A Literature Review Related to the Modern Harvesting - Forwarding Equipment and the Main Topics Concern of the Research Community

Andrei APĂFĂIAN¹⁾, Vasile BOGHIAN¹⁾, Alexandru BRATU¹⁾

¹⁾ Department of Forest Engineering, Forest Management Planning and Terrestrial Measurements. Transilvania University of Brasov, Romania.

^{*}Corresponding author, e-mail: andrei.apafaian@unitbv.ro

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ABSTRACT

A literature review on harvester and forwarder equipment was conducted using the open access international scientific databases. The aims of this study were to evaluate the main interests of different research topics elaborated in 28 countries around the world in the last 23 years. The time span of the main articles ranged from the beginning of the year 1990 to end of 2012. The evolution trend of research topics was analyzed for this time period in order to relate them to possible future research directions in Romania. Most of the used literature was extracted mainly from scientific journals and conference proceedings, summing up a total of 105 references that were further analyzed. As expected, the synthesis of the references, pointed out that most of the interests and attention of the scientists has been given to productivity, costs and time expenditure on one hand, followed by studies on soil impact, environment and tree damage on the other hand. Topics referring to fuel-lubricants consumption and computer simulations didn't had the same impact among the researched literature, accounting for the smallest number of the cited articles. The obtained results will fill in the gap in future research by using scientific approaches particular to the Romanian conditions.

Keywords: *forwarder, harvester, international database, open access, synthesis.*

Abbreviations:

CC – clear cut

T – thinning

M – mixed stand

S – shelterwood

SW – softwood

HW – hard wood

PW – pulp wood

SL – sawlogs

LR – logging residues

CW – chipwood

CTL – cut to length

WT – whole tree

W – willow

CFF – conventional felling

TC – tossing the caber

RC – regeneration cut

CF – clear fell

ST – seed tree cut

FF – final felling

CS – clear sanitary

SSC – selective sanitary cut

OC – other cut

IC – incidental felling

WF – wind fall

Sl – slope

Op – operator

D – diameter at breast height

Atv – average tree volume

Di – distance

De – delimbing

P – productivity

C – cost

Cu – cutting

F – forwarder

H – harvester

l – liter

L – loading

Ha – hectare

L – loading
 UL – unloading
 Hr – harvesting
 Fr – forwarding
 u.b – under bark
 Ho – productive working hour
 h – hour
 m – meters
 HW – harwarder
 Min – minutes
 WH – working hour
 Av – average volume

Y – yarder
 MF – midfield
 SR – skidroad
 SH – scheduled hour
 T – ton
 LCA – life cycle analysis
 ODT – oven dried tons
 GT – green ton
 SGH – single grip harvesters
 DGH – double grip harvester
 E₁₅/E – effective hour with/ without 15 min. delays

INTRODUCTION

Timber harvesting in Romania is performed mostly by traditional equipment such as skidders and forest-fitted farm tractors. Lately, modern forestry machinery such as the harvesters and forwarders started to be introduced in Romania. However, little is known about harvester and forwarder equipment in Romania and one way to assess either the benefits or bottlenecks of a given new technology is to do an extensive literature review.

The present literature review is an attempt to analyze the main topics that concerned the international forestry community, and to reveal which were the most debated subjects and results. The interests of researchers will automatically emphasize the most important trends.

MATERIALS AND METHODS

This paper aimed to describe a concise view on harvesting and forwarding equipment carried out in the last 23 years (1990-2012), by analyzing the main topics addressed by the forest scientists. Furthermore, it tried to identify the gaps in knowledge and synthesize the new scientific approaches in order to improve the general view on research methods when dealing with such equipment.

The considered time span was so extended because we tried to analyze all the information that could be found on every available source, although the biggest and important percentage of the articles was after the year 2000. To search for the needed information the data bases given in Table 1 were investigated. All the inquired

data bases belonged to the open access category, and they were used in order to review data that can be obtain without having to have an active subscription.

Each of the references was queried using the following keywords: harvester and forwarder, harvester, forwarder, cut-to-length harvester, hauling distances, soil damage forwarder, productivity, delays.

All the papers are written in English. All the main concerns regarding harvesting and forwarding were covered, some of them more than the others.

The research papers have been grouped into four sections with subsections as follows:

1. Productivity, time consumption, costs.

a. Productivity – this section describes the productivity in different cases for the harvester and forwarder.

b. Time consumption – this section describes the time spent for CTL technology and for loading short wood.

c. Costs – this section describes the value of the costs related to distance, management practices.

d. Delays – this section describes the delays that occurs in harvester operations

e. Loading – this section describes the loading phase made by the forwarder.

2. Fuel and lubricants consumption – this section describes the consumption related to hauling distance and mean tree diameter.

3. Tree damage and soil disturbance

Tab. 1 Open access inquired databases

Int. Journal of Forest Engineering	Forst und Technik Magazine	Int. Mountain Logging and 11th Pacific Symposium	Investigation agrariasistemas y recursosforestales
Journal of Forest Science	Forest product journal	PesquisaAgropecuáriaBrasileira	PesquizaAgropecuaria Tropical
Silva Fennica	IUFRO	Bosque	JMHT
Croatian Journal of Forest Engineering	AllgemeineForstZeitung	Canadian Journal of Forest Research	GozdarskiVestnik
Japanese Forest Society and Springer	Universities	PraceInstytutuBadawczego Leśnictwa	Advantage (FERIC)
European Journal of Forest Research	ForstlicheForschungsBerichte	Mondo Macchina	Proceedings of the Austro2003 meeting
Forestry reports	Forest ecology and management	InTech Journal	U.S Dept. Of Agriculture
Formec Croatia	Formec Italia	Formec Bulgaria	Formec Austria
Forest research instit. Of Canada	Soil Science Society of American Journal	Forsttechnischeinformationen	Sherwood-ForestedAlbertiOggi
Silva Fenica	Lesovedenie	Annals of forest science	Baltic Forestry

Tab. 2 Number of articles/abstracts per section

Articles/ Abstracts	Productivity, time, cost, delays, loading	Fuel	Soil and tree damage	Computer simulation	Total
Articles	40	5	26	6	76
Abstracts	14	0	14	0	29
Total	54	5	40	6	105

a. Tree damage – this section describes the damages that occur after using the harvester and forwarder equipment.

b. Soil disturbance – this section describes the different actions that are causing damage to the soil and different methods to improve the negative effects.

4. Computer simulations – different approaches are developed with the help of informatics in order to asses some hypothesis

RESULTS AND DISCUSSION

The sections are composed from a total of 76 papers and 29 abstracts made by 235 authors from 28 different countries. The most debated section is “productivity” and “soil and tree damage” summing up 90% of the articles where categories like “fuel consumption” and “computer simulation” are representing the rest of 10%.

Tab. 3 Source of the cited references

Source	Nr. of articles
Journals	72
Conference proceeding	23
Research institute	5
University research	4
Report	1

The papers are mostly published in journals, conferences, research institutes, university environment and reports (Tab. 3). In our review we didn't included any books.

The main source of literature that is analyzed in this study, almost 86% comes from scientific journals and conference proceedings while the rest has a small proportion.

For each section the articles are sorted in accordance to geographical region and publication date. The geographical grouping is mandatory to assess the “key-points” of each and every one of it and then to compare them in order to synthesize the similarities or differences. For each paper the research information has been summarized in accordance to type of forest, type of cut, stand characteristics in order to ease the analysis process.

Time span and country distribution of the cited articles

As it was expected the majority of the articles were written in countries that have a long tradition in using such equipment like the Nordic countries and U.S.A. (Fig. 1).

Fig.1 Researched geographical regions of the cited literature (www.douweosinga.com).

The references elapsing in time as well as their number in the given time period is shown in Fig. 2. We considered that calculating the mean of the number of articles per year would not be concluding given the significant differences which were observed in the period taken into study. Unfortunately, for the years 1993 and 2000 we didn't found any article in the open access databases.

Analysis of the productivity, time consumption, costs

Productivity plays an essential role in harvesting and forwarding operations and it is deeply related to time consumption and the involved costs. These three key words have a great importance in the stump to mill wood price. In this section the analysis of all the studies regarding the mentioned descriptors was made. A total of 54 references more than half of the 105 articles are composing this section. In those papers 78 descriptors (Tab. 4) are present.

As resulted from the table we can conclude that the descriptor productivity is present 41 times in the 54 articles. As predicted productivity is an important research topic all over the world.

Tab. 4 Number of descriptors in the references

Descriptor	Mentioned number
Productivity	41
Time consumption	20
Cost	17
Total	78

Fig. 2 Time distribution of the cited articles.

Time consumption and cost have almost the same number summing up a total of 37 articles. The data from the cited literature is presented in Table 5.

North American studies accounted for a total of 11 references from the total. Thinning was studied in 5 references revealing a diameter from 24 to 26.9 cm. The harvester productivity was 19.17 m³ / productive working hour or 39 to 55 trees / productive working hour in another study. For the forwarder productivity was 15.3 m³ / h for a distance of 267 m. In the case of a mixed stand the productivity was with 25% lower while the processed trees per hour remained the same. Harvesting costs varied from 4.46\$/m³ in 1994 to 5.54\$/m³ after 20 years. In the case of shelterwood cut productivity is slighter higher but with almost double the cost. Tree volume, stand density and distance are the main factors affecting productivity and cost. In the case of South America

region only one study is present, showing that the effective work was 75.6% for harvester and 84.7% for the forwarder, the rest of the time is summing up downtime.

Nordic countries have been always the pioneers regarding the harvesting and forwarding equipment in conifer stands. From the recorded references a large number of studies are in thinning followed by clear cut and final felling. The thinned stand's had the same tree diameter from 11.8 to 21.8 cm. Due to this fact productivity values are similar having an average of 10m³/h. Different harvesting methods like conventional feeling and tossing the caber have a productivity difference of only 1.3 m³/h. Only one topic was researched in a willow plantation showing the superior productivity and decreased cost of a harvester in relation to a harwarder system.

Tab. 5 Main findings of the cited literature in relation to productivity, cost and time consumption

North America				
References	Tree type	Type of cut	Stand characteristics	Major results
Lambert <i>et al.</i> (1990)	-	CC	Sl 27.5%	P 455 green tons/day. C 7.8\$/ton
Kellogg <i>et al.</i> (1994)	Co	T	D 25.9/26.9cm. Avt 0.09 m ³	Hr C 4.46\$/m ³ . F P 15.3 m ³ , Di 267m. Mixed load technique C 6.8\$/m ³
Richardson <i>et al.</i> (1995)	-	S,T	-	Hr P 46 to 58 trees/Ho in S and 39 to 55 trees/Ho in T. C are 10.18\$/ m ³ in T and 18.84\$/m ³ in S
Tufts (1997)	-	PW,SL	-	Hr P 29.2m ³ for PW and 33.8 m ³ for SL/Ho. F P 34.6m ³ /Ho and C of 53\$/m ³ /H.
Huyler <i>et al.</i> (1999)	M	CW,PW	D 20 cm, Atv1.87m ³	H 14.8 m ³ or 47.48 trees Avg. time for travel, Cu,De 1.29 min.
Bulley(1999)	-	-	-	Effect of Avt and stand density influence H and F P, C for slash loading and tree damage.
Meek (1999)	Co	T	-	Factors affecting the P in Co Tstands.
Ewing (2001)	M	T	-	Hr C 7-33\$/m ³ . Fr C 4 -14\$/m ³ Experienced drivers low cost.
Drewset <i>al.</i> (2001)	Co	-	D 12 cm, Sl 12 %	F vs. YC is 7\$ vs. 33\$/ton, F vs. Y P is 12T/SH vs. 9T/SH. Stump to mill F vs. YC are 46\$/Gt vs. 80\$/Gt
Douglas (2004)	Co	T	D 24 cm, Atv 0.28 m ³ , Sl 14%	H P was 19.17 m ³ /Ho while C are 5.54\$/m ³
Grebneret <i>al.</i> (2005)	-	-	-	Routechasser program assess the vehicle operating parameters, cost from stump to mill transport
Adebayo (2006)	-	WT/CTL	D 27.5 cm, Sl 18% Atv 0.53 m ³	P and C between the two harvesting methods

Tab. 5 (continued) Main findings of the cited literature in relation to productivity, cost and time consumption

South America				
Linhares <i>et al.</i> (2012)	-	-	-	H worked 480 h 18 min. 75.6% was effective work while 24.4% downtime. F worked 481 h 36 min were effective work was 84.7% and 15.3% downtime
Nordic countries				
Gullberg (1997)	-	-	-	L time is related to pile characteristics, L conditions and operator
Glade (1999)		S	D 32 to 38 cm	P between SGH/DGH. C 2.7- 5.7\$ for SGH and 3.3-6\$ for DGH
Glode <i>et al.</i> (2001)	-	CFF/TC	D 20 cm, Avt 27.4 m ³	CFF 27.4 m ³ /E ₁₅ , TC 26.1 m ³ /E ₁₅
Westeret <i>et al.</i> (2003)	Co	T	D 11.8-19.9 cm, Avt 0.18-0.26 m ³	P for final T is 10.9m ³ for rotatable load carrier and 10.3 m ³ for fixed carrier. For T P is 6 and 5 m ³ /E. 70%-80% used for L and Hr.
Siren <i>et al.</i> (2003)	Co	T/RC	Fr Di is 250 m	P for H-F is 3.81 m ³ /E ₁₅ for 1 st T and 7.87 m ³ /E ₁₅ in RC. For H an avg. P is 6.92m ³ /E ₁₅ in 1 st T and 16.18m ³ /E ₁₅ in CF.
Andersson <i>et al.</i> (2004)	Co	T	D 12.5-20.7 cm Atv 0.09-0.25 m ³ 0% Sl	Strip road cut backwards 12.1m ³ /E ₀ . Along the edge cut 13m ³ /E ₀ . Both sides tree cutting 11.9m ³ /E ₀ .
Karha <i>et al.</i> (2004)	Co	T	-	1 st T P 5.6 – 10.3m ³ /E ₁₅ , 2 nd T P 9.1 – 12.7 m ³ /E ₁₅ . C (small machines) 7.5 – 14.2 \$ and 5.7 – 10.5\$ (large ones). Operator skills influenced the P up to 40%.
Nurminen <i>et al.</i> (2006)	Co	CF,ST,T	D 14-33 cm, Avt 0.2-0.9 m ³ .	Stem increase from 0.4 to 0.6m ³ then P increase is in avg. 30%. New assortments decreases P to 1.5-4%. Increased loads increases P.
Woll <i>et al.</i> (2009)	Co	T	D 15.9 and 21.8cm	P is 1.1m ³ /h in 58h and P is 4.7m ³ /h in 29h
Lars <i>et al.</i> (2011)		dry/fresh LR		Fresh load was 7.1 T respectively 6.7 T when dried. UL time 509.8 min dried, respectively 508.1 min fresh. No major differences.
Fulvio <i>et al.</i> (2012)	SW	W	-	H-F P is 2.3ODT/Ho as for the HW 0.9 ODT/Ho. Op C 20E/WH. Op H C are 85.2E/WH, 70.4E/WH for F and 79.6E/WH H.C for HW are 43% more than for H-F.
Lindroos <i>et al.</i> (2012)	-	FF	Fr Di 300m to 500m	A trailer after F increased time and fuel consumption during transport but resulted in a reduction of fuel and time per Fr T
Mizaras <i>et al.</i> (2008)	-	SSC	0.1 to 1.0 m ³ 0.1 to 0.5 m ³	H P and HW is between 10.7-46.5 m ³ . C ranges from 1.7-8E/m ³ to 3.5-12.4m ³
Oceania				
Evanson <i>et al.</i> (1996)	Co	-	D 45 to 52 cm , Avt 1.5 to 3 m ³	Processing head P in stockpile is 77m ³ /H with an avg. vol. of 1.6m ³ , 77m ³ /H with an Av of 3.1m ³ in Y, 100m ³ /Ho Av of 1.95 m ³ for Hr and 143m ³ /Ho for De and bunching.

Tab. 5 (continued) Main findings of the cited literature in relation to productivity, cost and time consumption

Nichoolls <i>et al.</i> (2004)	-	-	-	Op fatigue in one/ two shiftwork operations was observed. Rest breaks of 10 min. taken every 90 min. contributes to increase P.
Visser <i>et al.</i> (2011)	Co	-	D 39 to 45 cm, Atv 0.3 to 5.2 m ³ . D 29 to 40 cm, Atv 0.1m ³ - 4.4 m ³	Time consumption was 40% for felling and delimbing while the rest of 60% for bunching, clearing, moving, delay.
North-west and West of Europe				
Esteban <i>et al.</i> (2002)	-	-	t-	P and C equations. High differences between small/large H. Tree/soil damage greater than the foreign regulations.
Jirousek <i>et al.</i> (2007)	-	CF	-	H P between 13.5 to 60.5 m ³ /Ho and H C of 105E/Ho. F C reached 68.5E/Ho
Central Europe				
Hoss <i>et al.</i> (1991)	-	T	winter/summer harvest	Better P in alternation of work between H and other related activities is recommended.
Verani (2001)	SW	-	Fr Di is 700 m	L of poplar with a F was very long (32.9% of the L cycle). Avg. cycle was 41.8min for an avg. load of 6.54 T over 700m
Stampfer <i>et al.</i> (2001)	M	-	Sl of 31 to 43%. Corridors from 84 to 167 m. Age 55-100	Hr time for 0.6m ³ tree is one minute. Avg. locomotion time is 0.3 min/stop. Soil bearing capacity is unfavorable
Ghaffarian <i>et al.</i> (2007)	Co	-	Sl 11%, Atv. 0.31m ³ to 0.7 m ³ .	Observed P was 17.9 m ³ /productive scheduled hour and the avg. load was 10.04m ³ /cycle. The avg. costs were 6.72E/m ³
Spinelli <i>et al.</i> (2008)	-	-	-	Delays avg. 28.9% of the total schedule time from 34 studies, comprising 7.1% mechanical, 4.7% Op and 17.1% other delays.
Holzleitner <i>et al.</i> (2010)	-	-	-	F have the largest P h/year from Fr machines of 2068/ Ho15, fuel consumption of 11.1l/h and repair costs of 11.8E/h
Zimbalatti <i>et al.</i> (2010)	B	-	S 25%, Fr Di 1084m Atv 1 to 1.54 m ³	Avg. Fr time is 37 min for a 8.6 m ³ load. Avg. P without delays is 14.41m ³ to 15.11m ³
Purfuerst <i>et al.</i> (2011)	Co	T	Atv 0.09 to 0.22 m ³	12 H Op and their long term output wee observed. Avg. P. was 7 to 16 m ³ /Ho ₁₅
Spinelli <i>et al.</i> (2011)	-	-	Avg. tree volume is 0.010 to 7 m ³ with an avg. of 0.346 m ³	General P model after 38 studies in which 5239 m ³ and 329 delay free hours were analyzed. Avg. P is 15.9 m ³ /delay free hour or 46 trees.
Cacot <i>et al.</i> (2012)	-	T,CF,OC	-	From French data base the H worked during 2010 and 2011 in 125 T sites, 126 CC while the F worked in 67 T and 52 clear cut stands
Balkan countries				
Stankic <i>et al.</i> (2011)	-	-	-	F P depends on the class, hauling Di, load characteristics, terrain and stand conditions
Stankik <i>et al.</i> (2012)	-	-	-	Analyzed the impact factors as a special aspect of primary transport of wood
East of Europe				
Jodlowski (1999)	Co	T	-	Hr C and damage were when chainsaw and F were used. Harvester and forwarder showed the higher costs.

Tab. 5 (continued) Main findings of the cited literature in relation to productivity, cost and time consumption

Suwala (1999)	Co	T	-	Smallest C was for chainsaw and F for hauling distances of 100 m and 30-40 m between tracks. The most efficient was the H F for dist. to 100 m.
Dvorak <i>et al.</i> (2006)	-	-	Sl 10% - 20%	Optimum diameter for H P is 0.3 to 0.35 m ³ while on volumes more than 0.45 to 0.5 m ³ the time consumption goes up. F maximum performance during the distance interval of 200-400 m and a mean vol. of 0.45-0.5 m ³ .
Mederski (2011)	Co	T	Stand age of 44 and 72 years old.	H P in MF and Sr in the 44 old stand is 5.87 m ³ respectively 4.52 m ³ and for the F P was 5.03 respectively 4.52 m ³ . For the 72 year old stand the H P is 11.53 in MF and 8.70 m ³ in SR while for the F P is 11.22 respectively 8.84m ³ . Fr C lower in MF than SR.
Dvorak <i>et al.</i> (2008)	-	-	-	Concluded that operator working experience is greater than the the education, differences in total of 64.95 second were found between two operators.
Macku <i>et al.</i> (2010)	Co	IF	D 26 to 30 cm, Atv 0.67 to 0.91 m ³	They found out that incidental felling is not lowering the efficiency of the harvester on a 25% Sl ground.
Szewczyk <i>et al.</i> (2010)	M	-	D 23.5 cm Atv 0.4 m ³	The H moves 31% of the working cycle and the cutting time is 45%. C were 3.97E/ m ³ /12 h shift and 3.47E/m ³ / 16 h shift. Chainsaw cost for 8 h shift is 4.02E/m ³ .
Dvorak <i>et al.</i> (2011)	-	-	Sl up to 33%	F P is 7.7 to 16.7 m ³ /h with an Av per load of 33m ³ . Ratio of work operations driving empty 15%, L time 43%, driving loaded 15% and UL time is 26%.Normal shift time consumption is 76% of the total shift time.
Mederski <i>et al.</i> (2011)	Co	T	55 year old pine	T intensity varied from 43.52 to 98.12m ³ /ha. An avg. T intensity of 57.56 to 75.56 m ³ /ha resulted in 21% better L P from 23.14 to 28.08 m ³ /ha
Brzozko <i>et al.</i> (2012)	Co	WF	Avg. vol. of 0.1 to 1.4 m ³	The productivity of an experienced operator ranges from 7 to 68 sec. while for the inexperienced one is 11 to 177 seconds
Gerasimov <i>et al.</i> (2012)	M	CF	Avg. stem volume is 0.31m ³ /under bark	The harvester produced from 4.3 to 14.9m ³ u.b/Ho and 16 to 49.5 m ³ u.b/stem processing machine hour. Time processing varied from 0.17 to 0.45

For Oceania the tree diameter had increased showing harvesting productivities of 143 m³/productive working hour. Another study was revealing 40% time consumption for felling and delimbing while the rest is for bunching, clearing, moving and delays.

For the rest of Europe the data was obtained mostly in thinned stands with average tree volumes ranging from 0.09 to 0.9 m³. Productivity was in average from 5 to 15 m³/ h for the harvester.

Analysis of the fuel, lubricants and spare part consumption

Consumption of fuel, lubricants and spare parts is an important factor which is influencing also the stump to mill wood price. An improper use of the technologies will have negative consequences on the economical side of the wood chain but also a great impact on the environment. From the five studies four of them are realized in the Nordic countries and one is developed in Continental Europe. A bench mark for reporting

consumption is at the round value of 1000 m³. Air pollution as well as soil has a great impact on the topics.

Analysis of soil and tree damage

Second largest section is analyzing the short and long term impact on trees and soil. Most of the samples were taken at depths from 0 to 30 cm to evaluate the compaction degree of the soil. Tire pressure and with is not so important as the number of passes and load of the machines. After

Tab. 6 Main findings of the cited references in relation to fuel, lubricants and spare parts consumption

Authors	Tree type	Type of cut	Stand characteristics	Major results
Athanassiadis <i>et al.</i> (1996)	-	t-	-	Consumption for 1000m ³ u.b was 935 l diesel for F and an avg. of 1088.5 l for the H, hydraulic oil was 17 l for F and 33.6 l for H, chainsaw oil 2.8 l. Spills were 20l for hydraulic oil and 35 l for chainsaw oil.
Nordfjell <i>et al.</i> (2003)	Co	SL/PW	Atv0.22 m ³ Fr Di 360 to 514 m	The consumption was with 53-83% higher for PW than SL. The P was with 37 to 50% lower for PW. Field consumption was 8.3 to 15.7l/Ho.
Nordfjell <i>et al.</i> (2007)	-	-	-	Lubrication characteristics of 2 vegetable and 1 mineral oil in laboratory. The study revealed that a oil flow of 2ml/min was found to be enough to prevent high temperature on all oil types.
Klavac <i>et al.</i> (2009)	-	CF	-	Co2 values was 9.63kg/m ³ of delivered timber for diesel and 10.64 kg/m ³ for rapeseed methyl ester.
Athanassiadis <i>et al.</i> (2000)	-	-	-	LCA analysis for 1000m ³ of Hr and Fr wood. 1321 spare parts were included in this study. Min. 46 kg of spare parts and a max. of 58 kg are used for this wood amount. On the life cycle of the machine about 38-45% of the total mass will be replaced.

Tab. 7 Main findings to the cited literature in relation to tree and soil damage

North America		
Authors	Forest type	Major results/ Research topic
McNeal <i>et al.</i> (1992)	Co	Studied 106 plots to find out that the tree damage is in avg. 40 cm ² , 20% of the surface is occupied by tracks, and 13% presents soil damage
Landsber <i>et al.</i> (2003)	M	Compaction was in the legal limits, on steep terrain the effect was less than on flat terrain
Sutherland (2003)	-	For limiting the negative effects of Hr by using tracked machines for low pressure on the soil, lowering the F payload, moving to drier frozen areas
Froese (2004)	Co	From 18.8 ha, 38.3% was moderate disturbed. Compaction was measured at 10-20-30 cm. Soil resistance for penetration grew with 13.8% after F pass.
Han <i>et al.</i> (2006)	Co	Samples taken at 10-20-30 cm. Results at 10 and 20 cm showed higher compaction but at 30 cm the penetration resistance was not significantly.

Tab. 7 (continued) Main findings to the cited literature in relation to tree and soil damage

Han S.,K., (2006)	Co	At the same humidity in soil both CTL and WT method produced the same compaction values. Heavy slash is reducing soil compaction on corridors.
Labelle <i>et al.</i> (2011)	M	Measured the compaction after 5 years from the Hr time. Soil density grew from with 15.5% respectively 17.5% after Hr. Compaction was present even at 1 meter aside the tracks. After 5 years the soil had not fully recovered.
South America		
Linerros <i>et al.</i> (2003)	Co	20 m circular plots were used to assess the tree damage, only 12.3% of the 16 year old pine trees had some kind of damage
Dias <i>et al.</i> (2007)	B	27 soil samples were taken before and after harvesting. After 8 years the soil had recovered after the harvesting process with harvester, forwarder and feller-buncher.
Oceania		
Wood <i>et al.</i> (2006)	-	Cone penetrations resistances were linear with depth, to approx. 20cm. Below that they are relatively constant. Penetration resistances increased with nr. of passes in dry season, in wet season the pattern was not evident.
North-West of Europe		
Nugent <i>et al.</i> (2003)	-	Erosion after harvester passes was 10.2×10^{-2} cm/m, and varied between 0.7 and 24.7×10^{-2} cm/m
Wood <i>et al.</i> (2003)	Co	Where terrain and slash road design are non-limiting, slash road have the potential to provide sustained ground protection.
Asia		
Matangaran (2012)	B	Measurement were take up to 50 cm in depth and soil humidity of 23 %. At one pass compaction was 32.22% more (no branches on the track) and 10% when branches were on the track
Nordic countries		
Siren (2001)	Co	65% of the tree damage was made by the falling trees. An avg. of 54 cm ² was for light injuries and 81cm ² was for severe injuries. 92.4% of the damages was observed on the stem and 7.6% was at the roots. The damages for the summer operation was double (78cm ²) than in winter operations (39cm ²)
Granhus <i>et al.</i> (2001)	Co	Studied the injury and mortality in 24x28m plots. Morality varied from 5 to 51% while the injury varied from 17 to 76%
Eliasson (2005)	Co	At tire pressure of 300-450-600 kPa the only factor that affects compaction is the number of passes. Harvester increased the soil density until depths of 30 cm
Eliasson <i>et al.</i> (2007)	-	Studied the effect of 0-10-20 cm of slash on soil compaction. Slash roads are reducing compaction on the first 20 cm of soil. One pass on 0 cm slash road equals with 5 passes on slash road regarding soil compaction
Sakai <i>et al.</i> (2008)	Co	They studied compaction degree after 1,8 and 24 passes at a soil humidity of 60%. After 8 passes the compaction degree was high. High tire pressure results in deep soil compaction
Lindroos <i>et al.</i> (2011)	-	For distances more than 200 m a forwarder + trailer showed the efficiency on larges loads with decreased damage.Also the cost are decreasing when using a cheap trailer after the forwarder
Central Europe		
Wilpert <i>et al.</i> (1992)	Co	Because using small class machines only 5% of the surface is damaged. In the future they predicted that 10% of the surface will be affected

Tab. 7 (continued) Main findings to the cited literature in relation to tree and soil damage

Matthies <i>et al.</i> (1995)	-	Revealed than a tire pressure of less than 500kPa will not affect the soil, it's functions will recover in time
Weise (2002)	-	Quantified the impact of heavy machinery (harvester, forwarder, skidder) on soil compaction in relation to tire pressure, load, type of tire
Limbeck-Lilienau (2003)	-	The harvester forwarder system caused in winter 3% to 6% tree damage while in summer 12 to 15% damage. The system forwarder cable yarder had 20 to 40% tree damage
Cacot <i>et al.</i> (2006)	-	Analyzed the soil impact of harvester with various tires and pressure during 1999 - 2002
Ampoorter <i>et al.</i> (2007)	-	Harvester induced an increase of soil properties in the upper 30 cm of the soil compared with undisturbed one. Sandy soils are expected to recover very slowly.
Ampoorter <i>et al.</i> (2012)	-	Literature review on impact on sandy and clayey forest soils during 1955-2007 periods. In most of the cases compaction reach 30 cm in depth with the 0-10 cm layer being the most affectedt. Number of passes varied from 1 to 12
Balkan countries		
Porsinski <i>et al.</i> (2006)	B	Used two methods to describe traffic on cohesive soils measuring humidity and penetration resistance at 0-15-30 cm
Mali (2007)	-	Studied the soil impact on the tracks used by the harvester and forwarder
Tsioras <i>et al.</i> (2010)	B	2 m away from the skidding road trees were observed, showed that 20% of the trees were damaged
Zoric <i>et al.</i> (2012)	B	Compaction due to forwarder passes (from 4 to 13 times) at a tested depth of 0 to 15 cm. On good bearing soil the effects are low. No correlation were found between nr. of passes and compaction
Porsinski <i>et al.</i> (2012)	-	Using tracked wheeled is lowering the soil damage while using 710 mm tires is not satisfactory with increased load compared to the 600 mm ones. Using 4 axes machines lowers also the soil pressure
Eastern Europe		
Moskalik <i>et al.</i> (1998)	-	Studied compaction and tree damage degree of horses, forwarder, harvester and skidders. The horse had the lowest compaction impact while the skidder had the greatest. Most tree damage was made by the skidder, the lowest were made by the forwarder
Suwla (1999)	-	Observed two harvesting methods. The first with chainsaw and horse 2.8% damage in 1 st thinning and 5.3% in 2 nd thinning. For the chainsaw and forwarder the damage was 3.4% in the first thinning respectively 3.9% in the 2 nd thinning
Rosnovski (2001)	Co	Determined the soil compaction degree on road with and without slash reinforcements
Gapsyte (2003)	Co	In a pine stand aged 35 to 98 years old the tree damage was 51% of the total tree number due to the working method. Lowest impact had the chainsaw and forwarder method
Dvorak (2006)	Co	Damages were 2 to 3.6% from the observed spruce trees. In the 3 years class a nr. 19-23 trees were damaged while in the 5 year age class a number of 23-28 trees were damaged

Tab. 7 (continued) Main findings to the cited literature in relation to tree and soil damage

Gerasimov <i>et al.</i> (2010)	-	The track influence on soil compaction varied, bulk density increased with 1.30 g/cm ³ vs. 1.24 g/cm ³ on moist soils and it was the same on wet soils by the 10 th pass.
Gebauer <i>et al.</i> (2010)	-	Demonstrated that the maximum soil compaction factor is exceeded due to the heavy machinery. Co ₂ level from soil and air raised after using the harvester and forwarder system.
Rejšek <i>et al.</i> (2011)	-	Measurements were taken in the upper soil horizon to reveal the soil compaction and impact. Measurements were repeated after 6 months. They showed that each area is responding different to compaction and soil recovery
Gerasimov <i>et al.</i> (2012)	-	Found that the damage on industrial round wood is made by feed rollers and delimbing knives. The rejection rate is low if the harvester head has sharp knives.

some authors the soil had fully recovered after 8 years had passed since the operation took place while after other after 5 years the soil had not recovered. Harvesting and forwarding operation during winter produces less damages than in summer, although soil impact due to the machines is varying from region to region.

Computer simulations

The last section refers to simulating the entire real work situation with the help of a computer. Soil compaction, productivity, different harvesting and forwarding systems operated with experienced and inexperienced operators are subject to the references.

CONCLUSIONS

Following this study, several conclusions may be drawn, especially in what concerns the forest type and topography specific to Romania. As shown by this literature review, the majority of the studies were made in coniferous stands where the forest equipment such as harvesters had normal working conditions, because such equipment was designed for such tree species. By considering that in Romania the percentage of coniferous species occupies 28% of the total forested area, deploying such equipment may lead to considerably increments of productivity, additionally serving to work safety. Nevertheless, forwarder equipment can be deployed also in broadleaved stands due to the fact that such equipment does not have

Tab. 8 Main findings of the cited references in relation to computer simulations

Authors	Forest type	Major results/ Research topic
Wang <i>et al.</i> (1999)	-	Are doing simulations in order to raise efficiency while stand slope and damage are not mentioned. Felling on a 0.16 ha stand took 10 to 35 min while skidding took 40 to 90 min on a 7.8 ha stand. Both methods were influenced by stand density, machine factors
Nuutinen <i>et al.</i> (2008)	-	Made time studies via the simulator screen with experienced and inexperienced operators. Inexperienced operators made more mistakes but statistically the difference was not significant between groups
Belbo (2010)	-	Simulated harvester efficiency which increased rapidly when the grapple diameter increased from 2 to 4 times the avg. diameter
Jori <i>et al.</i> (2010)	-	Are simulating how many passes can a forwarder do on a low bearing soil
Lamminen <i>et al.</i> (2011)	-	Found out 40 to 50% differences on simulator between experienced and inexperienced operators. They try to find out factors that influence prod. and also loading phase. The speed and boom out of the crane is most important in productivity
Talbot <i>et al.</i> (2003)	-	Are comparing a harvester with a harvester forwarder system, both systems show a competitive advantage, in forest structures with low object volumes or frequent relocation

specific limitations related to the tree species, which otherwise is the case of harvesters. On the other hand, there were only few international studies analyzing the work productivity when harvesting timber having tree diameter over 40 cm and terrain slope over 30%. Future analysis should be done also in this direction due to the fact that a large proportion of the Romanian forests are over 40 years old. Also, in the case of clear cuts or uniform selective cuts, harvesting volumes can range from 250 m³/ha in case of a 40 year old stand, up to 400 m³/ha in case of a 100 year old stand. Indeed in case of harvesting small volumes these machines are not profitable due to the low productivities and high operating costs. Another aspect that should be taken in account is the lack of special made harvester and forwarder corridors that these machines require in order to achieve their productive capacity. Also, little is known about how the effective tree marking operations, like those conducted in Romania, could influence the work productivity when using such forest equipment. Operator training, therefore his or her experience in operating harvesters or forwarders is an important issue not only in Romania; such aspects should be studied especially since in Romania no purpose designed training programs are available.

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