4	Demir et al.	2010	Turkey	9	1	7	4	0	12
				10	0	6	4	0	10
5	Ezzati et al.	2012	Iran	11	3	10	1	0	14
				12	3	10	1	0	14
				13	3	10	1	0	14
				14	3	10	1	0	14
6	Ilintsev et al.	2018	Russia	15	2	6	1	0	9
				16	2	6	1	0	9
7	Jamshidi et al.	2008	Iran	17	1	4	1	0	6
				18	1	4	1	0	6
				19	1	4	1	0	6
8	Jourgholami et al.	2014	Iran	20	3	5	1	1	10
				21	3	5	1	1	10
9	Majnounian & Jourgholami	2013	Iran	22	3	7	2	1	13
				23	3	7	2	1	13
				24	3	7	2	1	13
				25	3	7	2	1	13
10	Makineci et al.	2007	Turkey	26	1	6	4	0	11
				27	1	6	4	0	11
11	Modrý & Hubený	2003	Czech Republic	28	2	3	1	1	7
12	Naghdi & Solgi,	2014	Iran	29	1	10	4	2	17
				30	1	10	4	2	17
13	Naghdi et al.	2009	Iran	31	5	5	1	1	12
				32	5	5	1	1	12
14	Naghdi et al.	2015	Iran	33	3	9	4	2	18
				34	3	9	4	2	18
				35	3	9	4	2	18
15	Naghdi et al.	2016	Iran	36	2	5	4	2	13
				37	2	6	4	2	14
				38	2	6	4	2	14
				39	2	6	4	2	14
16	Najafi et al.	2009	Iran	40	1	7	4	2	14
				41	1	6	2	2	11
				42	1	6	2	2	11
				43	1	6	2	2	11
17	Najafi et al.	2010	Iran	44	1	5	1	1	8
				45	1	5	1	1	8
				46	1	5	1	1	8
				47	1	5	1	1	8
18	Nikooy et al.	2015	Iran	48	1	4	1	1	7
				49	1	4	0	1	6
				50	1	4	0	1	6
19	Proto et al.	2016	Italy	51	1	7	4	1	13
				52	1	9	4	1	15
				53	1	9	4	1	15
				54	1	9	4	1	15
				55	1	9	4	1	15
20	Solgi et al.	2015	Iran	56	3	8	2	1	14
				57	3	10	2	1	16
				58	3	10	2	1	16

Paper No.	Authors	Year	Country	* Number of case studies	Variable type - Description	Variable type - Study Area	Variable type - Stand Structural Parameters	Variable type - Experimental	Number of variables recorded
				59	3	10	2	1	16
				60	3	10	2	1	16
				61	1	5	3	1	10
				62	1	7	3	1	12
21	Solgi et al.	2016	Iran	63	1	7	3	1	12
				64	1	7	3	1	12
				65	1	7	3	1	12
				66	3	7	4	2	16
22	Solgi et al.	2017	Iran	67	3	9	4	2	18
				68	3	9	4	2	18
				69	3	6	4	2	15
23	Solgi et al.	2019	Iran	70	3	8	4	2	17
				71	3	8	4	2	17
				72	2	7	4	1	14
				73	2	8	4	2	16
24	Solgi et al.	2019	Iran	74	2	8	4	2	16
				75	2	8	4	2	16
				76	2	8	4	2	16
				77	1	1	1	1	4
25	Startsev & McNabb	2000	Canada	78	1	2	1	1	5
				79	1	2	1	1	5
				80	1	5	0	1	7
26	Šušnjar et al.	2006	Croatia	81	1	5	0	1	7
				82	1	5	0	1	7
27	Wang et al.		USA	83	3	2	0	1	6
				84	2	7	0	1	10
				85	2	7	0	1	10
28	Yazarlou et al.	2017	Iran	86	2	7	0	1	10
				87	2	7	0	1	10
				88	2	7	0	1	10
				89	2	7	0	1	10
29	Fredericksen & Pariona	2002	Bolivia	90	1	3	3	1	8
30	Jaafari et al.	2014	Iran	91	1	6	1	2	10
31	Kormanek & Gołąb	2021	Poland	92	0	4	2	0	6
				93	0	3	2	0	5
32	Reichert et al.	2018	Brazil	94	2	6	5	2	15
				95	2	6	5	2	15
33	Solgi et al.	2021	Iran	96	2	7	1	2	12
				97	2	7	1	2	12
				98	3	6	2	1	12
				99	3	6	2	1	12
				100	3	6	2	1	12
34	Tavankar et al.	2021	Iran	101	3	6	2	1	12
				102	3	6	2	1	12
				103	3	6	2	1	12
				104	3	6	2	1	12
				105	3	6	2	1	12

*** Note that the total number of papers taken into study was 34; however, some papers reported on a number of experimental designs giving the opportunity to form 105 data groups with their specific variables.**

EXTENDED ABSTRACT – REZUMAT EXINS

Titlu în română: *Impactul colectării mecanizate a lemnului asupra solurilor forestiere: studiu de sinteză.*

Introducere: *Prejudicierea solului este definită sub forma modificărilor proceselor fizice, chimice și biologice din sol, care sunt adesea interconectate. Colectarea mecanizată a lemnului contribuie semnificativ la creșterea gradului de compactare şi eroziunii solului, care depind în principal de intensitatea extracției și de gradul de deteriorare cauzat de metodele folosite în exploatarea lemnului. Circulația tractoarelor are efecte negative asupra componentelor fizice, chimice şi biologice ale solului. Scopul acestui studiu a fost de a identifica cele mai semnificative informații publicate de specialiști*

în ultimii ani, precum și de a sintetiza cunoștințele disponibile despre operațiile de colectare și impactul acestora asupra solurilor forestiere.

***Materiale şi metode**: Studiul a fost realizat pe baza informațiilor disponibile pentru țări și locații din întreaga lume pe o perioadă de 35 de ani (1986-2021). Revizuirea literaturii de specialitate s-a bazat pe căutarea articolelor legate de efectuarea operațiilor de colectare. Bibliografia și informațiile folosite în acest studiu au fost obținute din surse online și lucrări de cercetare publicate în engleză și spaniolă, indexate în baze de date cum ar fi Google Scholar, Web of Science, Scopus și CABI, prin utilizarea unor cuvinte cheie specifice precum și a unor combinații între acestea.*

***Rezultate şi discuții**: 22 de variabile ce caracterizează descrierea, zona de studiu, parametrii structurali ai arboretului și designul experimental au fost frecvent identificate în articolele analizate. Patru variabile au fost raportate în proporție de 7 - 7,8%, cum ar fi tipul de utilaj, precipitațiile, densitatea aparentă și textura solului. Luând în considerare variabilele înregistrate în cea mai mare parte de către autori, acestea au fost panta, specia și numărul de treceri ale utilajelor (6 până la 6,9%). 2 variabile care au fost înregistrate cu procente mai mari au fost temperatura și densitatea aparentă: 5,4% și, respectiv, 5,2%. Celelalte variabile au fost descrise în proporție mai mică de 5%.*

***Concluzii**: Se concluzionează că în studiile privind prejudicierea solului ca urmare a operaţiilor de colectare a lemnului au fost analizate 4 tipuri de variabile (parametri descriptivi, locali, structurali și experimentali), iar variabilele de localizare au fost cele mai analizate (54,7%); totuși, tipul de utilaj, precipitațiile, densitatea aparentă și textura solului au fost printre cele mai colectate date în studiile analizate. Se recomandă ca în studiile viitoare să se ia în considerare variabile legate de pregătirea muncitorilor, numărul de cicluri de muncă, viteza cu care este operat utilajul şi producția realizată.*

***Cuvinte cheie**: Prejudicierea solului, operații forestiere, colectare, sol, impact, sinteză.*

REFERENCES

1. Ferreira C., Seifollahi-Aghmiuni S., Destouni G., Ghajarnia N., Kalantari Z., 2022: Soil degradation in the European Mediterranean region: Processes, status and consequences. Science of the Total Environment, 805, 150106.
2. Food and Agriculture Organization of the United Nations (FAO), 2015: World fertilizer trends and outlook to 2018. Food Agriculture Organization United Nations, Rome, Italy.
3. Stolte J., Tesfai M., Oygarden L., Kvaemo S., Keizer J., Verheijen F., Hessel R., 2016: Soil threats in Europe. Status, methods, drivers and effects on ecosystem services. A review report, Deliverable 2.1 of the RECARE Project. European Union https://doi.org/10.2788/828742
4. Croke J., Hairsine P., Fogarty P., 2001: Soil recovery from track construction and harvesting changes in surface infiltration, erosion and delivery rates with time. Forest Ecology and Management, 143, 3-12.
5. Orgiazzi A., Ballabio C., Panagos P., Jones A., Ugalde O., 2018: LUCAS Soil, the largest expandable soil dataset for Europe: a review. European Journal of Soil Science, 69(1), 140-153.
6. Singh J., Gupta V., 2018: Soil microbial biomass: a key soil driver in management of ecosystem functioning. Science of the Total Environment, 634, 497-500.
7. Marsden C., Martin-Chave A., Cortet J., Hedde M., Capowiez Y., 2020: How agroforestry systems influence soil fauna and their functions-a review. Plant and Soil, 453(1), 29-44.
8. Rab M., Bradshaw, F., Campbell R., Murphy S., 2005: Review of factors affecting disturbance, compaction and trafficability of soils with particular reference to timber harvesting in the forests of south-west Western Australia, Consultants Report to Department of Conservation and Land

Management. Western Australia, Sustainable Forest Management Series, SFM Technical Report No. 2, 146.

9. Ares A., Terry T., Miller R., Anderson H., Flaming B., 2005: Ground-based forest harvesting effects on soil physical properties and Douglas-fir growth, Soil Science Society of America Journal, 69, 1822-1832.

10. Heinimann H., 2007: Forest operations engineering and management - the ways behind and ahead of a scientific discipline. Croatian Journal of Forest Engineering, 28(1), 107-121.

11. Stanturf J., Palik B., Dumroese R., 2014: Contemporary forest restoration: a review emphasizing function. Forest Ecology and Management, 331, 292-323

12. Nunes J., Naranjo Quintanilla P., Santos J., Serpa D., Carvalho-Santos C., Rocha J., Keizer J., Keesstra S., 2018: Afforestation, subsequent forest fires and provision of hydrological services: A model-based analysis for a Mediterranean mountainous catchment. Land Degradation & Development, 29(3), 776-788.

13. Fredericksen T., Putz F., 2003: Silvicultural intensification for tropical forest conservation. Biodiversity & Conservation, 12, 1445-1453.

14. Steinbrenner C., Gessel S., 1995: The effect of tractor logging on physical properties of some forest soils in Southwestern Washington. Soil Science Society of America Journal 19, 372-376. doi:10.2136/sssaj1955.03615995001900030030x.

15. Ebel A., 2006: Pressure distribution on contact surfaces under forest strips. Dissertation writing at the Faculty of Forest Sciences and Forest Ecology of Georg August Univesität, Göttingen, 1-134.

16. Cambi M., Certini G., Neri F., Marchi E., 2015: The impact of heavy traffic on forest soils: A review. Forest Ecology and Management, 338, 124-138.

17. Giannetti F., Chirici G., Travaglini D., Bottalico F., Marchi E., Cambi M., 2017: Assessment of soil disturbance caused by forest operations by means of portable laser scanner and soil physical parameters. Soil Science Society of America Journal, 81(6), 1577-1585.

18. Sist P., Ferreira F., 2007: Sustainability of reduced-impact logging in the Eastern Amazon. Forest Ecology and Management, 243(2-3), 199-209.

19. Douglas I., Greer T., Bidin K., Spilsbury M., 1993: Impacts of rainforest logging on river systems and communities in Malaysia and Kalimantan. Global Ecology and Biogeography Letters, 3, 245-252.

20. Department for international development (DFID), 1999: Indonesia towards sustainable forest management. Final report of the senior management advisory team and the provincial level forest management project, (2). DFID and Ministry of Forestry, Indonesia, Jakarta, Indonesia.

21. Romero E., 2014: Identification and evaluation of the environmental impacts, of the intervention by the population in the area of the Chokblades forest reserve in the village of Retiro de los Blancos in the municipality of Choconta. Libre University, Colombia. Available online at: ttps://hdl.handle.net/10901/10639

22. Froehlich H., McNabb D., 1984: Minimizing soil compaction in Pacific Northwest forests. In: Proc. of the Forest Soils and Treatment Impacts Conference, 1983. Stone East Tennessee State University ETSU, Knoxville. 159-192.

23. Froehlich H., Miles D., Robbins R., 1985: Soil bulk density recovery on compacted skid trails in Central Idaho. Soil Science Society of America Journal, 49, 1015-1017.

24. Kolkaa R., Smidt M., 2004: Effects of forest road amelioration techniques on soil bulk density, surface runoff, sediment transport, soil moisture and seedling growth. Forest Ecology and Management, 202, 313-323.

25. James A., Ferreira N., Graham J., 2004: Effects of near-surface environmental conditions on instability of an unsaturated soil slope. Canadian Geotechnical Journal, 41(6), 1111-1126.

26. Horn R., Vossbrink J., Peth S., Becker S., 2007: Impact of modern forest vehicles on soil physical properties. Forest Ecology and Management, 248, 56-63.

27. Botta G., Tolon-Becerra A., Lastra-Bravo X., Tourn M., 2010: Tillage and traffic effects (planters and tractors) on soil compaction and soybean (Glycine max L.) yields in Argentinean pampas. Soil and Tillage Research, 110(1), 167-174.

28. Kozlowski T., 1999: Soil compaction and growth of woody plants. Scandinavian Journal of Forest Research, 14, 596-619.

29. Naghdi R., Solgi A., Ilstedt U., 2016: Soil chemical and physical properties after skidding by rubber-tired skidder in Hyrcanian forest, Iran. Geoderma, 265, 12-18.

30. Murtaza G., Murtaza B., Niazi N., Sabir M., 2014: Soil contaminants: sources, effects, and approaches for remediation. In Improvement of crops in the era of climatic changes. Springer, New York, NY, 171-196.

31. Greacen E., Sands R., 1980: Compaction of forest soils: a review. Australian Journal of Soil Research, 18, 163-189.

32. Naghdi R., Lotfalian M., Bagheri I., Jalali A., 2009: Damages of skidder and animal logging to forest soils and natural regeneration. Croatian Journal of Forest Engineering, 30(2), 141-149.

33. Schweier J., Magagnotti N., Labelle E., Athanassiadis D., 2019: Sustainability impact assessment of forest operations: A review. Current Forestry Reports, 5(3), 101-113.

34. Edlund J., Keramati E., Servin M., 2013: A long-tracked bogie design for forestry machines on soft and rough terrain. Journal of Terramechanics, 50(2), 73-83.

35. Ezzati S., Najafi A., Rab M., Zenner, E., 2012: Recovery of soil bulk density, porosity and rutting from ground skidding over a 20-year period after timber harvesting in Iran. Silva Fennica, 46(4), 521-538.

36. Solgi A., Najafi A., Page-Dumroese D., Zenner E., 2020: Assessment of topsoil disturbance caused by different skidding machine types beyond the margins of the machine operating trail. Geoderma, 367, 114238.

37. Demir M., Makineci E., Comez A., Yilmaz E., 2010: Impacts of repeated timber skidding on the chemical properties of topsoil, herbaceous cover and forest floor in an eastern beech (Fagus orientalis Lipsky) stand. Journal of Environmental Biology, 31(4).
38. Solgi A., Najafi A., Ezzati S., Ferencik M., 2016: Assessment of ground-based skidding impacts on the horizontally rate and extent of soil disturbance along the margin of the skid trail. Annals of Forest Science, 73(2), 513-522.
39. Makineci E., Demir M., Comez A., Yilmaz E., 2007: Chemical characteristics of the surface soil, herbaceous cover and organic layer of a compacted skid road in a fir (Abies bornmulleriana Mattf.) forest. Transportation Research Part D: Transport and Environment, 12(7), 453-459.
40. Gerasimov Y., Sokolov A., 2014: Ergonomic evaluation and comparison of wood harvesting systems in Northwest Russia. Applied Ergonomics, 45(2), 318-338.
41. Laffan M., Jordan G., Duhig N., 2001: Impacts on soils from cable-logging steep slopes in northeastern Tasmania, Australia. Forest Ecology and Management, 144(1-3), 91-99.
42. Najafi A., Solgi A., Sadeghi S., 2009: Soil disturbance following four wheel rubber skidder logging on the steep trail in the north mountainous forest of Iran. Soil and Tillage Research, 103(1), 165-169.
43. Solgi A., Najafi A., Sadeghi S., 2014: Effects of traffic frequency and skid trail slope on surface runoff and sediment yield. International Journal of Forest Engineering, 25(2), 171-178.
44. Brock S., Jones K., Miller G., 1986: Felling and skidding costs associated with thinning a commercial Appalachian hardwood stand in northern West Virginia. Northern Journal of Applied Forestry, 3(4), 159-163.
45. Curro P., Verani S., 1990: On the maximum skidding output of the "Timberjack 380" forest tractor. Journal of Forest Engineering, 1(2), 35-39.
46. Kluender R., Stokes B., 1996: Felling and skidding productivity and harvesting cost in southern pine forests. Proceedings: Certification–Environmental implications for forestry operations; 1996 September. 9 (11); 35-39.
47. Kluender R., Lortz D., McCoy W., Stokes B., Klepac J., 1997: Productivity of rubber-tired skidders in southern pine forests. Forest Products Journal, 47 (11/12): 53-58.
48. Colton A., Brink M., 1999: Hitching optimal payloads increases skidder productivity. Southern African Forestry Journal, 186(1), 29-32.
49. Rollerson T., 1990: Influence of wide-tire skidder operations on soils. Journal of Forest Engineering, 2(1), 23-30.
50. Poje A., Potočnik I., 2007: Influence of working conditions on overlapping of cutting and ground skidding in group work. Croatian Journal of Forest Engineering, 28(2), 157-167.
51. Najafi A., Sobhani H., Saeed A., Makhdom M., Mohajer M., 2008: Planning and assessment of alternative forest road and skidding networks. Croatian Journal of Forest Engineering, 29(1), 63-73.

52. Tavankar F., Bonyad A., Majnounian B., 2011: Investigation of damages to stand caused by selection cutting using skidding system in the Asalem-Nav forest, Iran. Journal of Environmental Studies, 37(59), 89-98.

53. Vusić D., Šušnjar M., Marchi E., Spina R., Zečić Ž., Picchio R., 2013: Skidding operations in thinning and shelterwood cut of mixed stands - Work productivity, energy inputs and emissions. Ecological Engineering, 61, 216-223.

54. López M., Sun X., Onda Y., Kato H., Gomi T., Hiraoka M., 2017: Effect of tree thinning and skidding trails on hydrological connectivity in two Japanese forest catchments. Geomorphology, 292, 104-114.

55. Turc C., Mazzucco R., 1998: Characterization of the forest use systems used in the mountains of Santiago. Quebracho, 6, 59-68.

56. Cándano A., Vidal C., Leite A., Machado C., 2004: Evaluation of three methods for dragging wood in natural stands of Pinus caribaea var. Caribea. Árvore Journal. 28(3), 373-380.

57. Nájera J., Aguirre O., Trevino E., Jimenez J., Jurado E., 2011: Timber harvesting times and productivity in El Salto, Durango, Mexico. Revista Chapingo Serie Ciencias Forestales y del Ambiente, 17(1), 49-58.

58. Bray D., Duran E., Hernández-Salas J., Luján-Alvarez C., Olivas-García M., Grijalva M., 2016: Back to the future: The persistence of horse skidding in large scale industrial community forests in Chihuahua, Mexico. Forests, 7(11), 283.

59. Villalobos V., Meza A., Navarro A., 2019: Timber skidding system for forest plantations combining water buffaloes (Bubalus bubalis Simpson, 1945) with farm tractor. Revista Forestal Mesoamericana Kurú, 16(39), 53-60.

60. Guera O., Silva J., Ferreira R., Álvarez D., Barrero H., Díaz A., 2020: Multivariate approach in timber extraction experiments in forest plantations. Madera y Bosques Journal, 26(2).

61. Modrý M., Hubený D., 2003: Impact of skidder and high-lead system logging on forest soils and advanced regeneration. Journal of Forest Science, 49(6), 273-280.

62. Najafi A., Solgi A., Sadeghi S., 2010: Effects of skid trail slope and ground skidding on soil disturbance. Caspian Journal of Environmental Sciences, 8(1), 13-23.

63. Majnounian B., Jourgholami M., 2013: Effects of rubber-tired cable skidder on soil compaction in Hyrcanian Forest. Croatian Journal of Forest Engineering, 34(1), 123-135.

64. Jourgholami M., Majnounain B., Abari M., 2014: Effects of tree-length timber skidding on soil compaction in the skid trail in Hyrcanian forests. Forest Systems, 23(2), 288-293.

65. Naghdi R., Solgi A., 2014: Effects of skidder passes and slope on soil disturbance in two soil water contents. Croatian Journal of Forest Engineering, 35(1), 73-80.

66. Borchert H., Huber C., Göttlein A., Kremer J., 2015: Nutrient concentration on skid trails under brush-mats - Is a redistribution of nutrients Possible? Croatian Journal of Forest Engineering, 36(2), 243-252.

67. Allman M., Ferenčík M., Jankovský M., Stanovský M., Messingerová V., 2015: Damage caused by wheeled skidders on cambisols of Central Europe. Croatian Journal of Forest Engineering, 36(2), 205-215.

68. Jamshidi R., Jaeger D., Raafatnia N., Tabari M., 2008: Influence of two ground-based skidding systems on soil compaction under different slope and gradient conditions. International Journal of Forest Engineering, 19(1), 9-16.

69. Nikooy M., Ahrari S., Salehi A., Naghdi R., 2015: Effects of rubber-tired skidder and farm tractor on physical properties of soil in plantation areas in the north of Iran. Journal of Forest Science, 61(9), 393-398.

70. Naghdi R., Solgi A., Zenner E., 2015: Soil disturbance caused by different skidding methods in mountainous forests of Northern Iran. International Journal of Forest Engineering, 26(3), 212-224.

71. Solgi A., Naghdi R., Zenner E., Tsioras, P., Hemmati, V., 2019: Effects of ground-based skidding on soil physical properties in skid trail switchbacks. Croatian Journal of Forest Engineering, 40(2), 341-350.

72. Solgi A., Naghdi R., Marchi E., Laschi A., Keivan Behjou F., Hemmati V., Masumian A., 2019: Impact assessment of skidding extraction: effects on physical and chemical properties of forest soils and on maple seedling growing along the skid trail. Forests, 10(2), 134.

73. Solgi A., Naghdi R., Tsioras P., Nikooy M., 2015: Soil compaction and porosity changes caused during the operation of Timberjack 450C skidder in northern Iran. Croatian Journal of Forest Engineering, 36(2), 217-225.

74. Lotfalian M., Khosrozadeh S., Hosseini S., Kazemi M., Zare N., 2016: Determination of forest skid trail density in Caspian forests, Iran. Journal of Forest Science, 62(2), 80-87.

75. Pentek T., Nevečerel H., Poršinsky T., Pičman D., Lepoglavec K., Potočnik I., 2008: Methodology for development of secondary forest traffic infrastructure cadastre. Croatian Journal of Forest Engineering, 29(1), 75-83.

76. Duka A., Grigolato S., Papa I., Pentek T., Poršinsky T., 2017: Assessment of timber extraction distance and skid road network in steep karst terrain. iForest, 10(6), 886.

77. Rudov S., Voronova A., Chemshikova J., Teterevleva E., Kruchinin I., Dondokov Y., Motrena K., Burtseva A., Vyacheslav D., Grigorev I., 2019: Theoretical approaches to logging trail network planning: increasing efficiency of forest machines and reducing their negative impact on soil and terrain. Asian Journal of Water, Environment and Pollution, 16(4), 61-75.

78. Yazarlou H., Parsakhoo A., Habashi H., Soltauninejad S., 2017: Effect of the skid trail cross section and horizontal alignment on forest soil physical properties. Journal of Forest Science, 63(4), 161-166.

79. Macrì G., Russo D., Zimbalatti G., Proto A., 2016: Measuring the mobility parameters of tree-length forwarding systems using GPS technology in the Southern Italy forestry. Agronomy Research 14(3): 836-845.

80. Vossbrink J., Horn R., 2004: Modern forestry vehicles and their impact on soil physical properties. European Journal of Forest Research 123(4), 259-267. doi:10.1007/s10342-004-0040-8.

81. Ampoorter E., Goris R., Cornelis W., Verheyen K., 2007: Impact of mechanized logging on compaction status of sandy forest soils. Forest Ecology and Management, 241(1-3), 162-174.

82. Proto A., Macrì G., Sorgonà A., Zimbalatti, G., 2016: Impact of skidding operations on soil physical properties in southern Italy. Contemporary Engineering Sciences, 9(23), 1095-1104.

83. Šušnjar M., Horvat D., Šešelj J., 2006: Soil compaction in timber skidding in winter conditions. Croatian Journal of Forest Engineering, 27(1), 3-15.

84. Wang J., LeDoux C., Edwards P., 2007: Changes in soil bulk density resulting from construction and conventional cable skidding using preplanned skid trails. Northern Journal of Applied Forestry, 24(1), 5-8.

85. Han S., Han H., Page-Dumroese, D., Johnson, L., 2009: Soil compaction associated with cut-to-length and whole-tree harvesting of a coniferous forest. Canadian Journal of Forest Research, 39(5), 976-989.

86. Borz S.A., Marcu M.V., Cataldo M.F., 2021: Evaluation of an HSM 208F 14tone HVT-R2 forwarder prototype under conditions of steep-terrain low-access forests. Croatian Journal of Forest Research, 42(2), 185-200. https://doi.org/10.5552/crojfe.2021.775

87. Picchio R., Neri F., Petrini E., Verani S., Marchi E., Certini G., 2012: Machinery-induced soil compaction in thinning two pine stands in central Italy. Forest Ecology and Management, 285, 38-43.

88. Marchi E., Picchio R., Spinelli R., Verani S., Venanzi R., Certini G., 2014: Environmental impact assessment of different logging methods in pine forests thinning. Ecological Engineering, 70, 429-436.

89. Dymov A., Milanovskii E., 2013: Changes in the organic matter of taiga soils during the natural reafforestation after cutting in the middle taiga of the Komi Republic. Eurasian Soil Science, 46(12), 1164-1171.

90. Puettmann K, Wilson S., Baker S., Donoso P., Drössler L., Amente G., Harvey D, Knoke T, Yuanchang L., Nocentini S., Putz N., Yoshida T., Bauhus J., 2015: Silvicultural alternatives to conventional even-aged forest management-what limits global adoption? Forest Ecosystems, 2(1), 1-16.

91. Ilintsev A., Nakvasina E., Aleynikov A., Tretyakov S., Koptev S., Bogdanov A., 2018: Middle-term changes in topsoils properties on skidding trails and cutting strips after long-gradual cutting: A case study in the boreal forest of the north-east of Russia. Croatian Journal of Forest Engineering, 39(1), 71-83.

92. Pobedinskii A., 2013: Vodoohrannaja i pochvozashhitnaja rol'lesov: vtoroe izdanie (Water and soil protection role of forests). Pushkino: ALL-Russian Research Institute for Silviculture and Mechanization of Forestry.

93. Wäldchen J., Schulze E.D., Schöning I., Schrumpf M., Sierra C., 2013: The influence of changes in forest management over the past 200 years on present soil organic carbon stocks. Forest Ecology and Management, 289, 243-254.

94. Anshar M., Wahida N., 2019: The potential for rural resources development, specifically livestock commodities based on Geographic Information System (GIS) in Patukku Village, Bontocani District, Bone Regency. In IOP Conference Series: Earth and Environmental Science 247, (1), 012076. IOP Publishing.

95. Ziegler A., Negishi J., Sidle R., Noguchi S., Nik A., 2006: Impacts of logging disturbance on hillslope saturated hydraulic conductivity in a tropical forest in Peninsular Malaysia. Catena, 67(2), 89-104.

96. Muto T., Steel R., 2002: In defense of shelf-edge delta development during falling and low stand of relative sea level. The Journal of Geology, 110(4), 421-436.

97. Jaafari A., Najafi A., Zenner E., 2014: Ground-based skidder traffic changes chemical soil properties in a mountainous Oriental beech (Fagus orientalis Lipsky) forest in Iran. Journal of Terramechanics, 55, 39-46.

98. Kramer P., 1944: Soil moisture in relation to plant growth. The Botanical Review, 10(9), 525-559.

99. Allman, M., Jankovský, M., Allmanová, Z., Ferenčík, M., Messingerová, V., Vlčková, M., Stoilov, S. (2017). Work accidents during cable yarding operations in Central Europe 2006–2014. Forest Systems, 26(1), 13.

100. Cresswell H., Hamilton G., 2002: Soil physical measurement and interpretation for land evaluation. CSIRO publishing, Australia, 35-58.

101. Jourgholami M., Labelle E., 2020: Effects of plot length and soil texture on runoff and sediment yield occurring on machine-trafficked soils in a mixed deciduous forest. Annals of Forest Science, 77(1), 1-11

102. Dominati E., Patterson M., Mackay A., 2010: A framework for classifying and quantifying the natural capital and ecosystem services of soils. Ecological Economics, 69(9), 1858-1868.

103. Area U., Uintah P., 2010: United States Department of Agriculture Natural Resources Conservation Service. Available online at: https://efotg.sc.egov.usda.gov/references/public/ND/limy_residual_R054XY046ND.pdf (accessed on 15 June 2022).

104. Hussein M., Kariem T., Othman A., 2007: Predicting soil erodibility in northern Iraq using natural runoff plot data. Soil and Tillage Research, 94(1), 220-228.

105. Newton P., 1997: Stand density management diagrams: Review of their development and utility in stand-level management planning. Forest Ecology and Management, 98(3), 251-265.

106. Hernández J., García J., Muñoz J., García X., Sáenz T., Flores C., Hernández A., 2013: Density management guide for natural Pinus teocote Schlecht. et Cham. forest in Hidalgo. Revista Mexicana de Ciencias Forestales, 4(19), 62-77.

107. Connolly M., 1983: Analytical molecular surface calculation. Journal of Applied Crystallography, 16(5), 548-558.

108. Gering L., May D., 1995: The relationship of diameter at breast height and crown diameter for four species groups in Hardin County, Tennessee. Southern Journal of Applied Forestry, 19(4), 177-181.

109. Magarik Y., 2021: "Roughly speaking": Why do US foresters measure DBH at 4.5 feet? Society & Natural Resources, 34(6), 725-744.

110. McNab W., 1989: Terrain shape index: quantifying effect of minor landforms on tree height. Forest Science, 35(1), 91-104.

111. Jun H., Way T., Löfgren B., Landström M., Bailey A., Burt E., McDonald T., 2004: Dynamic load and inflation pressure effects on contact pressures of a forestry forwarder tire. Journal of Terramechanics, 41(4), 209-222.

112. Agherkakli B., Najafi A., Sadeghi S., 2010: Ground based operation effects on soil disturbance by steel tracked skidder in a steep slope of forest. Journal of Forest Science, 56(6), 278-284.

113. Anderson T., Coats J., 1995: Screening rhizosphere soil samples for the ability to mineralize elevated concentrations of atrazine and metolachlor. Journal of Environmental Science & Health Part B, 30(4), 473-484.

114. Jakobsen T., Nielsen N., 1983: Vesicular-arbuscular mycorrhiza in field-grown crops. New Phytologist, 93(3), 401-413.