Skidding operations in thinning and shelterwood cut of mixed stands– Work productivity, energy inputs and emissions

Vusić, Dinko; Šušnjar, Marijan; Marchi, Enrico; Spina, Raffaello; Zečić, Željko; Picchio, Rodolfo

Source / Izvornik: **Ecological Engineering, 2013, 61, 216 - 223**

Journal article, Published version
Rad u časopisu, Objavljena verzija rada (izdavačev PDF)

https://doi.org/10.1016/j.ecoleng.2013.09.052

Permanent link / Trajna poveznica: https://urn.nsk.hr/urn:nbn:hr:108:177645

Rights / Prava: In copyright / Zaštićeno autorskim pravom.

Download date / Datum preuzimanja: **2024-12-06**

Repository / Repozitorij:

University of Zagreb Faculty of Forestry and Wood Technology

DIGITALNI AKADEMSKI ARHIVI I REPOZITORIJI

Ecological Engineering 61 (2013) 216–223

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

Skidding operations in thinning and shelterwood cut of mixed stands – Work productivity, energy inputs and emissions

Dinko Vusić[a], Marijan Šušnjar[a], Enrico Marchi[b,*], Raffaello Spina[c], Željko Zečić[a], Rodolfo Picchio[c]

[a] University of Zagreb, Faculty of Forestry, Department of Forest Engineering, Svetošimunska 25, HR-10002 Zagreb, Croatia
[b] University of Florence, Department of Agricultural, Food and Forest Systems Management, Via S. Bonaventura 13, 50145 Firenze, Italy
[c] University of Tuscia, Department of Science and Technology for Agriculture, Forests, Nature and Energy (DAFNE), Via San Camillo de Lellis, 01100 Viterbo, Italy

ARTICLE INFO

Article history:
Received 14 May 2013
Received in revised form 8 July 2013
Accepted 20 September 2013

Keywords:
Skidding
Extraction
Emissions
Energy expenditure
Logging operations

ABSTRACT

The present study was conducted on the slopes of the Bilogora mountain in the central region of Croatia. Logging operations were performed at two felling sites with two different silvicultural treatments: thinning was performed at worksite A, and a regeneration cut was performed at worksite B. A half-length harvesting method and the skidding of half-processed wood assortments were used in the study areas. At both sites, the timber extraction was performed by a rubber-tired mini-skidder (Ecotrac 55V, Hittner tractors, Bjelovar – Croatia). The main aims of the present study were to provide limited but significant data regarding the experiences related to working times, productivity, energy inputs, and greenhouse gasses (GHG) emissions for timber extraction using a skidder. This skidder was an average, compact and highly specialised machine, and, as shown by previous studies, this mini-skidder can effectively replace forestry-fitted crawler tractors, common agricultural tractors and cable yarders under particular conditions. In the context of small-scale forestry this mini-skidder as when compared with common agricultural tractor or forestry-fitted tractors, is more environmentally friendly in terms of energy inputs and GHG emissions during the wood extraction operation. In addition, the most important parameters that affect the use of a similar machine during wood extraction were evaluated in the present work. The average extraction net (PSH_0) productivities ($m^3\ h^{-1}$) were 3.20 $m^3\ h^{-1}$ for worksite A and 4.95 $m^3\ h^{-1}$ for worksite B. The energy consumptions were 113.4 $MJ\ m^{-3}$ for worksite A and 56.1 $MJ\ m^{-3}$ for worksite B. Lower pollutant emission values were calculated for worksite B. At worksite B, the minimum value of CO_2 emissions on the environment caused by the skidding operation was determined.

© 2013 Elsevier B.V. All rights reserved.

1. Introduction

The mechanisation of timber harvesting depends on forest types, wood species, management methods and the terrain and climatic conditions. In several countries of south-Europe, motor-manual felling and processing are still very common (Brachetti Montorselli et al., 2010; Çalişkan, 2012; Picchio et al., 2009). After felling, processed or half-processed wood assortments are usually forwarded or skidded to the landing. Despite recent advances in dedicated harvesting technology, forestry-fitted farm tractors are still the backbone of the logging fleet in Mediterranean countries (Spinelli and Magagnotti, 2011), especially for the majority of forest owners and for a portion of the non-industrial private forestry population. Farm tractors are used for a variety of forest harvesting tasks, especially extraction (Picchio et al., 2009; Šušnjar et al., 2008), but their design and features are not developed for forest logging requirements. Rubber-tired mini-skidders can effectively replace forestry-adapted farm tractors under certain conditions, as outlined in previous studies (Savelli et al., 2010; Spinelli et al., 2012). Replacement is desirable in terms of environmental protection and labour safety and offers a substantial economic benefit (Spinelli et al., 2012, 2013).

In most Mediterranean countries, such as Croatia, Italy and Slovenia, the evolution of small-scale mechanisation is very important for forestry owners. Currently, the main method for wood extraction is winching-skidding, which is labour-intensive but still very popular among small scale operators (Picchio et al., 2012a). Methods should be identified to make wood extraction more

* Corresponding author. Tel.: +39 0553288609; fax: +39 055319179.
E-mail address: enrico.marchi@unifi.it (E. Marchi).

0925-8574/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.ecoleng.2013.09.052

effective, safe and comfortable. In addition, the growing need to implement sustainable forest management schemes often results in a massive shift towards continuous cover forestry (CCF) and reduced impact logging (RIL) (Picchio et al., 2012b); this shift has resulted in a real need for specialised and technologically advanced machines that are suitable for forestry.

Both industrial and non-industrial forestry are still under-investigated in terms of energy input and Greenhouse Gas (GHG) emissions (Heinimann, 2012). In forest harvesting, as in other productive sectors, each product, process or activity requires an energy input; forestry uses primary fossil resources and, hence, contributes GHG emissions into the environment. The impact of any technology (system) or product on the environment can be assessed by LCA methodology, which can identify inputs and outputs, including the environmental impact (ISO 14040-2 standards, revised in 14044) (Heinimann, 2012; Koponen et al., 2013; Maesano et al., 2013).

Studies regarding the performance, energetic inputs, and greenhouse gasses (GHG) emissions of timber extraction by skidding and that examine the opportunities for improvement remain limited (Picchio et al., 2009). Additional information on this topic is required, especially in terms of the energetic analysis and GHG emissions. Comparing these results to those obtained from earlier studies may help to evaluate the progress of technological development in the field.

The term “energetic analysis” refers to the study of the implied energy use in the production of a service or a product (Balimunsi et al., 2012; Picchio et al., 2009; Picchio et al., 2012c). This energy includes both the energy directly used during the production process (direct) and the energy stored in the materials used for the production (indirect). The direct and indirect consumption of fossil energy is just one aspect of the environmental impact of human activities, and its use as the main evaluation parameter may appear to be restrictive. Nevertheless, the use of fossil energy remains a good indicator of system sustainability (Magagnotti and Spinelli, 2011; Pervanchon et al., 2002; Picchio et al., 2012d; Maesano et al., 2013) and may partly reflect its other dimensions as well. Furthermore, fossil energy use has been adopted by other studies conducted on forest harvesting and may provide a good indicator for the comparison of results (Magagnotti and Spinelli, 2011).

Greenhouse gases essentially affect the climate, and a reduction of their emissions into the environment is one of the primary objectives of the current EU environmental policy (Viana et al., 2010). For this goal, it is absolutely necessary to increase the share of energy from renewable sources, where a zero balance of CO_2 originating from fossil resources can be expected. However, a zero balance of CO_2 is impossible in this case, as in many other systems of renewable energy production because of fossil fuel consumption during the production of renewable energy sources (Gustavsson et al., 2011; Klvac et al., 2012). In the case of forest harvesting, these emissions are mainly due to the use of tractors and mechanical equipment with internal combustion engines. The expected CO_2 emissions can be determined on the basis of the molecular formula, carbon–hydrogen ratio (C:H), energy content, and other factors associated with the fossil fuel source used (Calais and Sims, 2006). However, the simple calculation of CO_2 emissions based on the C:H ratio on a stoichiometric basis is rather naive because the emissions and their composition are also affected by other factors. Emissions generated during combustion can be related to the engine output power, where they depend on thermal efficiency, i.e., on the capacity of transforming fuel energy to engine efficiency. The emission factors of compression-ignition engines during combustion for harvester technologies were studied by (Athanassiadis, 2000; Klvac et al., 2012). The emissions generated by combustion, however, do

Table 1
Description of the worksites and stand characteristics.

Worksite	A (Forest office Kloštar Podravski)						B (Forest office Bjelovar)					
Location	45° 54′ 24″ N; 17° 06′ 06″ E						46° 02′ 19″ N; 16° 50′ 31″ E					
Area [ha]	13.56						40.14					
Age [years]	60						100					
Slope [%]	17 (extraction uphill)						0					
Altitude [m] a.s.l.	190–245						180–215					
Tree species	*Quercus petraea* (Matt.) Liebl.	*Fagus sylvatica* L.	*Carpinus betulus* L.	*Tilia* sp.	Other hard broadleaves	∑	*Quercus petraea* (Matt.) Liebl.	*Fagus sylvatica* L.	*Carpinus betulus* L.	*Robinia pseudacacia* L.	Other hard broadleaves	∑
Number of trees [N ha^{-1}]	30	340	67	14	45	496	11	133	34	8	2	188
Basal area [m^2 ha^{-1}]	1.52	13.87	2.05	0.77	3.29	21.5	1.82	27.6	2.39	0.24	0.11	32.16
Growing stock [m^3 ha^{-1}]	15.41	129.65	16.59	7.37	34.14	203.17	32.24	508.32	37.77	2.07	1.67	582.06
Average DBH [cm]	25	23	20	27	30	23.46	46	51	30	19	30	45.32
Average height [m]	20	19	17	21	22	–	33	35	29	20	29	–
Marked volume [m^3 ha^{-1}]	2.21	15.71	4.20	1.40	9.66	33.19	15.52	103.69	5.86	–	0.40	125.47

not include the emissions developing during the production and transformation of fuels (Davison and Lewis, 1999).

The main aims of the present study were: (i) to provide working times, productivity, energy inputs and GHG emissions for timber extraction by a rubber-tired mini-skidder in thinning and regeneration cut scenarios; (ii) to determine relationships among working parameters, energy inputs, and GHG emissions; and (iii) to compare our results with the data available from previous studies (Magagnotti and Spinelli, 2011; Picchio et al., 2009; Spinelli et al., 2012; Valente et al., 2011).

2. Materials and methods

The present study was conducted on the slopes of the Bilogora mountain in the central part of Croatia. Logging operations were performed at two felling sites, with two different silvicultural treatments: thinning was performed at worksite A, and a regeneration cut was performed at worksite B. The main data regarding the worksites were measured before logging on the total treated area for both sites (Table 1).

As usual in Croatia, logging operations were performed by a group of workers (on average 3) who felled and delimbed trees by chain saw, skidded half-stems, and processed them into wood assortments at the landing by chain saw (Vusić et al., 2011; Zečić et al., 2004b; Zečić and Marenče, 2005). These logging methods are mostly used in mountainous, selective forests (Sabo and Poršinsky, 2005; Zečić et al., 2010) and in the hilly, even-aged forests of Croatia (Zečić et al., 2004a). At both sites, timber extraction was performed by a rubber-tired mini-skidder (Ecotrac 55V, Hittner tractors, Bjelovar – Croatia).

The Ecotrac 55V mini-skidder is a Croatian-made skidder equipped with a double drum winch, Hittner 2×35 kN (Horvat et al., 2007; Šušnjar et al., 2008, Tomašić et al., 2009). Its dimensions (length 4550 mm, width 1600 mm, height 2490 mm), mass (3600 kg), and engine power (40 kW) are designed to fit timber extraction requirements in thinning operations. However, although the Ecotrac 55V is designed for thinning, due to a seasonal rotation between thinning and regeneration cuts, it is often also used for the latter to achieve better yearly machine utilisation (Figs. 1 and 2).

In the present study, the use of this skidder in the regeneration cut scenario occasionally required an adaptation of the harvesting method to adjust the volume of logs to the performances of the skidder, i.e., larger stems were crosscut into assortments at the felling site and not at the landing, as is usually performed when the half-length method is used.

The system boundaries for this study were set to those of the extraction operation, i.e., only the winching and skidding operations from the stump to the landing side were taken into consideration (felling, delimbing, and cross-cutting were not considered). The Functional Unit (FU) used in the analyses was the cubic meter (m^3).

A time study layout was adapted to the basic time concepts (Björheden, 1991; Magagnotti and Spinelli, 2012). The cycle time of the machine was divided into the time elements (working phases) typical of this extraction system. In this manner, time consumptions for unloaded travel, felling site works (positioning, line pulling, choking, winching, load manoeuvring, mounting), loaded travel, and landing works (unchoking, bunching, skidder turning, mounting) were recorded. Skidding work elements were precisely divided by fixed points, and the time consumption of each element was recorded by the snap-back chronometry method (Balimunsi et al., 2012; Harstela, 1991; Savelli et al., 2010). To calculate the outputs in different areas, effective time and delays of up to 15 min (UT, unavoidable time and AT, avoidable time) (Harstela, 1991; Picchio et al., 2009) were taken into consideration. Along with time consumption, skidding distance, line pulling/winching distance, and skidded load data were also recorded. The load volume was determined at the landing by the measurement of the processed wood assortments, according to the Croatian standards for products of forest harvesting (Anon., 1995). Skidding and winching distances were recorded by means of a laser gauge (Stanley TLM 300 TRU LASER). The productivities per worker for the different operations were then calculated as follows: average gross productivity (PSH_{15}), computed on the basis of time consumption, inclusive of all delays up to 15 min; and average net productivity (PSH_0), computed with the exclusion of delays.

Table 2
Emission factors of compression-ignition engines (C) and spark-ignition engines (S) in wheeled tractors as related to engine output power (kg kWh^{-1}) (USEPA, 1985 in Klvac et al., 2012; Athanassiadis, 2000). Conversion from kWh to MJ: 1 kWh = 3.6 MJ; PM_{10} – particular matters up to 10 μg and less; VOCs – volatile organic compounds.

Pollutant (g MJ^{-1})	Wheeled tractor	
	C	S
CO_2	263	263
CO	9.84×10^{-3}	1.90×10^{-1}
Formaldehyde	3.78×10^{-4}	3.41×10^{-4}
NO_x	1.60×10^{-2}	8.54×10^{-3}
PM_{10}	1.70×10^{-3}	4.84×10^{-4}
SO_2	1.14×10^{-3}	3.04×10^{-4}
VOC_s	2.36×10^{-3}	7.16×10^{-3}

The direct (fuel consumption of machinery) and indirect inputs (machinery and tools) were calculated according to the Gross Energy Requirements (GER) method (IFIAS, 1975; Picchio et al., 2009). The GER method is commonly used in energetic analyses. The method underlines the importance of fossil energetic sources in the actual productive systems and focuses only on the fossil energy flow (direct and indirect). The indirect inputs (II; MJ ha^{-1}) of machinery and tools were determined by the average energetic values of the raw materials in relation to the quantitative presence (pm; %), total machinery mass (m; kg), total hours scheduled (tl; h ha^{-1}) for the life cycle of the machinery and tools, and the number of hours of their use (ut; h) during the present study (Picchio et al., 2009).

To improve the energetic analysis, inputs were also recalculated in relation to the extraction distance and load volume, by means of a regression analysis.

Pollutant emissions due to the extraction operations at both sites were also determined. Emissions generated from the fuel were calculated as the sum of emissions produced by fuel combustion (Efc) and emissions produced during the fuel production, transport, and distribution (Efp).

The calculated pollutant emissions resulting from fuel combustion (Efc) take into account the energy content of fuel, emission factors related to the engine output power, and the thermal efficiency of the fuel combustion process. The calculations were made using the formula suggested by Klvac et al. (2012), applying the emission factors used for wheeled tractors (Table 2), with the exception of the CO_2 emissions, which were determined by applying the emission factor adopted by Athanassiadis (2000).

The calculation of emissions generated during fuel production, transport, and distribution (Efp) were based on the fuel energy content and emission factors as published by Klvac et al. (2012). Only the emission factor of 0.0862 for HC was adopted from Athanassiadis (2000). The emissions related to lubricant consumption were calculated as the sum of the emissions produced by both the production processes (Eop) and the reprocessing of used oils for the purposes of combustion (Eor), as proposed from Athanassiadis

Fig. 1. Ecotrac 55V skidder in thinning.

Fig. 2. Ecotrac 55V skidder in regeneration cut.

(2000) and Klvac et al. (2012). The emission factors for the lubricant were selected on the basis of oil types, i.e., fully mineral gear oils, semi-synthetic engine oil, with an 80:20 ratio, and mineral lubricants. The fuel and oil consumptions were determined on the basis of nominal engine power, engine load factor, engine specific fuel consumption, and time of use per output unit, as reported in Picchio et al. (2009).

After checking for the normality (Kolmogorov–Smirnov test) and homogeneity of variance (Levene test), *t*-tests for independent samples were applied to the collected data. The *t*-tests for independent samples were applied to test the hypotheses that there would be no significant differences between the measured tree volumes, tree heights or DBHs for the two studied worksites (A and B). To test the hypotheses that there would be no significant

Table 3
Average (±standard deviation) value of extraction parameters (*t* test results for indipendent samples).

Worksite	Logs per trip [n°]	*p*	Load volume [m^3]	*p*	Extraction distance [m]	*p*
A	3.4 ± 0.88	<0.05	1.037 ± 0.33	0.16	210 ± 32.6	<0.05
B	1.4 ± 0.61		1.191 ± 0.41		260 ± 28.4	

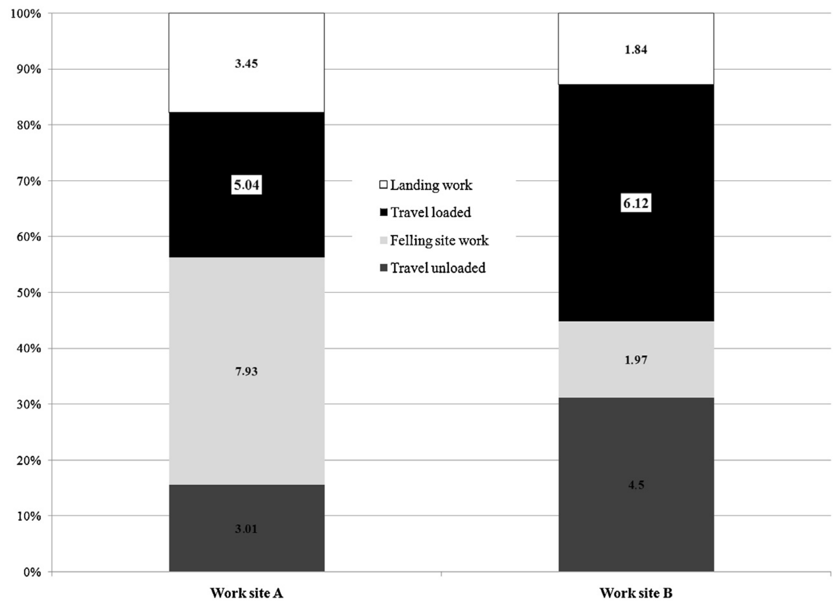

Fig. 3. Time structure of the average cycle, represented as percents (Y axis) and absolute values (in the columns in minutes) for the two worksites.

differences between the extraction parameters and the working times at cycle terminals (loading area and landing) between the sites, independent-sample t-tests were applied.

Regression analyses were applied to define the effects of total extraction distance and load volume on both extraction time and energy inputs. This is the logical choice for determining the extraction time because the extraction distance is the main influencing factor for travel time consumption, and the load volume is a good parameter for terminal time consumption (Savelli et al., 2010). Analyses were performed with Statistica 2007 software.

3. Results

3.1. Working time and productivity

The results showed that the tree volumes, tree heights, and DBHs of the two studied worksites (A and B) were significantly different ($p < 0.01$).

During logging, 31 and 62 skidding cycles were recorded in the thinning (worksite A) and in the regeneration cut (worksite B) worksites, respectively. Extraction parameters and working times at cycle terminals showed significant differences between worksites, except for the average load volumes, mounting times at landing, and skidder turning (Tables 3 and 4). One skidding cycle at worksite A, with an average skidding distance of 210 m, required 19.41 (±8.26) min to extract an average of 1.037 m^3 in 3.4 pieces per load (Fig. 3). At worksite B, one skidding cycle, with an average skidding distance of 260 m, required 14.44 (±3.44) min to extract an average of 1.191 m^3 in 1.4 pieces per load.

The regression analyses were statistically significant ($p < 0.01$) for both working sites. The equations of the fitted models were:

$$\text{Extraction time[min]} = -13.26 + 9.04 * (\text{extracted volume}) + 0.047 * (\text{total extraction distance})$$

for worksite A; and

$$\text{Extraction time[min]} = -52.70 + 2.19 * \text{Ln(extracted volume)} + 10.77 * \text{Ln(total extraction distance)}$$

for worksite B.

The R^2 statistic indicated that the fitted models explained 58% and 62% of the variability in the extraction time cycles at worksites A and B, respectively.

The average extraction net (PSH_0) and gross (PSH_{15}) productivities ($m^3\,h^{-1}$) were significantly different (t-test, $p < 0.01$) between the two working sites. At worksite A the PSH_0 was 3.20 $m^3\,h^{-1}$ and the PSH_{15} was 2.56 $m^3\,h^{-1}$, while at worksite B the PSH_0 was 4.95 $m^3\,h^{-1}$ and the PSH_{15} was 4.57 $m^3\,h^{-1}$.

Table 4
Average (±standard deviation) work element times at the two terminal sites (t test results for indipendent samples).

Terminal	Work element	Felling site A		Felling site B		p
		min	%	min	%	
Felling site	Positioning	1.10 ± 0.87	9.65	0.54 ± 0.19	14.17	<0.01
	Line pulling	1.61 ± 0.72	14.12	0.27 ± 0.23	7.09	<0.01
	Choking	1.54 ± 0.82	13.51	0.43 ± 0.14	11.29	<0.01
	Winching	1.81 ± 0.61	15.88	0.29 ± 0.11	7.61	<0.01
	Load manoeuvring	1.43 ± 0.46	12.54	0.04 ± 0.01	1.05	<0.01
	Mounting	0.45 ± 0.19	3.95	0.41 ± 0.18	10.76	<0.01
Landing	Mounting	0.31 ± 0.12	2.72	0.38 ± 0.15	9.97	0.15
	Unchoking	1.36 ± 0.53	11.93	0.51 ± 0.27	13.39	<0.01
	Bunching	1.49 ± 0.29	13.07	0.55 ± 0.11	14.44	<0.01
	Skidder turning	0.30 ± 0.14	2.63	0.39 ± 0.14	10.24	0.61

Table 5
Enrgetic inputs in the two worksites.

Worksites	Direct input	Indirect input	Total input
A ($MJ\,m^{-3}$)	95.7	17.6	113.4
B ($MJ\,m^{-3}$)	44.7	11.4	56.1

3.2. Energy inputs

The average fuel consumption was 1.8 $kg\,m^{-3}$ at worksite A and 0.8 $kg\,m^{-3}$ at worksite B, while the average oil consumption was 0.03 $kg\,m^{-3}$ and 0.02 $kg\,m^{-3}$ at worksites A and B, respectively.

The energy consumption was higher at worksite A than at worksite B (Table 5). The largest share of the total energy consumption was due to direct inputs: 85% at worksite A and 80% at worksite B.

The regression analyses applied to the energetic input were statistically significant ($p < 0.001$) for both working sites. The equations of the fitted models were:

$$\text{Energetic input} \quad [\text{MJ}^{-1}] = -122.41 + 71.56 * (\text{extracted volume}) + 0.336 * (\text{total extraction distance})$$

for worksite A; and

$$\text{Energetic input} \quad [\text{MJ}^{-1}] = 14.93 * (\text{extracted volume}) + 0.091 * (\text{total extraction distance})$$

for worksite B.

The R^2 statistic indicated that the fitted models explained 59% and 98% of the variability in Energetic input at worksites A and B, respectively.

3.3. Pollutant emissions

The lower pollutant emission values were calculated for worksite B. At this site, the minimum value of CO_2 emissions on the environment by the skidding operations was determined. Detailed calculated emissions associated with the consumption of fuel and lubricant are shown in Table 6.

The emissions due to the fuel production process (Efp) were negligible in comparison with those due to fuel combustion (Efc), with the exception of HC. The combustion process was responsible, on average, for 94% of CO_2, 99.5% of CO, 32.7% of HC, 98% of NO_x, and 99.3% of PM emissions.

4. Discussion

The present study was performed at two felling sites of different stand and harvesting conditions to test different scenarios of skidding extraction performances with a mini-skidder, in terms of productivity, energy input, and pollutant emissions.

The analyses of working time (Table 4) in relation to the extraction parameters (Table 3) showed that the skidding productivity is affected by the “piece-volume-law” (Stampfer and Kanzian, 2006) and the felling intensity. In fact, the large number of pieces that have to be gathered during thinning to compose an acceptable load increases the line pulling, choking, winching, unchoking, and bunching times. Moreover, the stand characteristics (density of residual trees) increase the positioning and load manoeuvring time. The felling intensity and tree dimensions deeply affect the time needed to form a desired load. At worksite A, both winch drums were used most of the time (77%). At worksite B, the higher dimensions of the trees did not require the use of both drums very frequently; both drums were used approximately 15% of the time. At worksite B, fewer pieces were required to compose a load, and lower winching distances were recorded. Both of these factors had a crucial impact on the cycle time consumption.

The remarkable differences in productivity between the worksites was likely due to the different terrain slopes (worksite A had an average slope of 17%, while worksite B had an average slope of 0%), different silvicultural treatments (worksite A used thinning, while worksite B used regeneration cut), and different unitary volumes per log (the worksite A mean volume was 0.36 m^3, while the worksite B mean volume was 0.98 m^3). The lower log volumes required a higher time consumption at both terminals (landing and felling areas). All of the mentioned variables were often used to mark the differences between treatments (Olsen and Seifert, 1984), and they justify the significantly higher productivity observed at worksite B when compared to worksite A, as was also demonstrated in previous studies (Magagnotti and Spinelli, 2011; Savelli et al., 2010; Spinelli et al., 2012).

The results of the present research were compared with the data available from previous studies (Magagnotti and Spinelli, 2011; Picchio et al., 2009; Spinelli et al., 2012; Valente et al., 2011), as shown in Table 7. The studies chosen for comparisons consider environmental and operational situations in which a machine such as the one examined in the present research could be properly used. Certainly, the variables are many and do not allow a detailed comparative analysis, but the arguments that arise can be a good starting point for further research. In terms of the productivity values, those recorded in the present research are good for both worksites when compared with those recorded in previous studies. Only the use of the cable yarder appears to provide values approximately double those reported previously, but, in the publication of comparison (Valente et al., 2011), the silvicultural treatment is very different from the thinning and the shelterwood cut presented in this study.

The differences in energetic inputs between worksites could be explained mainly by the differences in the slope between the two sites, by the different unitary volume per log, and only marginally by the different silvicultural treatments applied (worksite A used thinning, while worksite B used regeneration cut). In this case, the loaded travel phase highly affected the energetic inputs because it required higher engine power and fuel consumption. In uphill extraction, the power and fuel requirements reach the highest values. At worksite A, the skidder often worked with an engine load

Table 6
Pollutant emissions due to diesel [$g\,m^{-3}$] and lubricants consumption [$g\,1000\,m^{-3}$] in the two worksites.

	Worksite A					Worksite B				
	CO_2	CO	HC	NO_x	PM	CO_2	CO	HC	NO_x	PM
Efc diesel	6765.41	71.12	2.73	115.64	12.29	3006.85	31.61	1.21	51.39	5.46
Efp diesel	442.35	0.36	5.61	2.55	0.08	196.60	0.16	2.49	1.13	0.03
Total diesel	7207.76	71.48	8.34	118.19	12.36	3203.45	31.77	3.71	52.53	5.49
Eop	7328.82	3.99	60.83	70.74	7.56	6107.35	3.33	50.69	58.95	6.30
Eor	1698.45	2.01	0.45	8.04	0.41	1415.38	1.68	0.38	6.70	0.34
Total oil	9027.27	6.00	61.28	78.78	7.97	7522.73	5.00	51.06	65.65	6.64

Table 7
Comparison conducted between the result of this study and others forestry energetic studies, focused only on the extraction operation.

Working system	Silvicultural treatment	Extraction method	Trees	Extracted volume [$m^3\,ha^{-1}$]	Average slope [%]	Average distance [m]	Net productivity [$m^3\,h^{-1}$]	Energy input [$MJ\,m^{-3}$]	CO_2 emission [$kg\,m^{-3}$]	Reference
SWS	Coppice conversion	Animals and tractor	*Quercus cerris* L.	177	45	770	1.2	161.4	–	Picchio et al. (2009)
SWS	Coppice conversion	Tractor	*Quercus cerris* L.	177	45	612	2.4	150.7	–	Picchio et al. (2009)
SWS	Coppice conversion	Chutes and tractor	*Quercus cerris* L.	177	45	656	2.2	70.2	–	Picchio et al. (2009)
SWS	Selection cut in high forest	Animal	*Fagus sylvatica* L.	78	14	160	1.9	12	–	Magagnotti and Spinelli (2011)
SWS	Selection cut in high forest	Animals	*Fagus sylvatica* L.	78	14	141	3.0	14	–	Magagnotti and Spinelli (2011)
SWS	Selection cut in high forest	Tractor	*Fagus sylvatica* L.	78	14	218	4.0	112	–	Magagnotti and Spinelli (2011)
SWS	Thinning	Tractor	*Picea abies* L. and *Abies alba* Mill.	111	42	131	3.6	45–111	–	Spinelli et al. (2012)
SWS	Thinning	Skidder	*Picea abies* L. and *Abies alba* Mill.	111	42	154	4.7	18–32	–	Spinelli et al. (2012)
WTS	Final cutting	Cable yarder	Coniferous	–	>25	–	9.6	15.2	1.3	Valente et al. (2011)
SWS	Final cutting	Cable yarder	Coniferous	–	>25	–	7.4	–	2.0	Valente et al. (2011)
SWS	Thinning	Skidder	*Quercus petrea* L. and *Fagus sylvatica* L.	33	17	210	3.2	113.4	7.2	Case of study
SWS	Final cutting	Skidder	*Quercus petrea* L. and *Fagus sylvatica* L.	125	0	260	5.0	56.1	3.2	Case of study

factor very close to 1 (calculated on the basis of engine rpm), with clear repercussions on fuel consumption.

Based on the comparisons with previous studies, shown in Table 7, overall, the required energy inputs were not high, and they amounted to medium-high values in the case of thinning (worksite A) and to medium-low values for regeneration cut (worksite B). During thinning, both the productivity and energy inputs recorded in our study with the mini-skidder showed similar values to those reported with a tractor in Spinelli et al. (2012) and Spinelli and Magagnotti (2011), while the values recorded with a skidder in Spinelli et al. (2012) showed a higher productivity and a lower energy input. However, when comparing these results, it is important to take into consideration that the performances were affected by the differences in felling intensities (lower in our study) and extraction distances (higher in our study).

The different emission loads for the two worksites could also be explained mainly by the differences in slope between the two sites, just as for the energy inputs. As shown in Table 5, the energy inputs were mainly due to the direct inputs (consumption of fuels and lubricants), and the emission load is proportionally related to the combustion of fuel.

Energy and emissions due to oil use were negligible in comparison with the emissions related to fuel consumption.

The comparison with previous studies, regarding CO_2 emissions, has been limited because the only comparable publication is one where the cable yarder is used for wood extraction (Valente et al., 2011). In this case, the values of emissions calculated in our study were higher than those of the comparison study, which is in agreement with the efficiency of the cable yarder in regards to GHG emission, as was demonstrated by previous studies (Klvac et al., 2012).

5. Conclusions

The primary aims of this study were to provide data regarding the experiences related to working times, productivity, energy inputs, and GHG emissions in timber extraction by a mini-skidder. In the context of small scale forestry, this mini-skidder may compete with the common agricultural tractor or forestry-fitted tractors in terms of energy inputs and GHG emissions during wood extraction operations.

The analysis of working time indicated that equipping a mini-skidder with a double drum winch is important in high forest thinning, due to the low size of trees, while, for regeneration cut in a high forest, the double drum winch becomes almost redundant.

In terms of productivity, energy inputs, and emissions, skidding is negatively influenced by the slope (uphill over 15%). This is an important variable to be taken into consideration in the planning and construction of forest roads (Cavalli and Grigolato, 2010).

The regression analyses performed in this study may allow reliable estimates of extraction times and energy inputs for similar forestry yards to be made, on the basis of extraction distances and extracted volumes.

Efforts at improving the efficiency of modern logging operations should now focus on increasing energy efficiency, a challenge that is already being pursued by the forest machine industry, judging by the recent appearance of new, smaller machine models that are equipped with low-emission and energy saving engines.

Acknowledgements

This study was performed in the context of the PRIN 2009 project "in_FLAMING: Developing innovative models and techniques for integrated fuel management for fire prevention in

Mediterranean and temperate forests" (national coordinator: P. Corona), funded by the Italian Ministry for Education, University and Research.

The field research was conducted with the financial support and with the human resources provided by the company "Hrvatske šume" d.o.o. Dr. R. Spina's mission to Croatia was partly sponsored by COST Action FP0902, within the scope of its 4th STSM programme.

References

Anon., 1995. Hrvatske norme proizvoda iskorištavanja šuma (Croatian standards for products of forest harvesting). Državni zavod za normizaciju i mjeriteljstvo, Zagreb, pp. 1–30.

Athanassiadis, D., 2000. Energy consumption and exhaust emissions in mechanised timber harvesting operations in Sweden. Sci. Total Environ. 255, 135–143.

Balimunsi, H., Grigolato, S., Picchio, R., Nyombi, K., Cavalli, R., 2012. Productivity and energy balance of forest plantation harvesting in Uganda. Forest. Stud. China 14 (4), 276–282.

Björheden, R., 1991. Basic time concepts for international comparisons of time study reports. Int. J. Forest Eng. 2 (2), 33–39.

Brachetti Montorselli, N., Lombardini, C., Magagnotti, N., Marchi, E., Neri, F., Picchi, G., Spinelli, R., 2010. Relating safety, productivity and company type for motor-manual logging operations in the Italian Alps. Accid. Anal. Prev. 42 (6), 2007–2012.

Calais, P., Sims, R., 2006. A Comparison of Life-Cycle Emissions of Liquid Biofuels and Liquid and Gaseous Fossil Duele in the Transport Sector. Mudroch University, Pert, Australia http://www.biodiesel.org.au/Documents/Calais_Sims_Life%20cycle%20comparison.pdf

Çalişkan, E., 2012. Productivity and cost analysis of manual felling and skidding in oriental spruce (*Picea orientalis* L.) forests. Ann. Forest Res. 55 (2), 297–308.

Cavalli, R., Grigolato, S., 2010. Influence of characteristics and extension of a forest road network on the supply cost of forest woodchips. J. Forest Res. 15 (3), 202–209.

Davison, P., Lewis, C.A., 1999. Methodology for calculating transport emissions and energy consumption, Part E. In: Hickman, A.J. (Ed.), Projekt Report SE/491/98. Transport Research Laboratory, Crowthorne, UK, p. 362.

Gustavsson, L., Eriksson, L., Sathre, R., 2011. Costs and CO_2 benefits of recovering, refining and transporting logging residues for fossil fuel replacement. Appl. Energy 88, 192–197.

Harstela, P., 1991. Work study in forestry. Silva Carelica 18, 1–41.

Heinimann, H.R., 2012. Life cycle assessment (LCA) in forestry – state and perspectives. Croat. J. Forest Eng. 33 (2), 357–372.

Horvat, D., Zecic, Z., Susnjar, M., 2007. Morphological characteristics and productivity of skidder Ecotrac 120 V. Croat. J. Forest Eng. 28, 11–25.

IFIAS, 1975. Energy analysis and economics. Workshop report, Stoccolma., pp. 9.

Klvac, R., Fischer, R., Skoupy, A., 2012. Energy use and emissions from the medium distance cableway system operation phase. Croat. J. Forest Eng. 33 (1), 79–88.

Koponen, K., Soimakallio, S., Tsupari, E., Thun, R., Antikainen, R., 2013. GHG emission performance of various liquid transportation biofuels in Finland in accordance with the EU sustainability criteria. Appl. Energy 102, 440–448.

Maesano, M., Picchio, R., Lo Monaco, A., Neri, F., Lasserre, B., Marchetti, M., 2013. Productivity and energy consumption in logging operation in a Cameroonian tropical forest. Ecol. Eng. 57, 149–153.

Magagnotti, N., Spinelli, R., 2011. Financial and energy cost of low-impact wood extraction in environmentally sensitive areas. Ecol. Eng. 37 (4), 601–606.

Magagnotti, N., Spinelli, R. (Eds.), 2012. COST Action FP0902 – Good Practice Guideline for Biomass Production Studies. CNR IVALSA, Florence, Italy, ISBN 978-88-901660-4-4, 41 p., available at: www.forestenergy.org

Olsen, E.D., Seifert, J.C.W., 1984. Machine performance and site disturbance in skidding on designated trails. J. Forest 82 (6), 366–369.

Pervanchon, F., Bockstaller, C., Girardin, P., 2002. Assessment of energy use in arable farming systems by means of an agro-ecological indicator: the energy indicator. Agric. Syst. 72, 149–172.

Picchio, R., Maesano, M., Savelli, S., Marchi, E., 2009. Productivity and energy balance in conversion of a *Quercus cerris* L. coppice stand into high forest in Central Italy. Croat. J. Forest Eng. 30, 15–26.

Picchio, R., Magagnotti, N., Sirna, A., Spinelli, R., 2012a. Improved winching technique to reduce logging damage. Ecol. Eng. 47, 83–86.

Picchio, R., Neri, F., Petrini, E., Verani, S., Marchi, E., Certini, G., 2012b. Machinery-induced soil compaction in thinning two pine stands in central Italy. Forest Ecol. Manage. 285, 38–43.

Picchio, R., Sirna, A., Sperandio, G., Spina, R., Verani, S., 2012c. Mechanized harvesting of eucalypt coppice for biomass production using high mechanization level. Croat. J. Forest Eng. 33 (1), 15–24.

Picchio, R., Verani, S., Sperandio, G., Spina, R., Marchi, E., 2012d. Stump grinding on a poplar plantation: working time, productivity, and economic and energetic inputs. Ecol. Eng. 40, 117–120.

Sabo, A., Poršinsky, T., 2005. Skidding of fir roundwood by Timberjack 240 C from selective forests of Gorski Kotar. Croat. J. Forest Eng. 26 (1), 13–27.

Savelli, S., Cavalli, R., Baldini, S., Picchio, R., 2010. Small scale mechanization of thinning in artificial coniferous plantation. Croat. J. Forest Eng. 31 (1), 11–21.

Spinelli, R., Magagnotti, N., 2011. The effects of introducing modern technology on the financial, labour and energy performance of forest operations in the Italian Alps. Forest Policy Econ. 13, 520–534.

Spinelli, R., Magagnotti, N., Relaño, R.L., 2012. An alternative skidding technology to the current use of crawler tractors in Alpine logging operations. J. Clean. Prod. 31, 73–79.

Spinelli, R., Lombardini, C., Magagnotti, N., 2013. Salvaging windthrown trees with animal and machine systems in protected areas. Ecol. Eng. 53, 61–67.

Stampfer, K., Kanzian, C., 2006. Current state and development possibilities of wood chip supply chains in Austria. Croat. J. Forest Eng. 27 (2), 135–145.

Šušnjar, M., Horvat, D., Kristić, A., Pandur, Z., 2008. Morphological analysis of forest tractor assemblies. Croat. J. Forest Eng. 29 (1), 41–51.

Tomašić, Ž., Šušnjar, M., Horvat, D., Pandur, Z., 2009. Forces affecting timber skidding. Croat. J. Forest Eng. 30 (2), 127–139.

USEPA, 1985. Compilation of Air Pollutant Emission Factors. Volume 2: Mobile Sources, fourth edition, A-42. Section 2.7 Heavy Duty Construction Equipment. United States Environmental Protection Agency, Office of Air and Radiation, Office of Mobile Sources Test and Evaluation Branch, Ann Arbor, MI, USA.

Valente, C., Spinelli, R., Hillring, B.G., 2011. LCA of environmental and socio-economic impacts related to wood energy production in alpine conditions: Valle di Fiemme (Italy). J. Clean. Prod. 19, 1931–1938.

Viana, H., Cohen, W.B., Lopes, D., Aranha, J., 2010. Assessment of forest biomass for use as energy. GIS-based analysis of geographical availability and locations of wood-fired power plants in Portugal. Appl. Energy 87, 2551–2560.

Vusić, D., Zečić, Ž., Papa, I., Lepoglavec, K., Pandur, Z., 2011. Optimization of teamwork in tree-length harvesting. In: Bieniek, J., Sowa, J.M., Barszcz, A., Szewczyk, G. (Eds.), Technology and Ergonomics in the Service of Modern Forestry. Publishing House of the University of Agriculture in Krakow, Krakow, pp. 159–168.

Zečić, Ž., Marenče, J., 2005. Mathematical models for optimization of group work in harvesting operation. Croat. J. Forest Eng. 26 (1), 29–37.

Zečić, Ž., Krpan, A.P.B., Stankić, B., 2004a. Privlačenje oblovine traktorom Timberjack 240 C iz oplodne sječe u uvjetima Šumarije Velika Pisanica (Skidding of rounwood by tractor Timberjack 240 C from regeneration felling in conditions of forest office Velika Pisanica). Šum. List 128 (11/12), 671–678.

Zečić, Ž., Poršinsky, T., Šušnjar, M., 2004b. Some harvesting results in hilly stands by group labor with a review of selection of time study method. Šum. List 128 (7/8), 381–389.

Zečić, Ž., Vusić, D., Prka, M., Klepac, S., 2010. Utjecaj nagiba traktorskog puta na proizvodnost traktora Timberjack 240 C pri privlačenju drvnih sortimenata u prebornim šumama (Influence of skidding road slope on productivity of skidding timber assortments with tractor Timberjack 240 C in selective forests). Šum. List 134 (3–4), 103–114.