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How Different Distribution of Assortments on Worksites Influences Forwarder Performance in Coniferous Plantations

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Abstract

Forwarders often load logs organized in large piles by modified farm tractors, skidders, animals, other forwarders, etc., but currently, there are no studies on how the different concentrations of logs affect forwarder performance in terms of time consumption, productivity, and costs in forwarding operations. A study was conducted in three locations situated in Bulgaria (sites A and B) and in southern Italy (site C): in site A the logs were spread in the stand, in site B they were concentrated in large piles at the roadside, whereas in site C the logs were organized at the roadside in piles of medium size. The average forwarder productivity in site A obtained at an average forwarding distance of 1780 m, an average payload volume of 9.83 m^3, and an average number of grips of logs with the crane grapple, during loading (22.97) and during unloading (8.97) per cycle, is 10.43 m^3·PMH^{-1} (PMH, productive machine hour) and 9.93 m^3·SMH^{-1} (SMH, scheduled machine hour), respectively. In site B the productivity rate was lower than that registered by the forwarder operated in site A: 9.38 m^3·PMH^{-1} and 8.81 m^3·SMH^{-1}, respectively, at an average forwarding distance of 3760 m, average payload volume of 15.04 m^3, and a mean number of grips of logs with the crane grapple, during loading and during unloading, of 23.57 and 14.10 per cycle, respectively. With regard to site C, the average machine productivitiy was 12.39 m^3·PMH^{-1} and 11.85 m^3·SMH^{-1}, travelling a mean forwarding distance of 1630 m, transporting a mean load volume of 13.63 m^3, and performing an average number of grips of logs with the crane grapple, during loading of 26.52 and during unloading of 12.36 per cycle. The ratio between the number of grips of logs with the crane grapple during loading and unloading operations in site A is on average 2.56, but in site B it is significantly smaller – mean of 1.67, due to the larger number of logs in the grapple when loading from large piles. Site C shows a loading and unloading number of grips ratio intermediate between the two Bulgarian sites. This ratio is characterized by the concentration of logs in the stand. Concentration in larger piles results in a larger volume of grappled logs by crane, and hence, lower time for loading of the forwarder and higher productivity. The obtained results show that the dispersion of small piles of logs results in a smaller volume grappled, a greater number of crane cycles and a larger loading distance, which generally, increases loading time. The larger volume of logs in the crane grapple and the shorter loading distance, when the loading operation is carried out from larger piles at the roadside, lead to less loading time. Gross costs for forwarders were 65.14 € PMH^{-1} at Site A, 72.96 €·PMH^{-1} at Site B, and 85.58 €·PMH^{-1} at Site C. When the forwarders were productive, the costs were 6.35 €·m^{-3} in site A, 7.90 €·m^{-3} in site B, and 6.90 €·m^{-3} in site C.

Keywords: forest operations, productivity, economic analysis, work elements, loading phase, piles

1. Introduction

In Europe, forests play a crucial role in the sustainable development of society and the improvement of living conditions. In particular, east-central European forests, as the Mediterranean forests, can represent a fundamental resource in rural and mountainous regions (Shuleva and Kolev 2022). Bulgaria and southern Italy, in addition to sharing many characteristics of forest territories, such as steep terrain and small extensions of most logging areas, also present similarities regarding wood harvesting systems. In particular, the most widespread harvesting system in both countries is based on felling trees using chainsaws, and wood processing and extraction adopting systems based on different level of forest mechanization (Borz et al. 2013, 2015, Spinelli et al. 2013, Moskalik et al. 2017, Bodaghi et al. 2018, Proto et al. 2018a, 2018b, Cataldo et al. 2020).

However, both in Italy and in Bugaria, a certain level of mechanisation has been applied to timber extraction in the last decades: thanks to the use of machines, such as forwarders, that are increasingly specialized and with a high level of mechanisation in timber logging and bunching operations. In fact, the increasing use of forwarders in timber extraction over the last decade (Stoilov 2021) has stimulated a significant development of this type of machine (Nordfjell et al. 2019) to address the challenges encountered in forestry operations. In fact, the degree of accessibility to forest stands and the density of roads reflect the difficulty, and therefore the cost, of logging operations (Sanchez-García et al. 2016, Proto et al. 2017).

Considering that the performance of forwarder wood extraction is mostly influenced by travel distance (Sever 1988, Tiernan et al. 2004, Ghaffarian et al. 2007, Spinelli and Magagnotti 2010, Cataldo et al. 2022), the characteristics and the organization of the stand, in particular the distribution of landed timber ready to be extracted (Manner et al. 2013), have a considerable effect on productivity rate. In fact, the loading and unloading operations of timber proved to be the most time-consuming phases of the forwarder work cycle (Minette et al. 2004). In particular, in thinning operations, load characteristics (i.e. volume, number of logs, quantity of timber on a felling site), influenced by the harvesting system adopted, affect the productivity rate (Tufts and Brinker 1993, Tufts 1997, Sampietro et al. 2022). A study conducted in Finland reported that harvesting density, extraction distances, forwarder payload capacity, timber logs and bunching of logs had significant effects on the productivity of the extraction systems (Nurminen et al. 2006). The slope of the terrain also negatively affects the efficiency of forwarding machines; if it exceeds 30%, forwarders suffer a reduction in mobility and therefore productivity (Zimbalatti and Proto 2010). The terrain slope of 25° is the upper limit for the efficient use of harvesters and forwarders due to their productivity decrease of 25–35% (Slugeň and Stoilov 2009).

Taking into account the economic aspects, forwarder efficiency also depends on its payload, as forwarders of higher capacity normally achieve lower costs and higher productivity per product unit (Jiroušek et al. 2007, Proto et al. 2018b). The use of semi-tracks in conditions of limited soil bearing strength increases fuel consumption but provides increased vehicle

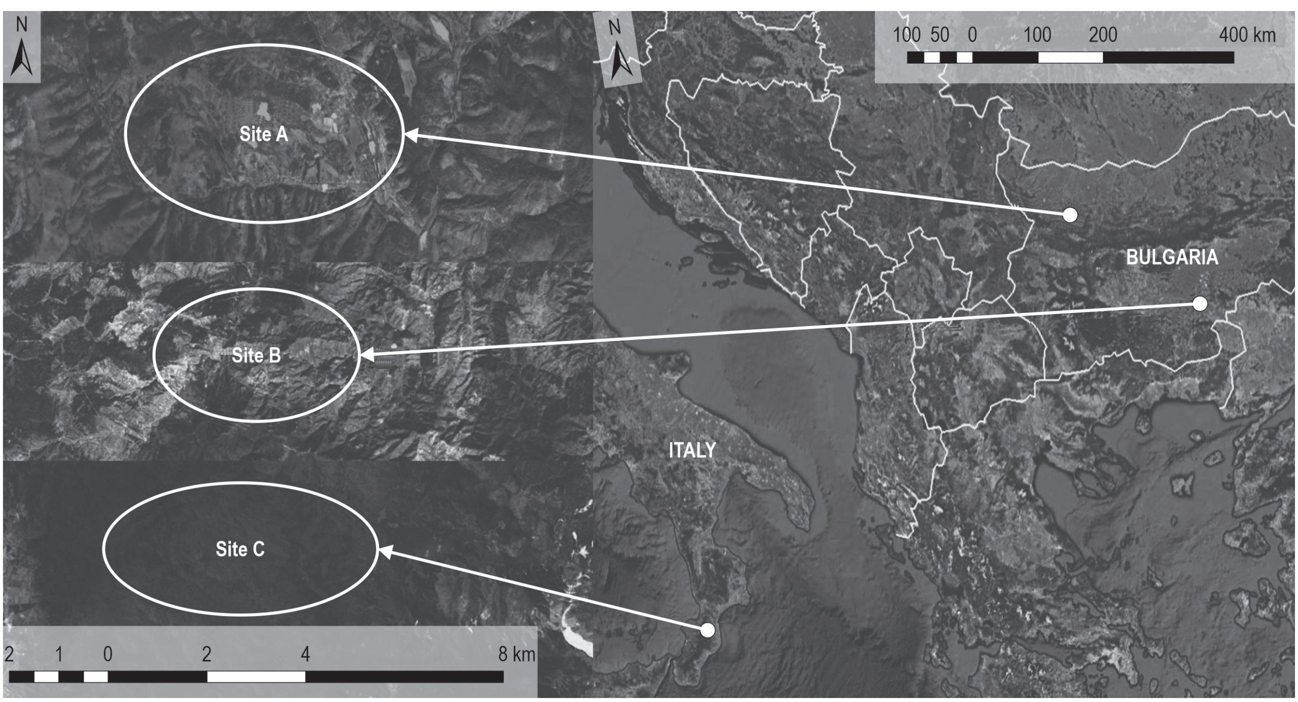

Fig. 1 Map of study sites

mobility (Wästerlund et al. 2011, Poršinsky et al. 2012, Proto et al. 2018c).

To the best of the authors' knowledge, currently, there is no research related to the study of the effects of different concentrations of logs on forwarder performance.

In this context, the study's objectives were:

⇒ to calculate productivity rates and respective costs of forwarding operations

⇒ to develop predictive models of work cycle time and forwarder productivity

⇒ to assess the influence of concentration of logs in piles of different sizes on forwarder efficiency.

2. Materials and Methods

2.1 Study Sites and Work Organization

The research was conducted at three experimental sites located in Bulgaria and Italy (Fig. 1): site A located in the Zemen Mountains, in the western part of Bulgaria; site B in the eastern Rhodope Mountains in southern Bulgaria, and site C in the Serre Massif in the southern part of the Apennine mountain in South Italy.

Table 1 shows the main information about the study sites and operations performed, while Figs. 2, 3 and 4, show the relative slope profiles of the land of each site.

The organization of the forest worksite stands consisted of manually felling and cross-cutting trees of Scots pine, Austrian pine, and Calabrian pine into logs by chainsaw or by harvester. Regarding site A, the logs were left at the landing area spread in the stand, in site B they were concentrated at the roadside in large piles about 1.5 m high and about 6 m long, whereas, in site C the logs were organized at the roadside in piles of the same height and medium-sized long. In both site B and site C, the logs where organized into piles with the help of the harvester head during cross-cutting operations. Timber extraction was carried out by forwarders (Table 2) in a downhill direction for the three sites. Data collection focused on the forwarder activities carried out during 30 work cycles for each machine: the Ponsse Gazelle forwarder (Ponsse Plc, Vieremä,

Table 1 Description of study sites

Site	A	B	C
Machine (Forwarder)	Ponsse Gazelle	John Deere 1420	John Deere 1110D
Province	Pernik (Bulgaria)	Kardzhali (Bulgaria)	Vibo Valentia (Italy)
State forest range	Zemen	Krumovgrad	Serre Regional Park
Coordinates	42°34'50.07734" N, 22°42'57.66008" E	41°19'54.56" N, 25°36'39.25" E	38°33'19.13" N, 16°22'32.90" E
Elevation, m	800	550	1280
Species	SP 100%	SP 80%, AP 20%	CP 100%
Stand type	High forest plantation	High forest plantation	High forest plantation
Operation type	Regular thinning and sanitary felling	Regular thinning and shelterwood cutting	Selective cut and thinning
Total area, ha	16.1	22.2	18
Site volume, $m^3 \cdot ha^{-1}$	222	336	650
Removal volume, $m^3 \cdot ha^{-1}$	100	84	130
Average tree volume, m^3	0.6	0.65	0.67
Average DBH, cm	20	SP 24; AP 30	30
Average height, m	16	SP 17, AP 16	20
Average slope, %	31	34	40
Roughness	Medium	Medium	Medium

Note: SP (Scots pine – *Pinus sylvestris* L.), AP (Austrian pine – *Pinus nigra* Arn.), CP (Calabrian pine – *Pinus nigra* Arn. ssp calabrica (Land) (E. Murray)

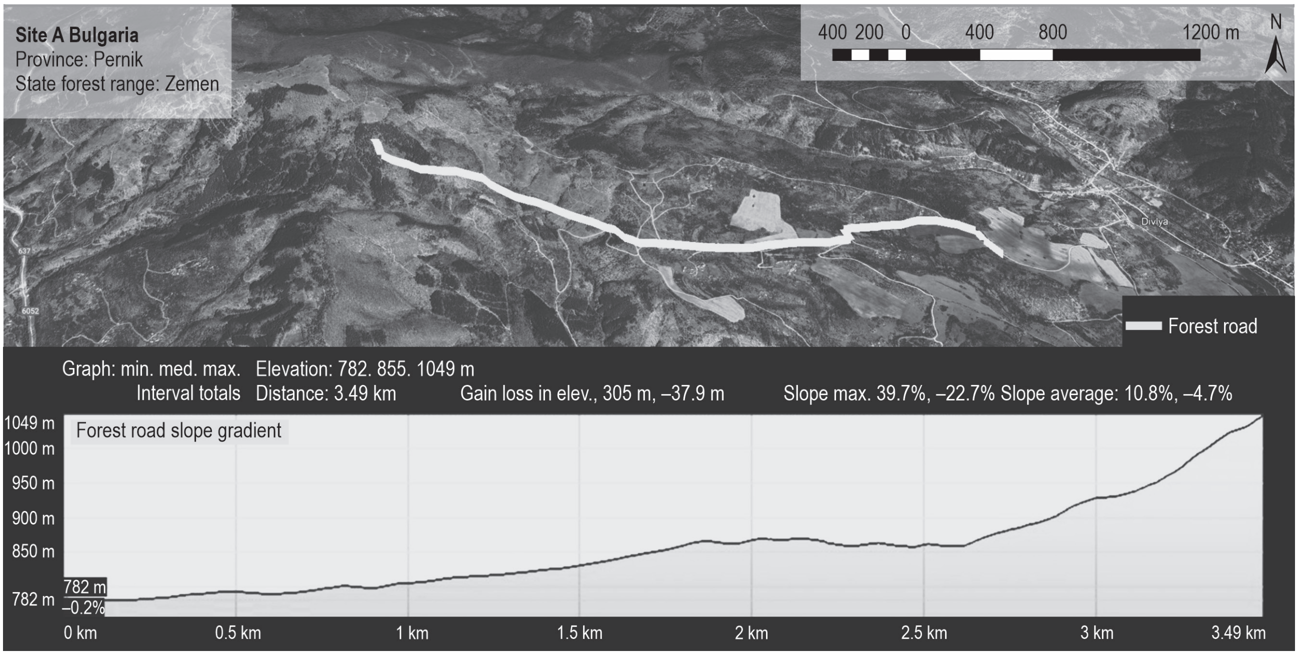

Fig. 2 Study site A and land profile gradient

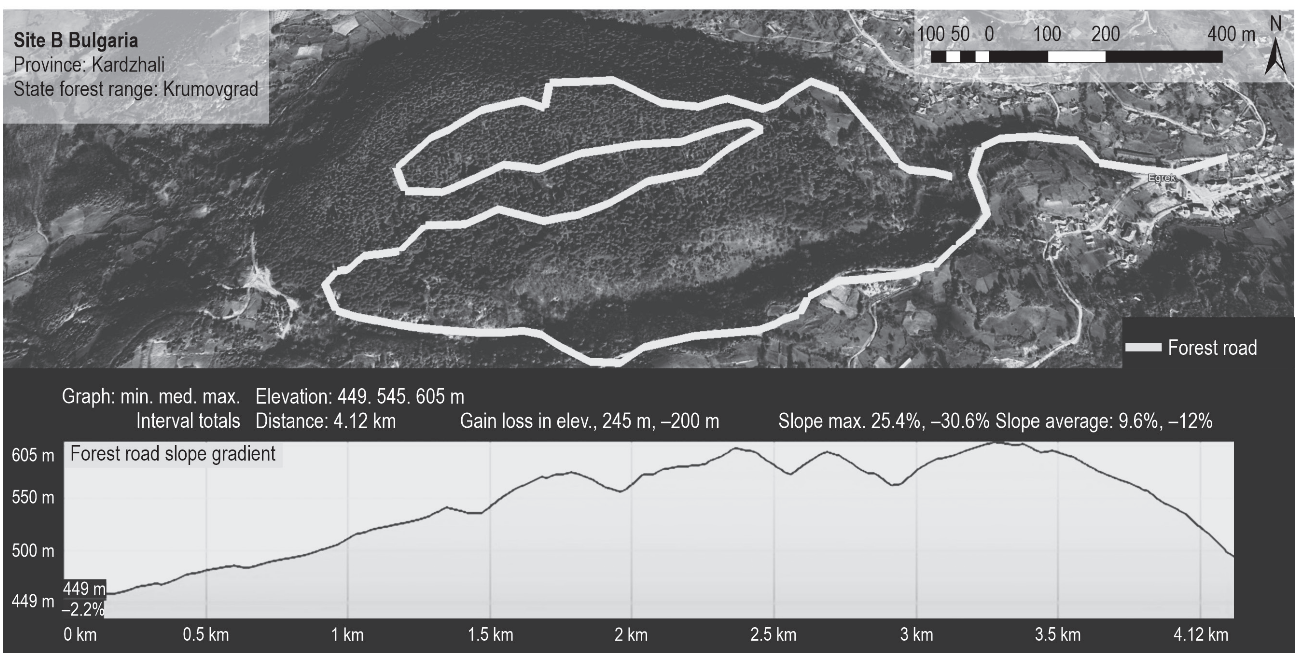

Fig. 3 Study site B and land profile gradient

Finland), shown in Fig. 5A, operating in Site A, the John Deere 1420 forwarder (Deere & Company, Moline, USA) operating in site B (Fig. 5B), and the John Deere 1110D forwarder (Deere & Company, Moline, USA) operating in site C (Fig. 5C).

2.2 Productivity and Data Analysis

The forwarder productivity was conducted by analyzing the work cycle, dividing it into work elements to estimate the productivity of the forwarders under certain standard conditions of measurement

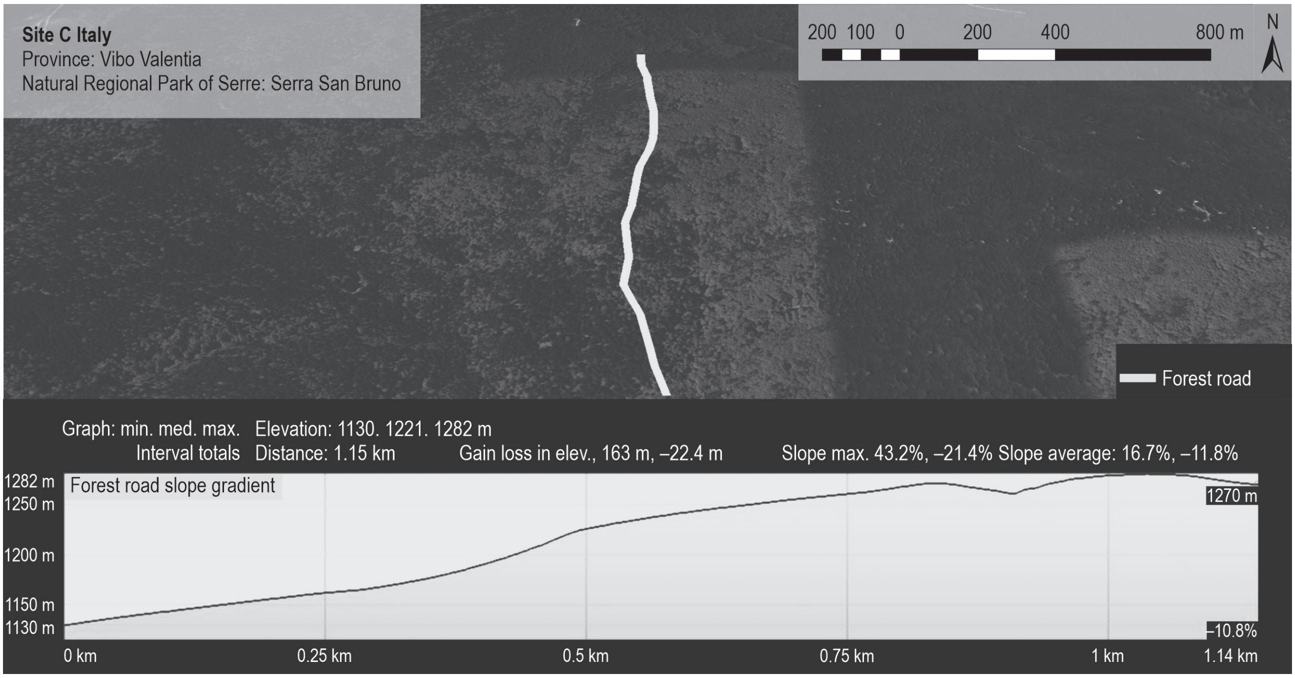

Fig. 4 Study site C and land profile gradient

Fig. 5 Forwarders tested (A) Ponsse Gazelle, (B) John Deere 1420, and (C) John Deere 1110D working in site A, B, and C, respectively

(Nurminen et al. 2006, Proto et al. 2018b, Borz et al. 2021, Cataldo et al. 2022) as follows:

⇒ travel unloaded (*TU*): the unloaded forwarder drives from the landing to the felling area after unloading logs at landing

⇒ loading (*L*): the forwarder displacement stops, and the crane arm begins loading the logs and finishes when the forwarder bunk is full

⇒ travel loaded (*TL*): the forwarder bunk is full, and the machine moves to the landing area

⇒ unloading (*U*): the machine uses the crane to unload the logs from its bunk. The operation also includes short travels and small movements performed to sort the materials into piles

⇒ delays (*D*): operational, mechanical or personal rests.

Table 2 Main characteristics of machines

Features	Unit	Forwarders		
		Ponsse Gazelle	John Deere 1420	John Deere 1110D
Engine power	kW	150	129.1	120.1
Max. torque	Nm	850	779.6	718.6
Cylinders	–	4	6	6
Number of wheels	–	8	8	8
Number of drive wheels	–	8	8	8
Max. travel speed	$km \cdot h^{-1}$	20	22	22
Total weight empty	kg	15,400	17,500	12,000
Max. load capacity	kg	10,000	14,000	13,000
Tire size	–	600/50-22,5	700-26,5	600x34-14
Crane	–	K70+	CF 785	CF 5
Gross lifting capacity	kNm	106	125	102
Max. reach lengths	m	10	7.8	7.2

Forwarding distance and slope gradient were recorded by the GPS receiver. Huber's formula was applied to determine the logs volume.

To develop prediction models to evaluate forwarder performance, the experimental data collected were analyzed carrying out a stepwise backward regression analysis for independent variables using Statistica 8 (StatSoft Inc., Tulsa, OK, USA). The confidence level used for regression analysis was 95% (α=0.05) and the assumed probability p<0.05.

2.3 Cost Analysis

In terms of cost analysis, as in other forest machines studies (Williams and Ackerman 2016, Cataldo et al. 2020), the hourly machine costs were described both as productive machine hours (PMHs), and as scheduled machine hours (SMHs). The cost analysis used the COST model (Ackerman et al. 2014) to calculate the production cost for 1 m^3 of timber, considering the following parameters: the hourly operator cost, the hourly machine cost, the volume of transported logs, and the PMHs. The accounting records were used to extrapolate the information requested by the cost calculations (Proto and Zimbalatti 2016).

3. Results and Discussion

Table 3 and Fig. 6 show the relevant descriptive statistics of time consumption and operational variables. The observations cover a total of 125.20 h, of which 34.96 h were recorded at site A, 51.69 h at site B, and 38.54 h at site C. During the studies, the forwarders extracted a total of 1196.04 m^3 of timber, of which 295.00 m^3 was from site A, 451.10 m^3 from site B, and 449.94 m^3 from site C.

3.1 Work Cycle Time

Excluding and considering delays, in site A, the working cycle elements with largest duration were the loading (34% and 32%, respectively), followed by travel loaded (32% and 31%, respectively), travel unloaded (26% and 25%, respectively), and, at the end, the shortest one was unloading (8%). In site B, the arrangement of the work cycle elements in descending order of duration was different compared to site A, namely travel unloaded (40% and 37%, respectively), travel loaded (37% and 35%, respectively), loading (15% and 14% respectively), and the shortest one was unloading (8%). In site C, travel loaded represented the largest working cycle element (37% and 35%, respectively), followed by travel unloaded (32% and 30%, respectively), loading (23% and 22%, respectively), and unloading (9%). The delays amounted to 4%, 6%, and 4% of the total working time, respectively, for site A, site B, and site C due to organizational reasons, mechanical delays, unfavorable weather conditions, and poor access to the stand. A detailed breakdown of time categories in sites A, B, and C shows the predominance of the movement (travel) of the forwarders with the larger share of 58%, 77%, and 68%, respectively, whereas loading and unloading account for 42%, 23%, and 32%, respectively.

Within the work cycle in site B, the share of travel unloaded is larger by 3% than the travel loaded. This is perhaps due to the travel uphill, the difficult terrain in some places and the poor condition of some road sections. In both site A and C, the loaded travel was the most consistent element of the working cycle time. However, the two sites do not share the reason for this; in fact, despite the very similar forwarding distance, site C was characterized by a higher slope (40%) than site A (23%), which affected the machine movement. Furthermore, the higher average wood volume of the payload also affected travel times of the forwarder at site C.

Impressive is the fact that the share of loading in Site B (15% in PMH) is 43% that of Site A (34% in PMH), as it was characterized by piles 1 m high, located at the roadside. Loading time at site C was 23% of productive time due to the larger piles, which permitted the forwarder to load more timber while staying close to the same loading place. In terms of the ratio of the logs found during loading and unloading in the forward grapples at the three sites, the data

Table 3 Cycle time and productivity of different sites

Variables	Unit	Site A	Site B	Site C
		Mean value±SD	*Mean value±SD*	*Mean value±SD*
Unloaded Travel, *TU*	min	17.63±12.21	38.67±12.21	21.24±8.82
Loading, *L*	min	22.70±4.28	14.16±0.54	15.18±1.28
Loaded Travel, *TL*	min	21.48±14.39	36.29±4.33	24.61±7.97
Unloading, *U*	min	5.27±1.38	8.17±0.34	6.25±1.12
Delays, *D*	min	2.38±5.11	6.10±3.71	2.79±3.49
Total cycle time	min	69.92±27.96	103.39±10.46	70.08±8.74
Delay-free cycle time	min	67.08±28.03	97.29±10.78	67.28±9.42
Loading distance, *l*	m	19.63± 4.65	11.37±2.79	15.18±1.28
Travel Unloaded distance, TU_d	m	1783.33±1173.66	3760.28±283.71	1629.70±181.92
Travel Loaded distance, T_d	m	1783.33±1173.66	3760.28±283.71	1629.70±181.92
Number of grips of logs with the crane grapple during loading per cycle, n_l	–	22.97±3.53	23.57±1.07	26.52±2.33
Volume of logs in the crane grapple during loading, V_l	m^3	0.44±0.06	0.64±0.03	0.52±0.07
Number of grips of logs with the crane grapple during unloading per cycle, n_{un}	–	8.97±0.81	14.10±1.12	12.36±1.14
Volume of logs in the crane grapple during unloading, V_{un}	m^3	1.10±0.11	1.07±0.08	1.11±0.12
Cycle payload volume, *V*	m^3	9.83±0.86	15.04±0.06	13.64±1.04
Productivity, PMH	m^3 h^{-1}	10.43±4.17	9.38±1.05	12.39±1.96
Productivity, SMH	m^3 h^{-1}	9.93±3.99	8.81±0.89	11.85±1.70
Number of cycles per SMH	–	0.99±0.35	0.59±0.06	1.12±0.16

indicate that their volume during loading averaged 39.5% at site A and 59.6% at site B those at unloading, while site C showed intermediate values (46.8%). Obviously, the conditions in unloading logs from the forwarder bunk using the crane are similar for the three machines. Therefore, the difference in the volumes of timber in the grapples during loading and unloading is due to the different concentrations of logs in site A, B, and C. It was seldom necessary for the forwarder in sites B and C to leave the road and move along the terrain in the cutting area. In fact, loading times were a bit more than twice the corresponding unloading time, while, in terms of duration in site A, the loading operations, due to frequent movement of the forwarder between the felled trees, was about four times that of unloading.

The mean duration of the delay-free work cycles in sites A, B and C were 67.08 min, 97.29 min, and 66.67 min, respectively, whereas the mean durations of the work cycles including delays were 69.92 min, 103.39 min, and 69.47 min, respectively. Thus, in the given conditions per 8 h-shift in site A and C, the forwarder made 6–7 (mean 6.9) work cycles, and in site B 4–5 (mean 4.69) work cycles.

Data analysis developed the prediction equations for the forwarder time consumption by the regression procedure distinguishing the exclusion and inclusion of delay (T_{net} and T, respectively) in the calculation, each shown in Table 4.

Eq. (1) suggests that the shortest forwarding distances F_d and small number of grips during loading n_l (i.e., a large volume of logs in the grapple of the crane) guarantee the fastest cycle time $T_{net,A}$ (site A). In a complete forwarding cycle considering delay T_A (Eq. 2), the forwarding distance has a similar influence as in Eq. (1). The loading time in site A decreases with an increase in the ratio between the payload volume of the forwarder and the number of grips with the crane grapple during loading per cycle, i.e. the volume of logs gripped in the grapple. The unloading time depends on the payload volume of the forwarder and the number of grips during unloading per cycle; it will be minimal when increasing the ratio between these two factors. In Eq. (3), a minimum delay-free cycle time $T_{net,B}$ (site B) will result in the case of short forwarding distances F_d, but also with a decreased number of grips of logs with the crane grapple during unloading per cycle and skid trail gradient *i*. In site B, the cycle time including delays T_B given by Eq. (4) depends on

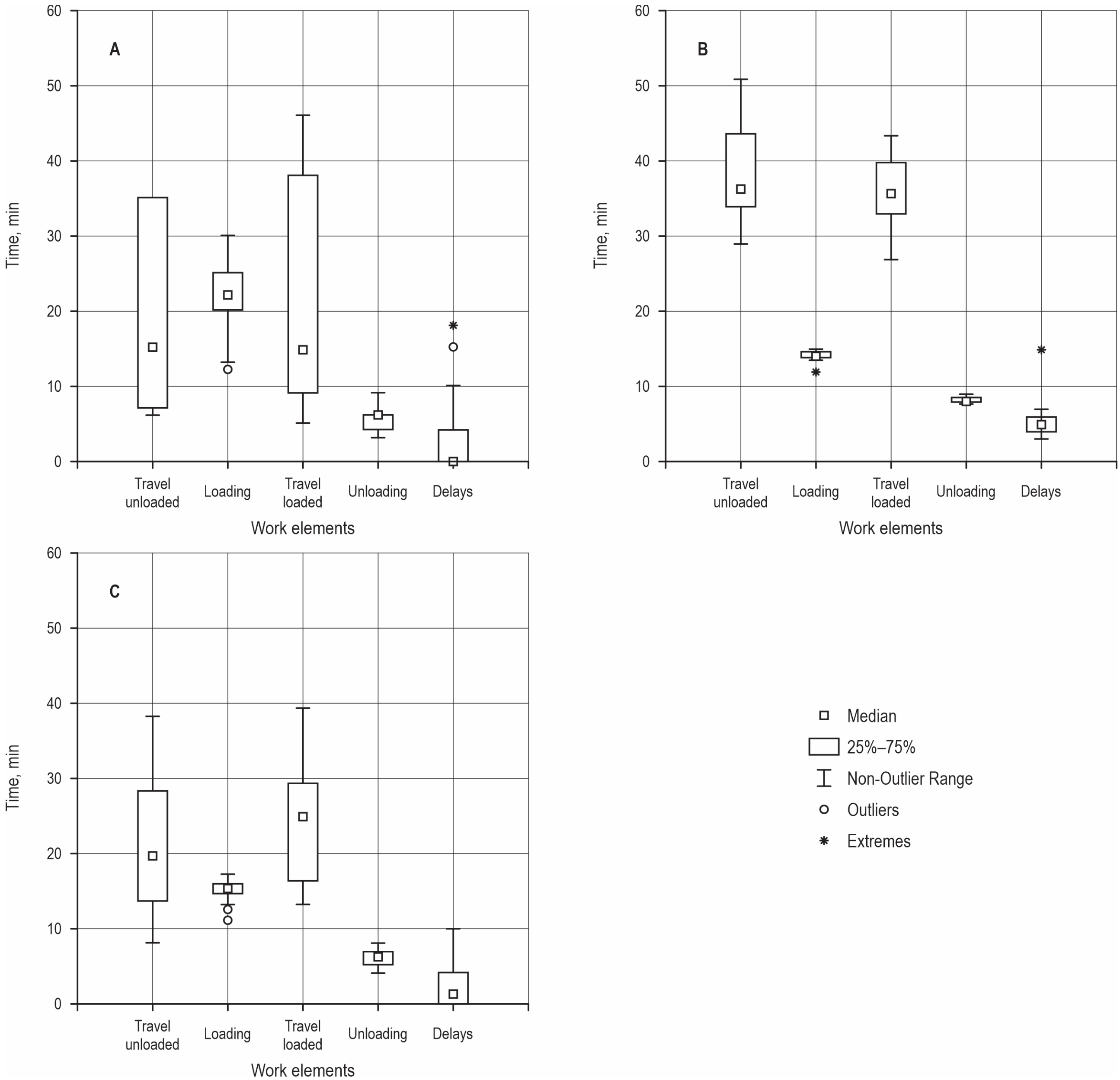

Fig. 6 Elemental time consumption of forwarders at three sites: (A) Site A, (B) Site B and (C) Site C

forwarding distances F_d and skid trail gradient i, and it will decrease as the values of these factors decrease. $T_{net,C}$ (site C) depends on skid trail gradient i and forwarding distances F_d, but also on the ratio between the payload volume of the forwarder and the number of grips of logs during loading per cycle V/n_l (Eq. 5); it will be minimal when increasing the ratio between these two factors. In Eq. (6), the cycle time including delays T_c depends on skid trail gradient i, and it will increase as the slope increases. The general prediction models of the T_{net} and T (Eq. 7 and Eq. 8, respectively) take into consideration skid trail gradient i and forwarding distances F_d that increase the cycle time, and the number of grips during loading n_l and the ratio between the payload volume of the forwarder and the number of grips of the crane grapple during loading per cycle V/n_l, that decrease the cycle time when the two factors are at a high level.

3.2 Productivity Analysis

The forwarder productivity in site A obtained from a mean forwarding distance of 1780 m, an average load volume of 9.83 m^3, and a number of grips of logs

Table 4 Work cycle time (minutes) models

	Equations	F	R^2	R^2_{adj}	Std. Error	*p*-Value
(1)	$T_{net,A} = 27.58 + 0.22 \cdot F_d$	172.24	0.86	0.86	10.67	$p < 0.05$
(2)	$T_A = 60.61 + 0.023\ F_d$	142.08	0.91	0.91	8.53	$p < 0.05$
(3)	$T_{net,B} = 0.93 \cdot n_{ul} + 0.041 \cdot F_d + 3.05 \cdot i$	140.63	0.93	0.91	2.15	$p < 0.05$
(4)	$T_B = 0.037 \cdot F_d + 3.46 \cdot i$	31.41	0.87	0.84	4.19	$p < 0.05$
(5)	$T_{net,C} = 0.89 \cdot i + 0.012 \cdot F_d – 34.35 \cdot V/n_l$	42.35	0.89	0.87	3.45	$p < 0.05$
(6)	$T_C = 1.55 \cdot i$	75.33	0.71	0.70	4.80	$p < 0.05$
(7)	$T_{net} = 87.37 – 1.63 \cdot n_l + 22.90 \cdot F_d + 0.05 \cdot i – 60.99 \cdot V/n_l$	227.75	0.91	0.91	6.89	$p < 0.05$
(8)	$T = 72.74 – 1.09 \cdot n_l + 22.95 \cdot F_d + 0.36 \cdot i – 48.24 \cdot V/n_l$	271.36	0.93	0.92	6.59	$p < 0.05$

Note: T_{net} – delay-free cycle time; T – cycle time including delays; F_d – forwarding distance; n_{un} – number of grips during unloading; n_l – number of grips during loading; i – trail gradient; V/n_l – payload volume/ number of grips during loading ratio

during loading n_l of 22.97 per cycle and during unloading n_{un} of 8.97 per cycle is 10.43 $m^3 \cdot PMH^{-1}$ and 9.93 $m^3 \cdot SMH^{-1}$, respectively (Table 3). These productivity rates are higher than those registered by the forwarder operated in site B (9.38 $m^3 \cdot PMH^{-1}$ and 8.81 $m^3 \cdot SMH^{-1}$, respectively), but with a forwarding distance of 3760 m (double compared to site A), larger mean load volume of 15.04 m^3, and a number of grips of logs with the crane grapple during loading n_l, and during unloading n_{un} of 23.57 and 14.10, respectively, per cycle (Table 3). With regard to site C, the average machine productivity was 12.39 $m^3 \cdot PMH^{-1}$ and 11.85 $m^3 \cdot SMH^{-1}$, transporting a payload of 13.63 m^3 for 1630 m, and performing an average number of grips of logs with the crane grapple during loading of 26.52, and during unloading of 12.36 per cycle.

In this study, the doubled distance at site B had little influence on productivity, contrary to the results obtained in other studies (Sever 1988, Raymond 1989, Valenta and Neruda 2004). This was likely caused by concentration of larger stacks, which results in a higher volume at site B and therefore in high productivity despite the long distance. A similar phenomenon has also been observed in other research. In the last decade, many studies have found that the forwarding time was larger in the case of extraction of logs with small volume due to the increase of the number of grips and due to more gripper movements to fill the forwarder bunk (Strandgard et al. 2017, Holzfeind et al. 2018, Hildt et al. 2020). Comparing this study with another conducted in Sweden (Erikson and Lindroos 2014), where the extraction distance was 2–5 times shorter, the results obtained show a smaller productivity. The forwarder productivity in Southern Austria at a distance of 97 m was estimated around 17.9 m^3 per PMH with a payload of 10.04 m^3 (Ghaffariyan et al. 2007).

The ratio between the number of grips of logs with the crane grapple during loading and unloading in site A is in a mean of 2.56, in site B it is significantly smaller (on average 1.67), and in site C this ratio has

Table 5 Productivity equations ($m^3\ h^{-1}$)

	Equations	F	R^2	R^2_{adj}	Std. Error	*p*-Value
(9)	$P_{PMH,A} = 1.24 \cdot V – 0.0026 \cdot Fd$	121.58	0.93	0.93	1.13	$p < 0.05$
(10)	$P_{SMH,A} = 1.14 \cdot V – 0.003 \cdot F_d$	193.86	0.93	0.93	1.06	$p < 0.05$
(11)	$P_{PMH,B} = 1.79 \cdot V – 0.087 \cdot n_{un} – 0.0039 \cdot F_d – 0.20\ i$	233.47	0.97	0.97	0.18	$p < 0.05$
(12)	$P_{SMH,B} = 0.003 \cdot F_d – 0.25 \cdot i$	32.22	0.87	0.84	0.35	$p < 0.05$
(13)	$P_{PMH,C} = 16.01 – 0.22 \cdot n_{un} + 0.73 \cdot V – 0.17 \cdot i + 6.28 \cdot V_l – 0.002\ F_d$	75.54	0.93	0.92	0.55	$p < 0.05$
(14)	$P_{SMH,C} = 10.76 + 0.85 \cdot V – 0.27 \cdot i$	59.93	0.80	0.79	0.78	$p < 0.05$
(15)	$P_{PMH} = 6.86 + 0.98 \cdot V – 3.18 \cdot F_d - 0.071 \cdot i$	378.48	0.91	0.91	0.85	$p < 0.05$
(16)	$P_{SMH} = 6.82 + 0.90 \cdot V – 3.00 \cdot F_d - 0.06 \cdot i$	259.46	0.90	0.89	0.96	$p < 0.05$

Note: P_{PMH} – productive machine hours; P_{SMH} – scheduled machine hours; V – payload volume; F_d – forwarding distance; n_{un} – number of grips during unloading; i – slope; n_l – number of grips during loading; V_l – load volume per grips during loading an intermediate average value (2.17) between the values shown by the other two sites. The small ratio is due to the larger number of logs in the grapple when the loading is carried out from large piles. This ratio is characterized by the concentration of logs in the stand. Concentration in larger piles results in a larger volume of logs grappled by crane, and hence, lower time for loading of the forwarder and higher productivity. In fact, the number of logs in the load and the felling density influenced productivity during forwarding operations (Tufts 1997, Tufts and Brinker 1993).

The forwarder productivity of site A is defined by the regression Eq. (9) that indicates the increase in PMH in site A as a consequence of increasing the payload volume V and decreasing the forwarding distance F_d. The effect of these two factors on productivity with delays is similar (Eq. 10 – Table 5).

According to Eq. (11), to increase the delay-free productivity of the forwarder in site B, the payload volume V should be increased, whereas the number of grips of logs with the crane grapple during unloading n_{un}, forwarding distance F_d, and road slope gradient i should be decreased. The scheduled machine hours (P_{SMH}) in site B would increase by increasing the forwarding distance F_d and decreasing the road slope gradient i (Eq. 12).

The regression Eq. (13) defines the productive machine hours (P_{PMH}) in site C. Increasing payload volume and grips volume during loading operation, the PMH increases; whereas it decreases when increasing the number of grips of the grapple during unloading, the skid trail gradient and forwarding distance. The forwarder productivity of site C, including delays (P_{SMH}), is positively affected by payload volume and negatively by skid trail gradient (Eq. 14). Generally, the productivity of forwarders in all sites, excluding delays (Eq. 15) and including them (Eq. 16), can be maximized by reducing the forwarding distance F_d, and skid trail gradient i and by increasing payload volume.

Dispersion of small piles of logs results in a smaller volume grapple and a greater number of crane cycles and loading distance and generally increases loading time. The larger volume of logs in the crane grapple and the shorter loading distance when loading from larger piles at the roadside result in less loading time. A large payload volume of the forwarder loaded in short time thanks to a better concentration of the logs in piles, especially along the roadside, would reduce loading time and, consequently, increase forwarder productivity. Productivity of site A, in fact, demonstrated the lowest productivity rate of the forwarder, where moving of the machine accounted for most cycle time.

3.3 Cost Analysis

Cost analysis results are reported in Table 6 and Fig. 7. Gross costs for forwarders were determined at 65.14 € per PMH at Site A, 72.96 €·PMH^{-1} at Site B, and 85.58 €·PMH^{-1} at Site C. Therefore, when the forwarders were productive, the costs were 6.35 €·m^{-3}, 7.90 €·m^{-3}, and 6.90 €·m^{-3} in site A, site B and site C, respectively. Therefore, the productive time of all forwarders affects fixed and hourly operating costs. In fact, it is observed that the cost per cubic meter of wood was lower at site C than at the other sites studied, although the costs per PMH were higher. Although labor, fixed and variable costs were higher at site C due to higher cost of living, higher productivity at Site C decreased the costs per m^{-3} of wood used showing similar values to the other two sites.

In the distribution of net costs of forwarders operating at site A, B and C, variable costs dominated, followed by labor costs and fixed costs. Overall, the distribution of net costs among the three sites was very similar, even for site C, where, despite a higher

Table 6 Calculation of different costs of forwarders

Costs	Site A		Site B		Site C	
	Costs per PMH €	Costs €·m^{-3}	Costs per PMH €	Costs €·m^{-3}	Costs per PMH €	Costs €·m^{-3}
Fixed costs	12.81	1.23	15.78	1.68	19.53	1.57
Variable costs	24.64	2.46	28.14	3.11	30.20	2.43
Labor costs	17.92	1.72	17.92	1.91	23.00	1.85
Net costs (excluding profit)	55.37	5.41	61.84	6.70	72.73	5.87
Overheads and management costs	3.85	0.37	4.49	0.48	5.25	0.42
Profit	5.85	0.58	6.63	0.72	7.60	0.61
Gross costs (including profit)	65.14	6.35	72.96	7.90	85.58	6.90

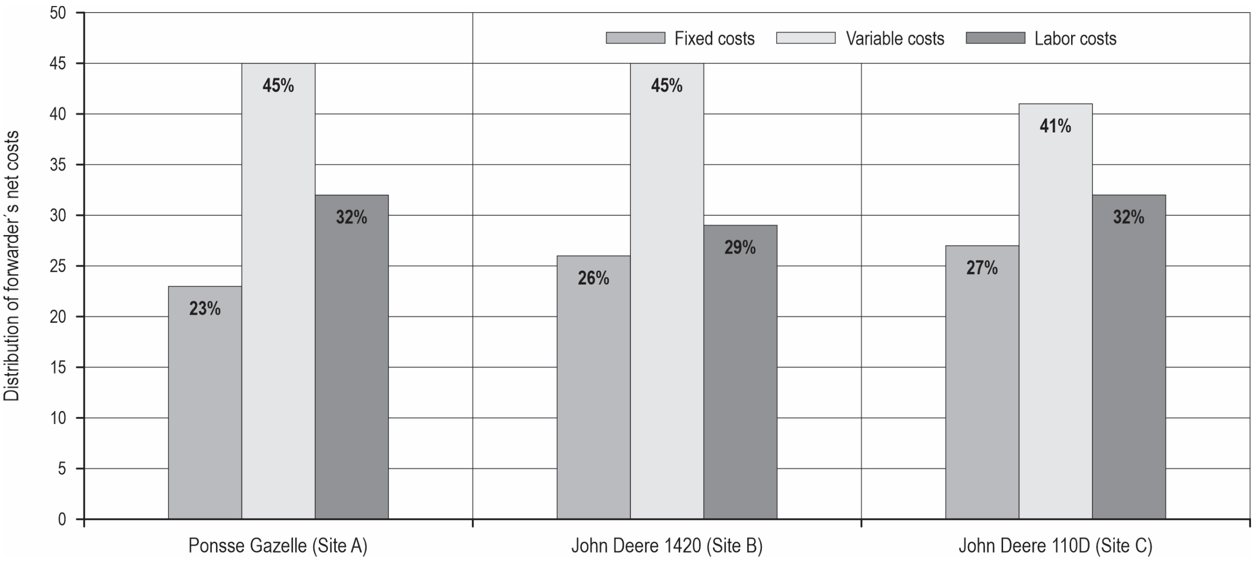

Fig. 7 Percentage distribution of forwarder net costs

operator's labor cost, the percentage distribution of net costs was in line with the other sites. Proto et al. (2018c) calculated the forwarding costs at 3.40 €·m^{-3} and 4.50 €·m^{-3} at a mean extraction distance of 306 m and 597 m in two stands in southern Italy, which was lower than the costs we found at more than 5-time longer extraction distances.

4. Conclusions

In Bulgaria and Italy, forwarders often load logs from large piles that are extracted by modified farm tractors and animals but, currently, there are no information available on time consumption, productivity and cost of forwarder operating at different concentrations of logs – in small piles in the stand versus concentrated in greater piles at the roadside, on the loading process and on overall forwarder performance.

This study contributes to partially fill this gap adding information on the productivity of forwarders in different mechanized harvesting conditions favoring the rationalization of work, and cost estimation.

In fact, the scattering of small stacks of logs results in a smaller grip volume, an increased number of crane cycles and load distance, which generally increases load time. The handling of logs in larger piles along the road and the greater volume of logs in the crane grapple associated with shorter loading distances result in shorter loading times and higher productivity. The results obtained from this first study in the territories of Bulgaria and Southern Italy could help predict and plan better productivity of the system under similar conditions and characteristics.

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