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ORIGINAL RESEARCH

Performance of Forwarding Operations in Biomass Recovery from Apple Orchards

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Abstract
In recent decades, the use of forwarders in agroforestry systems has been increasing. In agroforestry systems, the possibility to use these machines in various operational contexts allows the reduction of hourly costs and favors its use also in small enterprises. In Europe, agroforestry or farm forestry represents an important resource that offers alternative and more sustainable land uses in agricultural or forestry areas. By covering large areas, fruit orchards represent an important source of income, but they require annual pruning which leaves abundant residues on the ground. And when fruit production declines, the trees are dismantled to make room for new ones. This study evaluated the performance of biomass recovery from dismantled apple orchards using a HSM 208 F forwarder. Time studies were implemented to estimate the productivity and fuel consumption of forwarding operations. Data was collected by means of a GPS unit, a video camera and an electric fuel pump, and 30 work cycles divided into elemental tasks were monitored. Models for time consumption and productivity as a function of extraction distance were developed by means of least-square simple regression, at different scales needed to characterize the forwarding operations. The average forwarding distance was of ca. 830 m and the net and gross forwarding production rates were of 21.79 and 15.35 loose m^3 h^{-1} (volume of woodchips produced), respectively. The study provides reference data for forwarding operations and demonstrates the successful use of forestry machines in the agricultural sector.

Keywords Woodchips · Forwarder · Productivity · Functional models

Extended author information available on the last page of the article

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Introduction

Biomass is one of the resources that play a substantial role in sustainable energy (Borz et al. 2019a; Cheng 2017; Mirza et al. 2008; Moneti et al. 2015). The global energy potential of biomass is very large. It is estimated that the world's standing terrestrial biomass (i.e., the renewable, above-ground biomass that could be harvested and used as an energy resource) is approximately 100 times the world's total annual energy consumption (Klass 2004). Agriculture and forest industries provide a wide range of products and services such as food, feed, fiber, shelter, packaging and clothing (Klass 2004; Chum and Overend 2001) and, conventionally, biomass and any waste that results from its processing or consumption is left in the growth areas where natural decomposition occurs. Nevertheless, several studies showed that traditional sources for bioenergy production would not be enough to meet future energy needs nor to respond to the new targets set by the EU 2030 framework for climate and energy policies (European Parliament 2014; Stelte et al. 2012; Talagai et al. 2020; Toscano et al. 2018). This implies the need to find alternative and sustainable ways to obtain lignocellulosic material. In this regard, an option is given by agricultural residues which can contribute to the biomass supply chain. In Europe, agroforestry system or farm forestry represents an important resource that offers alternative and more sustainable modes of land use, but is typically poorly developed. The residues produced from fruit tree replacement have been managed with general-purpose machines, borrowed from the forest or the construction industry (Picchi et al. 2016; Assirelli et al. 2019). Meanwhile, fruit orchards represent a global business covering large areas and generating substantial income for many regions. During their management, they require annual pruning operations, which leave abundant residues on the ground, and when the plants get depleted and production declines, the old fruit trees need to be replaced (Nati et al. 2018).

The most common fruit tree in Europe is the apple tree (Malus sp.), which covers 35% of the total orchard area (Eurostat 2015). At the European level, Romania produces significant amounts of apples and the area covered by apple orchards represents 12% of the total EU orchard area (Badiu et al. 2015; Eurostat 2020). This kind of crop requires annual and cyclical operations (annual pruning and tree cutting at the end of the fruit production cycle) to achieve the targeted tree systems and to optimize the production of fruits. These activities generate woody biomass materials such as branches, trunks, and rootstocks (Boschiero et al. 2016; Lo Monaco et al. 2015). The annual pruning itself generates a substantial quantity of residues which needs to be disposed (Proto et al. 2019; Proto et al. 2021). In addition, frequent renewal of the trees would benefit from a cost reduction in order to minimize the financial burden on orchard management (Badiu et al. 2015), and there is a strong interest in finding cost-effective techniques that may reduce the financial strain. In response, research over the past decades estimated carried out to estimate the productivity and cost of harvesting agricultural pruning residues for energy applications (Brand and Jacinto 2020). The authors agree that harvesting and transportation costs, coupled with the small and bulky payloads and with a low quality of biomass, are typical challenges that are challenging to overcome, a fact which is similar to the forest operations carried out to recover fuel wood (Erber and Kűhmaier 2017). As a consequence, the biomass produced in fruit plantations is not currently used to its full potential to produce bioenergy. Among the reasons for this situation are the technical problems related to harvesting and the lack of information on the quantity and quality of the residues (Dyjakon et al. 2016). When orchard trees fail to produce enough fruits due to their age, fruit tree replacement by harvesting operations is expected. For this reason, recent studies were conducted to evaluate the performance of harvesting whole fruit trees to see if this procedure guarantees the quality and quantity requirements of the biomass supply chain. Since the characteristics of the wood produced by orchards trees (irregular shapes and small tree diameters) do not allow the use of this resource for more noble uses, biomass is the best use of these materials. This is important as the residues of permanent crops from Europe are a substantial reservoir of renewable biomass for energy and industrial use but they were poorly utilized until now for bioenergy purposes (Pari et al. 2017). Accordingly, the biomass yielded by orchards may be an attractive renewable source of energy for the local power generation market, and offer additional revenues to farmers.

In the framework of a logistics supply chain, harvesting plays a pivotal role and, regardless of the crop type, tree replacement yields significant volumes of biomass, which can be used as a renewable fuel in bioenergy facilities (Assirelli et al. 2019). However, handling of whole trees represents an important phase that will affect the costs and productivity. The most common solution to harvesting the trees from orchards is the removal of the above-ground tree portion following tree felling and, in a second step, the extraction and collection of tree stumps. Harvesting and transportation of whole trees is typically operationalized by the use of a farm tractor and a trailer equipped with a hydraulic crane. However, the limited loading capacity and a slow movement velocity, as characteristic of this option, negatively affect the productivity and cost-effectiveness of operations. An interesting alternative, that could have a great potential, is the use of purpose-built vehicles designed to transport roundwood in the forestry sector. As many studies describe (Cremer and Velázquez-Martí 2007; Kaleja et al. 2018; Nakahata et al. 2014; Proto et al. 2018a), forwarders have been designed to carry out strictly forestry tasks such as the extraction of logs or logging residues. However, the use of these machines in the agroforestry sector can enable the collection and removal from the fields of wood biomass produced by orchard pruning or dismantling (Velázquez-Martí et al. 2012). Meanwhile, finding some use for orchard pruning residues would allow converting a disposal problem into collateral production, with a potential for revenues or reduced management costs (Emer et al. 2011).

Given the above described context, the aim of this study was to evaluate the performance of biomass extraction from dismantled apple orchards by means of a forwarder. In particular, the objectives were to: *i*) evaluate the time consumption and productivity in forwarding operations, *ii*) evaluate the fuel consumption in forwarding operations and *iii*) develop models of time consumption and productivity as a function of extraction distance.

Materials and Methods

Study Site

Field data collection was carried out in an area located at approximately 380 m above sea level (N 46° 57’ 59”−E 24° 25’ 21” E), near Dipşa village, Bistriţa-Năsăud county, Romania (Fig. 1). The landscape in the area is characterized by many intensively-cultivated apple orchards exhibiting variability in age and management states. As some of them have reached their economic life, their owners have decided to restock them, and they were scheduled for the extraction of old trees. At the harvesting time, the apple orchard used in the study was 20-years old and had a spacing of 2 by 4 m between the trees. Observations made during this study on the forwarding operations covered approximately 53% (3.6 ha) of the orchard’s area, involved a total of 979 trees, and was based on the free will of the forwarder’s driver to approach the operations.

Harvesting System Description and Work Organization

Harvesting operations were implemented using the complete tree harvesting method, which involves removal of trees including their stumps and major roots (Pulkki 2014). Compared to the traditional harvesting methods, the complete tree method requires the use of equipment able to uproot the trees by some sort of mechanical means (Oprea 2008), and to enable this type of operations, an agricultural telehandler Manitou MLT 845−120 (74.4 kW of engine power), equipped with an agricultural bucket with a capacity of 2000 l, was used. These operations were carried out in advance (approximately 6 months ahead of time) of the extraction and chipping

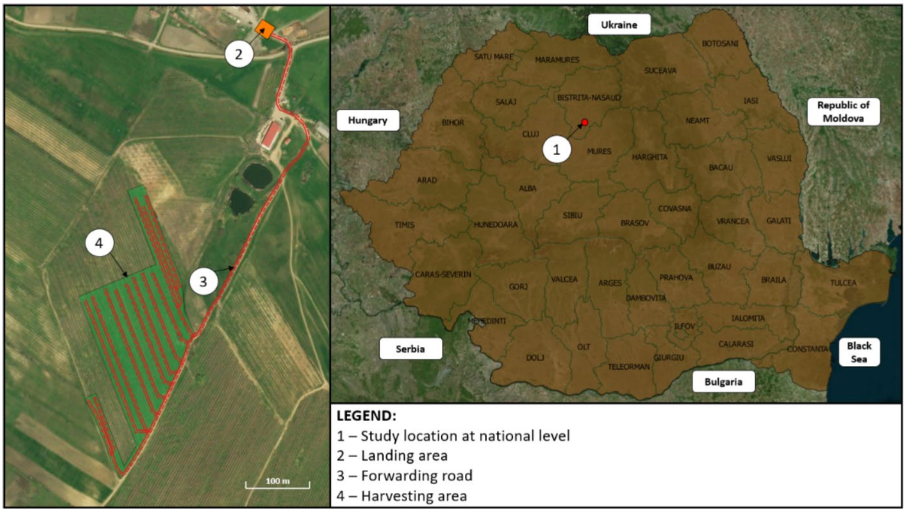


Fig. 1 Study location

operations, therefore the trees to be extracted were already available as small bunches of felled trees. Then, a HSM 208 F series forwarder (Table 1) was used to load and transport the trees to a landing area where a chipper (Jenz BA 725) with a power rating of 375 kW was used to convert them into woodchips.

As the chipping tasks were stationary, the same telehandler used for the felling operations was used to move and load the woodchips into a truck (Model S1 J02VLN3) having a 90 m^3 of capacity, propelled by a MAN trailer (Model L.2007.46.001 TGX) equipped with a 324-kW diesel engine. This truck transported the chips from the site to a biomass terminal located in Toplița, Romania. The chipper, however, was not equipped itself with a crane for biomass handling and feeding, therefore this operational task was fulfilled by the forwarder at the end of each work cycle.

The division of work on elemental tasks and categories of time consumption was based on the typical functions and work elements that a forwarder may carry on in forestry operations (Table 2) (Björheden et al. 1995; Proto et al. 2020, Kaleja et al. 2018; Apăfăian et al. 2017; Cataldo et al. 2020; Proto et al. 2018b). Nevertheless, the division and documentation of work and time at the elemental level was carried out in the office phase of the study based on data collected via GPS (Global Positioning System) and video recording. Forwarding work was carried out by a driver having more than 5 years of experience in such operations. The company bases its supply portfolio to a great extent on the biomass recovery from dismantled apple orchards. Prior to data collection, the verbal consents of the company owner and workers engaged in operations were obtained in order to collect the data needed in the study and the workers were asked to carry on their jobs as usual. The time study data were collected in September 2019.

Data Collection

Field data collection was designed to capture mainly information on the time, fuel consumption and productivity of the forwarder. Time consumption data were col-

Table 1 Technical description of the HSM 208 F forwarder

Parameter	Unit	Value
Axles total	n°	4
Power	kW	185
Weight	t	18
Payload capability	t	14
Width	mm	2860
Length	mm	10,920
Clearance	mm	661
Transmission	Type	Hydrostatic
Transmission	Gear	2
Fuel tank capacity	l	225
Crane type	-	Epsilon M70 F80
Crane range	m	8
Gripper type	-	FG43S
Speed at 1st gear	km h^{-1}	0–14

Table 2 Concept of work organization observed and used in the study

Work (time) element	Abbreviation	Description
Empty turn	*ET - (tET)*	Machine movement from the landing to the orchard (loading) area where either, return maneuvers or loading tasks were carried out as a consecutive task.
Moving to load	*ML - (tML)*	Any moving maneuvers between the locations in which the machine stopped to carry on loading tasks as well as returning maneuvers before engaging in loading tasks. Occurred several times per turn (work cycle).
Loading	*L - (tL)*	Maneuvers undertaken to load and arrange the trees into the bunk at each stop to do so in the orchard area. Occurred several times per turn (work cycle).
Loaded turn	*LT - (tLT)*	Machine movement from the last point of loading to the landing area.
Unloading	*U - (tU)*	Any maneuvers undertaken to unload the trees from the bunk and to place them on the ground, including small movements to do so. Includes the crane work and machine movement as well as a combination with chipper feeding in some work cycles.
Feeding the chipper	*FC - (tFC)*	Any maneuvers undertaken to unload the trees from the bunk and to feed them directly to the chipper, including small movements to do so. Includes the crane work and machine movement as well as a combination with unloading in some work cycles.
Moving at landing	*M - (tM)*	Any movements undertaken to return the machine for a new empty turn. Excludes any other moving maneuvers that had nothing to do with the work.
Moving	*MOV - (tMOV)*	The sum of time spent in empty and loaded turns, including the time spent in moving to load and moving at landing, computed on a work cycle basis.
Miscellaneous	*MIS - (tMIS)*	Any other maneuvers, including machine movement, that had nothing to do with the work tasks observed. Observed, usually, at the end of a workday.
Undocumented	*UD - (tUD)*	Time in which no tasks were carried out in relation to the job and in which no video data coverage was available for interpretation.
Delays caused by study	*SD - (tSD)*	Time in which occurred events such as dataloggers setup and placement on the machine as well as their check.
Personal delays	*PD - (tPD)*	Delays caused by personal reasons in which the machine was not engaged in productive tasks.
Other delays	*OD - (tOD)*	Delays caused by organizational and other reasons in which the machine was not engaged in productive tasks.
Observation time	*TO*	Total time, including all the events documented above.
Workplace time	*TW*	Total time, excluding time consumption categories such as the miscellaneous, undocumented and delays caused by study.
Work cycle time	*CT*	Productive time (delay-free cycle time) including only the time spent to carry on the production. Includes loaded and empty turns, moving to load, loading, unloading and chipper feeding as well as moving at the landing. Excludes all the delays, miscellaneous and undocumented time.

lected using a Garmin GPSMAP 64 STC unit which was placed on the machine's cab and set to collect locations at a sampling rate of one second. The resulting data was later used to document the time consumption and operational speed and to map the forwarding operations using QGis software (QGis 3.4.12, www.qgis.org). Since the GPS data alone may have its own limitations in accurately separating the time consumption on specific tasks (Talagai et al. 2020; Proto et al. 2020; Borz et al. 2019b), a small video camera was used to further document the operational behavior during the observed time. The camera was placed inside the cab with the field of view oriented towards the forwarder's bunk, in a location that enabled a good view on the bunk and the crane. As the video camera used in this study is capable to collect video data on extended periods of time and it has a battery life covering more than 8 h, it was set to continuously collect video files having an approximate duration of 20 min each. The resulting video files were organized on days of operation and they were used to document the data by a coding procedure.

In what regards the estimation of productivity, and by taking into consideration that the forwarded biomass (Fig. 2) consisted of small parts of trees and many branches for which it was virtually impossible to estimate the volume, as a supplementary measure, the total loose (or bulk) volume of forwarded woodchips was estimated based on the recommendations provided by Acuna et al. (2012).

To do this, the volume estimation was based on the truck dimensions which were measured in advance and the number of loaded trucks (n = 6) counted during the field observation time. Then, an estimate of the cyclical production was made based on the total volume of woodchips produced. Given the approach used to load and chip the whole trees (above-ground biomass, including stump and major roots), the homogeneity in size of the trees (they have the same age and similar dimensions) allowed a tree-level characterization of production. The average loose volume per tree was estimated from the total woodchips volume divided by the total number of forwarded trees (979 trees). Based on a similar study (Hildt et al. 2020), the volume of each load was estimated by multiplying the average tree volume by the number of trees extracted per load counted through the videos recorded during the forwarder loading activity. This data was used to model the variation of productivity as a function of extraction distance.

Fuel consumption (liters, l) only concerned the forwarder and it was estimated on a daily basis using an electric pump connected to an external 400-l fuel tank. For this, the refilling to full method was used each day (Acuna et al. 2012; Proto et al. 2020).

Fig. 2 A loaded forwarder on the left; the telehandler loading woodchips into the lorry on the right

At the beginning of a work day, the machine was fully fueled after placing it on a location characterized by completely flat terrain. After the completion of operations from a day, the machine was placed on the same location and refilled to full. Fuel consumption at daily level was computed as the difference of readings at an accuracy of 0.01 l.

Data Processing

The files collected via GPS were pre-processed using the Garmin BaseCamp® (Version 4.7.0) software using procedures similar to those described by Borz et al. (2019b, 2018). GPX files collected in the four days taken into study were merged into a common spreadsheet and then, based on the time and date labels contained in it, the video files were analyzed in detail and two new attribute fields were created to document the engine state and the task type. By a stepwise approach, and also based on the GPS speed contained into the database, each one-second sample was documented based on the video files using the relevant codes given in Table 2. Engine state was coded by a binary approach to document the time spent with engine on and off. Then, logical functions were used to categorize and allocate each 1-second sample to tasks and a reorganization of the spreadsheet was implemented to summarize the time consumption on work elements at the work cycle level. In this spreadsheet, the time consumption categories of unloading, feeding the chipper and unloading and feeding the chipper were merged because many of the work cycles contained combinations of these tasks. Nevertheless, each cycle was supplementary coded by a string attribute to document the type of tasks undertaken at the landing. Besides the payloads per turn, the operational variables taken into study were the moving distances. As the terrain inclination was very low in the area (less than 5%) the effect of slope was omitted in this study. Operational distances (empty turn—*ETD*, moving to load—*MLD*, loaded turn—*LTD* and moving at landing—*MD*) were estimated based on the map of locations collected in the field via GPS. Each category of distance was extracted, cycle-wise, using the measurement functionality of the Garmin BaseCamp® software. Then, the estimated distances were included in the database developed at work cycle level. Based on these figures, two additional categories of distances were computed: total moving distance (*TMD*, m) and the average forwarding distance (*AFD*, m), with the latter computed by dividing *TMD* by 2. Finally, the spreadsheet was complemented by the payload per turn, based on the above descriptions.

A separate data processing workflow consisted of categorizing the operational speed per work tasks and the tasks under question were the empty turn, moving to load, loaded turn and moving to landing. The small movements during unloading and chipper feeding tasks were excluded. The workflow used logical functions similar to those of extracting the data on time consumption with the difference being the data on speed was prepared in advance by conversion from strings to numbers.

Statistical Analysis

Statistical analysis was designed to describe the data and to develop relational models for the prediction of time consumption and productivity as a function of operational distance. The general workflow and the statistical approaches were those used for similar forest productivity studies (Proto et al. 2020; Borz et al. 2019b). A first step consisted of a normality check that used the Shapiro-Wilk test to see what kind of descriptive statistics could be used to characterize the data and as a prerequisite for modeling approaches. Then, the main descriptive statistics were used to characterize the data on time consumption, operational speed and operational variables. Time consumption and productivity models were developed by the means of least-square simple regression techniques, at different scales needed to characterize the forwarding operations. The significance of the developed models was judged based on the p-values and the values of the determination coefficients (Acuna et al. 2012), using a confidence threshold of $\alpha = 0.05$. Data analysis was carried using Microsoft Excel® fitted with RealStatistics ® freeware add-in.

Table 3 Descriptive statistics of time consumption

Time consumption variable	Abbreviation (unit)	Sum	Min. value	Max. value	Mean (median) value	Standard deviation	Normality check
Empty turn time	*tET* (s)	11,499	249	515	383.30 (388.50)	±70.71	W = 0.97305 $p = 0.6256$
Moving to load time	*tML* (s)	5312	74	400	177.07 (158.50)	±87.35	W = 0.86042 $p = 0.0010$
Loading time	*tL* (s)	26,627	410	1193	887.57 (915.50)	±172.42	W = 0.95037 $p = 0.1730$
Loaded turn time	*tLT* (s)	14,098	270	855	469.93 (470.00)	±125.01	W = 0.93772 $p = 0.0767$
Unloading and chipper feeding time	*tUFC* (s)	29,274	141	2276	975.80 (1047.00)	±520.30	W = 0.93417 $p = 0.0634$
Moving at landing time	*tM* (s)	889	-	183	29.63 (23.50)	±34.73	W = 0.65000 $p < 0.0001$
Moving time	*tMOV* (s)	31,798	644	1517	1059.93 (1029.00)	±212.85	W = 0.98621 $p = 0.9560$
Miscellaneous time	*tMIS* (s)	3236	-	-	-	-	-
Undocumented time	*tUD* (s)	1578	-	-	-	-	-
Delays caused by study	*tSD* (s)	1293	-	-	-	-	-
Personal delays	*tPD* (s)	32,436	-	-	-	-	-
Other delays	*tOD* (s)	4367	-	-	-	-	-
Observation time	*TO* (s)	103,609	-	-	-	-	-
Workplace time	*TW* (s)	124,502	-	-	-	-	-
Work cycle time	*TC* (s)	87,699	1937	4130	2923.30 (3051.00)	610.95	W = 0.95361 $p = 0.2111$

Results

Time Consumption, Operational Variables, Production Estimates and Productivity Models

The data used in this study covered 30 forwarding work cycles. In total, the covered distance by forwarding operations was close to 50 km (Tables 3 and 4) and it varied, at work cycle level, between 1.25 and 2.14 km. Based on the 979 forwarded apple trees, a total production of an estimated 530 loose m^3 of woodchips was produced, and the forwarder payload per turn varied between 14.64 and 21.68 loose m^3 of woodchips, depending of the number of trees transported per load (average = 33 trees per load; maximum = 40 trees). Important within the time consumption of a work cycle were the empty and loaded turns due to their corresponding distances which averaged close to 790 and 730 m, respectively. They varied, however, quite widely, in between 540 and 980 m, a fact that enabled the development of time consumption and productivity models.

In total, the study covered 36.3 h of which, undocumented, miscellaneous and delays caused by the study itself amounted 1.7 h. The rest was the workplace time (34.6 h). Of that, productive time accounted for 70% while the personal and other delays accounted for the rest. In the workplace time, the greatest share was that of feeding the chipper and unloading (33.4%), tasks that were analyzed together in terms of time consumption and which were followed by loading tasks (30.4%), loaded (15.6%) and empty turns (13.5%). Moving to load and moving at landing accounted together for 7.1% of the productive time. For the operations done at the landing, it is worth mentioning that predominant were feeding the chipper directly from the forwarder's bunk (n = 23 cases), followed by unloading directly on the ground (n = 5 cases) and unloading and feeding the chipper (n = 2 cases). On average, unloading

Table 4 Descriptive statistics of operational variables and production

Category & variable	Abbreviation (unit)	Sum	Min. value	Max. value	Mean (median) value	Standard deviation	Normality check
Empty turn distance	*ETD* (m)	23,630	567	979	787.67 (778.50)	±121.97	W = 0.9565 $p = 0.2510$
Moving to load distance	*MLD* (m)	3565	47	319	118.83 (108.00)	±58.17	W = 0.8827 $p = 0.0033$
Loaded turn distance	*LTD* (m)	22,011	537	977	733.70 (715.00)	±107.38	W = 0.9779 $p = 0.7672$
Moving at landing distance	*MD* (m)	740	-	169	24.67 (19.00)	±30.62	W = 0.5953 $p < 0.0001$
Total moving distance	*TMD* (m)	49,946	1254	2140	1664.87 (1660.50)	±227.94	W = 0.9492 $p = 0.1604$
Average forwarding distance	*AFD* (m)	24,973	627	1070	832.43 (830.25)	±113.97	W = 0.9492 $p = 0.1604$
Payload	*PL* (loose m^3)	531	14,64	21,68	17.69 (17.62)	±2.24	W = 0.9359 $p = 0.0704$

solely took far less time (222.4 ± 55.2 s) compared to unloading and feeding the chipper (1071.5 ± 188.8 s) and to feeding the chipper solely (1131.3 ± 446.7 s).

Four basic models of time consumption were developed for moving events recorded during the field study (Fig. 3). The operational distance specific to each work element was found to be highly significant ($p < 0.05$) in explaining the variation of time consumption ($R^2 = 0.70$–0.90). The best fit dependence relationship was found between the cycle-wise time consumption and distance covered for moving at landing (the black line in Fig. 3). For the loaded turn, time and distance had a standard deviation of 125.0 s and 107.4 m, respectively, and the coefficient of determination characterizing their dependence relationship was the lowest ($R^2 = 0.70$).

The average forwarding distance (AFD, m) explained the variation of time consumption at the work cycle level only to a limited extent (30%, $R^2 = 0.29$) (Table 5). Nevertheless, it was found to be a significant predictor of the work cycle time ($p = 0.002$, $\alpha = 0.05$). The rest of the variability may be the effect of other factors. In fact, by comparing the distribution of the time recorded only during the operations in which the forwarder was in motion (tMOV) with the work cycle time (CT), it was evident that there was a strong linear dependence between the former and the distance ($R^2 = 0.71$), unlike in the case of the total cycle time, which also included the tasks of loading, unloading, and feeding the chipper (periods in which the machine had no wheel motion) which generated a high variation in the time consumption at work cycle level without being linked to distance (Fig. 4). Based on the production output, which was estimated at 531 loose m^3, the gross productivity of operations was estimated to be 15.35 loose m^3 h^{-1}. This figure includes all the time spent as workplace time. By excluding the delays, the net productivity rate was estimated at 21.80 loose m^3 h^{-1}. In the same conditions, the gross and net efficiency rates were estimated at 0.065 and 0.046 h loose m^{-3}, respectively. These results stand for an average forwarding distance of 830 m and they should be used only as a reference, for the reasons explained above, such as the effect of the forwarding distance which has the greatest potential to significantly affect the productivity rate (Table 5; Fig. 5). For instance, by considering only the moving tasks, the average net production rate for a distance of 830 m was found to be 63 loose m^3 h^{-1} which increased significantly

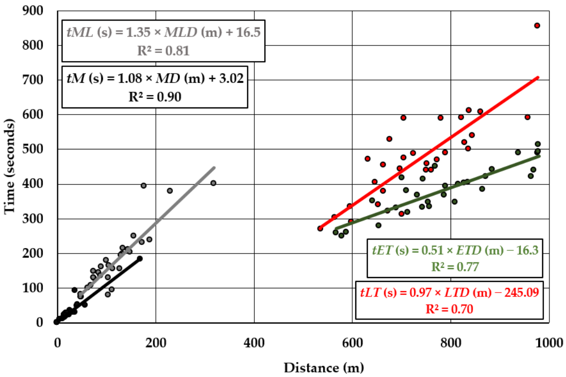


Fig. 3 Time consumption models of tasks that involved forwarder movement (tML: moving to load time; tM: moving at landing time; tET: empty turn time; tLT: loaded turn time; MLD: moving to load distance; MD: moving at landing distance; ETD: empty turn distance; LTD: loaded turn distance)

Table 5 Cycle time consumption and productivity model

Work cycle time and productivity model	N	R^2	*p* value	Predictor	Sig.
T_C (s)=2.91 × *AFD* (m) + 497.04	30	0.29	0.002	*AFD*	yes
NPRmov[1] (loose m^3 h^{-1})=−0.0965 × *AFD* (m) +142,62	30	0.65	0.000	*AFD*	yes

[1]Net productivity rate computed based on the moving distance

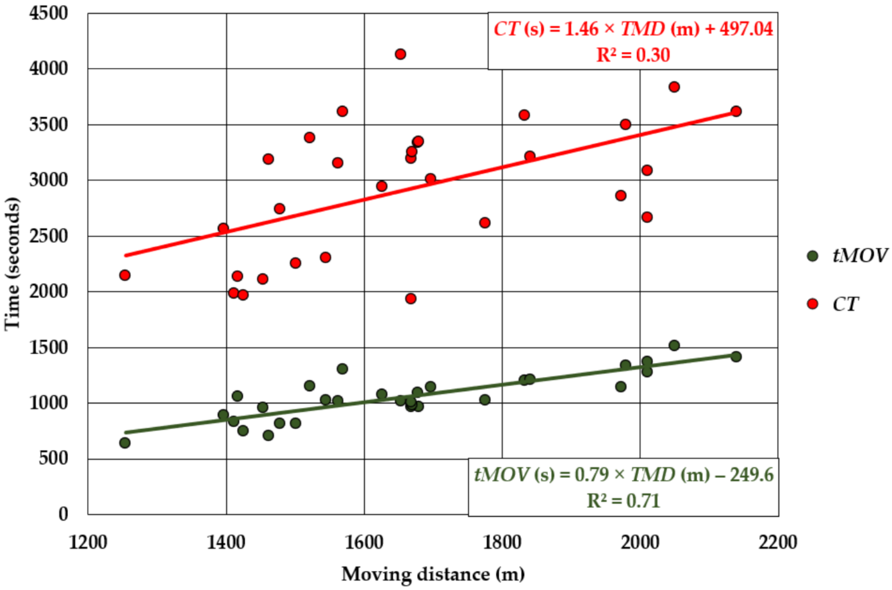
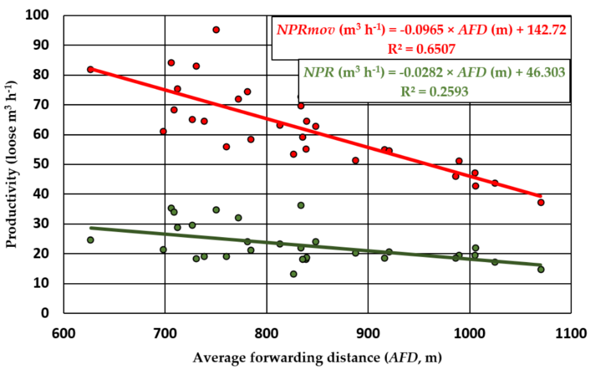


Fig. 4 Effects of loading, unloading and feeding the chipper on the work cycle time: a comparison between cycle time (CT) and moving time (tMOV) (TMD: Total moving distance)

Fig. 5 Net productivity rate models computed based on time in motion only (NPRmov) (red) and work cycle time (NPR) (green) (AFD: average forwarding distance)



to 82 loose m^3 h^{-1} for a forwarding distance of 630 m and decreased to 43 loose m^3 h^{-1}

for a distance of 1030 m, indicating a productivity loss of 9.7 loose m^3 h^{-1} for every 100 m traveled in addition.

Operational Speed and Fuel Consumption

Figure 6 shows the main descriptive statistics of operational speed in those tasks that involved the machine movement. The data shown may be analyzed in conjunction with the results reported in Fig. 3, indicating that the empty turn was done at the highest operational speed (SET, km h^{-1}), which varied between 4 and 11 km h^{-1}, and averaged 7.4 km h^{-1}.

Next in line was the loaded turn (SLT) that averaged 5.6 km h^{-1}, moving at landing (SM=3.2 km h^{-1}) and moving to load (SML=2.5 km h^{-1}). Minimum values of zero indicated for the rest of operational speeds are the effect of very short breaks that were unfeasible to separate from the data pools of each task.

The total fuel consumption measured during the field study amounted to 313.18 l. At the same time, the machine's engine was in a working state for 26.5 h, resulting in a fuel consumption of 11.82 l h^{-1}. While it was virtually impossible to account for the fuel consumption only in productive tasks (the engine was in the working state in some miscellaneous tasks and delays), the figure given here stands for a gross figure, as the difference between the time spent with the engine on and productive time was of 2.1 h. Nevertheless, miscellaneous tasks are not necessarily non-related to productivity; therefore, the figure is a good approximation of the fuel consumption in the described operations. Altogether, the machine was found to have the engine working 73% of the total observed time and the engine was off for the rest.

Discussion

It is difficult to compare the results of this study with general reference figures, because, to our knowledge, the topic of the present work is rather specific and very few works about complete-tree removal of terminated orchards can be found in the recent bibliography, especially in regards to apple orchards. Nevertheless, the time consumption of work elements that involve machine moving depends on the operational distance (Apăfăian et al. 2017; Picchio et al. 2018; Proto et al. 2018a; Proto et

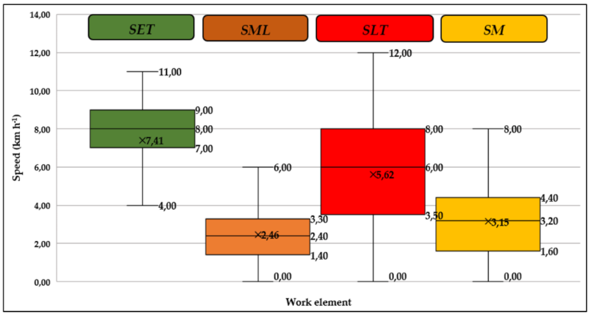


Fig. 6 Descriptive statistics of operational speed in different types of tasks involving the machine movement (SET: empty turn speed; SML: moving to load speed; SLT: loaded turn speed; SM: moving at landing speed)

al. 2018b) and speed, which in turn are mainly determined by geophysical factors. Given that the terrain was relatively flat in the study area and the fact that there were no evident obstructions due to canopy or other factors, the speed recorded can be interpreted as a good approximation of the real operational speed. In this regard, other studies have shown the utility of customer-grade GPS units in assisting time-and-motion studies (Borz et al. 2019a; Borz et al. 2019b; Talagai et al. 2020), including those carried out for forwarder machines (Apăfăian et al. 2017).

From the analysis of time consumption, the highest dependence relation was found between time and distance of moving at landing, which was also the least time-consuming operation. However, the average operating speed of this task was 3.2 km h^{-1}. The results of this study about the operational speed in machine movement tasks were found to indicate higher speeds compared to other studies. Hildt et al. (2020) studied the performance of some heavy, medium and light forwarder models tested in different working conditions, finding that the average speed of empty and loaded forwarder's turns were 4.3 and 4.5 km h^{-1}, respectively, without any significant differences depending on the forwarder size. In Central Sweden, Berg et al. (2019) studied the performance of two heavy forwarders during final fellings in a forest with terrain conditions varying from easy to moderate. They found an average speed of 3.4 km h^{-1} for the empty turn and 2.9 km h^{-1} for the loaded turn. Similar to our results, Belbo and Talbot (2014) estimated a fuel consumption of 12.35 l h^{-1} for a traditional forwarder (130 kW) in conditions of a mean travel speed of 2.3 km h^{-1}.

The number of trees and the volume per load did not influence the cycle time which was probably an effect of lower masses transported in bulky loads per cycle and of the fact that several trees were loaded in the same work cycle of the crane. As such, the most important factor influencing the time consumption of forwarding operations was the extraction distance, which, as reported by several authors, is rather typical for forwarding operations (Proto et al. 2018a; Sever 1988). When chipping at the roadside, chips can be blown into a truck, trailer, container or directly on the ground. In this case, chips will be reloaded on trucks and some contractors prefer to reload the chips from a heap in an effort to reduce truck waiting time. On the other hand, a loader can fill up a standard highway truck faster than the average professional chipper could (Laitila et al. 2015). Conversely, our results show that productivity of forwarding operation may be significantly affected by the option taken to feed the chipper since feeding the chipper directly from the forwarder bunk was five times more time consuming that unloading the biomass directly on the ground. We speculate that significant reductions in time consumption, as well as significant increments in productivity of forwarding and of all analyzed could be achieved by using a chipper equipped with self-feeding capabilities. On the other hand, costs of production in this configuration, could be increased compared to the studied system, a hypothesis that needs additional validation. Accordingly, a comparison of the productivity results to those reported by other studies was difficult, mainly due to the measurement unit of the volume estimation, which used as a background the data of the amount (in loose m^3) of woodchips produced during the study. Concerning the productivity rate, Elmer et al. (2011) studied a system for the energy-wood harvesting in Austrian flat terrains by the means of a HSM208 forwarder and a Moipu 300ES feller-buncher, finding a net productivity of 5 m^3 h^{-1}. In Germany, other authors have tested a HSM208 forwarder, finding a net productivity which, according to Ghaffariyan et al. (2017), was of 8 m^3 h^{-1}. Laina et al. (2013) monitored three whole tree chipping operations applied in oak thinnings deployed in moderate to flat terrains (slope less than 30%). These operations included felling and bunching with a feller-buncher, extraction of full trees with a forwarder, chipping at landing with a mobile chipper, stacking in piles along the roadside, and loading in the truck with a hydraulic crane. They found an average productivity of 38.4 oven-dried tons (odt) ha^{-1}.

Having these caveats in mind, this study demonstrates the successful use of industrial machines brought from the forestry to the horticultural sector. This has been possible thanks to the characteristics of the machine such as the payload capability, the boom length of the crane, and the engine which, in addition to showing consistent fuel consumption levels to those reported by Spinelli et al. (2015), 11.5 l h^{-1}, and Holzleitner et al. (2011), 11.1 l h^{-1}, allowed an average operating speed during the empty turn of 7.4 km h^{-1}, which peaked at 11 km h^{-1}. High operational speeds were also specific to loaded turn work tasks that were carried out, on average, at 6 km h^{-1}. As such, an increased speed may compensate for the productivity loss due to the bulky payloads transported in operations and, given the gears used by the transmission system at high running speeds, it could also yield lower operational fuel consumptions (Borz et al. 2021), facts which, together, may validate this operational option in biomass recovery from apple orchards and similar situations.

Last but not least, the flow of woodchips in terms of quantity and quality is important to sustain local, small-scale bioenergy facilities. For doing so, quality assessments need to be implemented in the future to examine the condition, type, shape, and thickness of the woodchips harvested from such orchards. The quality of woodchips represents an important parameter to validate and for use of biofuel in different types and sizes of energy plants. Having in mind the great diffusion of small farms, the establishment of small to medium energy plants will be very likely and, consequently, the quality of the woodchips will have a greater importance. On the other hand, additional studies are needed to encourage the creation of a robust biomass supply chain networks because the low economic value of biomass harvesting leaves no room for incorrect choices concerning trails, location of energy plants, and logistical transportation (Picchio et al. 2019).

Conclusions

This study evaluated the performance of a forwarder-chipper system to harvest horticultural residues from dismantled apple orchards. The results demonstrated that it is possible to recover this type of biomass residues while ensuring the sustainability of the wood-energy chain, demonstrating the versatility of purpose-built forest machines that can be adapted to a wide range of operations, a fact that could substantially contribute to the machine utilization rate and to the efficiency increment of orchard tree removing operations. While the productivity and fuel consumption were found to be within acceptable limits and they were affected by the forwarding distance, type of payload transported, and the specificity of unloading-chipping operations, the use of this system has to be evaluated by considering some of the characteristics required by specific energy conversion plants, in particular those related to woodchips quality.

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