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ORIGINAL PAPER

Factors affecting forwarder productivity

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Abstract

Modern forwarders are an effective extraction option for timber harvesting operations that provide the opportunity for higher levels of mechanization. With their ability to carry logs from the forest to the roadside or processing areas, they have an established lower environmental impact in comparison to tree-length skidding options. However, little is published regarding their productivity potential or the factors that influence productivity. Three case studies were carried out; (1) a selective harvest in Calabria, Italy, with a smaller 12 t capacity John Deere 1110E, (2) a clear-cut on the West Coast of New Zealand, with a larger 19 t capacity John Deere 1910E and (3) a larger clear-cut operation in Canterbury, New Zealand, with two John Deere 1910E forwarders. An elemental time and motion study was used resulting in 73.4 h of detailed data, with 159 cycles extracting 2241 m^3 of timber. Productivity models were created for all three sites as well as one combined model. Average cycle time was 33.2, 24.2 and 22.8 min, and average productivity 24.6, 37.1 and 42.7 t per productive machine hour, respectively. Cycle time was the fastest, and consequently productivity the highest, at the Canterbury site where the terrain roughness was low, overcoming any effect of the average small piece size (0.59 m^3). Travel speed was slowest at the West Coast site showing the effect of wet and difficult terrain, with travel empty speed being just 3.8 km/h, compared to 6.7 and 6.9 km/h at the other two sites. Productivity at the two clear-cut operations was significantly higher than the selective cut, compounded by the use of the larger capacity forwarders. Distance and payload were significant factors for each cycle time model; in the combined model the sites were also significant. The calculated unit cost of forwarder extraction in the sites ranged from €2.55 to €4.70/m^3. For regions such as southern Italy that have relatively low levels of forest mechanization, this information can be used to help design and improve more traditional labor-intensive harvesting systems.

Introduction

One of the common ground-based harvesting systems used in pine plantations is cut-to-length (CTL). The CTL system consists of felling, delimbing and bucking trees into logs of specified lengths at the stump. Logs are then transported to a roadside or landing area by a forwarder (Spinelli et al. 2004; Proto et al. 2017b). This system offers several advantages compared to the other ground-based systems: notably less road construction, lower levels of soil disturbance, smaller landing size through reduced processing requirements, minimal damage to the logs during handling and extraction and fewer workers (Bettinger and Kellogg 1993; Cambi et al. 2017). The fully mechanized CTL timber harvesting system has become widely used in many industrialized European countries where the conditions and the stands are favorable such as in Sweden (ca. 98%), Ireland (ca. 95%) and Finland (ca. 91%), as compared to motor-manual harvesting (Karjalainen et al. 2001).

In Italy forests account for about 10.9 million hectares, corresponding to 37% of the land area and are mainly located in hill and mountain ranges (Zimbalatti and Proto 2009a). Italian forestry is characterized by steep terrain, ownership fragmentation and the application of close-to-nature management criteria such as continuous-cover forestry (Mason et al. 1999; Cosola et al. 2016; Mologni et al. 2016). Forests in southern Italy are important, having the largest percentage forest cover of all regions of the country, even though the highest concentration of productive woodlands occurs in the northern regions of Italy. These southern forests can provide a significant resource

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for the economy of the entire Mediterranean basin; an objective that could be attained with better and more efficient mechanization of timber harvesting systems (Istat 2013; Proto et al. 2017a). The most common harvesting system in southern Italy, referred to as “traditional,” can be considered as an early stage of mechanization. Traditional methods are based mainly on agricultural tractors, sometimes equipped with specific forest-related accessories such as winches, hydraulic cranes and log grapples. This level of mechanization has to date been adequate due to the characteristics of the forest ownership and the small dimensions of many forest enterprises (Zimbalatti and Proto 2009b; Proto and Zimbalatti 2016). However, there is growing interest in Southern Italy toward fully mechanized CTL systems due to their lower unit harvesting costs and higher productivity compared to traditional methods. In order to successfully transition from traditional to fully mechanized CTL systems in Southern Italy, an improved understanding of factors affecting the productivity and costs is necessary.

Productivity of a CTL system depends on the forest stand, site and operational factors such as ground conditions, slope, operator’s motivation and skill, branch size, operational layout, tree size, tree form, log assortments processed, numbers of un merchantable and merchantable trees per unit area, hauling distance, undergrowth density and machine design (Spinelli et al. 2002; Stampfer 1999; Proto et al. 2016a). Timber extraction (e.g., forwarding in CTL systems) from stump to landing is one of the most time-consuming and expensive operations of harvesting systems (Mousavi 2009). There have been a number of previous studies on various aspects of forwarders (e.g., Brunberg 2004; Nurminen et al. 2006; Spinelli et al. 2003), but few have been conducted in Southern Italian forest types like pine plantations. Furthermore, researchers have used differing definitions of cycle elements, investigated different factors affecting productivity and used different methods to measure variables; forwarding distance in particular. Therefore, there is a need for a production study to benchmark current forwarding operations in Southern Italy and compare with other nations using a common study methodology.

One nation that shares similarity with pine plantation harvesting methods is New Zealand. Although full-tree-length extraction by grapple skidders to large landings is by far the most common ground-based extraction system (Visser 2015), CTL systems are also common.

The aim of this study was to better understand factors that affect productivity of forwarders in pine plantations by comparing larger-scale New Zealand operations with the newly introduced southern Italian system. Specific study objectives were to:

1. Analyze operational time consumption for estimating the productivity of two different models of forwarders (John Deere 1910E and 1110E).
2. Estimate productivity in relation to common factors in harvesting operations.
3. Determine the operation cost for the two forwarders studied.

Materials and methods

Site description

The forwarder productivity study was recorded in three different locations, indicated with letters A, B and C, respectively. The plantation at site A was a stand of *Calabrian Pine (Pinus nigra Arn. ssp. laricio Poiret var. Calabrica Delamare)*, at an altitude of 1200 m above sea level (Table 1). The study was conducted in a selective felling site that was 22 ha in size, with south-east exposition. The forest area was classified as class I for roughness, while the slope was between class III and IV, in accordance with terrain classification of UK Forestry Commission (1995). The density of the forest was generally uniform; small gaps were present only in the areas with lower soil depth. The area had a good main road network and was flanked by the provincial road; the trails opened during felling were used as the secondary road network (Cavalli and Grigolato 2010).

The clear-cut operations in the New Zealand radiata pine (*Pinus radiata* D.Don) forests were both in the South Island; B was located on the West Coast and C in Canterbury at an altitude of 280 and 230 m above sea level and 25 and 27 ha in size, respectively. The West Coast forest area was split into a grid pattern by well-constructed roads that were suitable for log trucks. In between this grid pattern was general clear-cut operations where an excavator with bucket attachment would cut tracks through the clear-cut for the forwarder to extract the timber. These tracks became very muddy and the forwarder often had to travel over wet gullies and ditches. This slowed the machine down considerably as the machine was not using chains or band tracks, as the machine would rarely venture off these tracks. Conversely the Canterbury site was dry. The terrain class at both sites would be rated as 1 (UK Forestry Commission 1995).

Machines used

Forwarders can be classified by tare weight, load capacity or gross mass (vehicle + load) (Porsinsky 1997). However, they are more commonly rated according to their loading capacity (payload), from light (< 10 t), medium (10–14 t) to heavy forwarders with a load capacity over 14 t (Brunberg 2004). At site A the forwarder studied was

Table 1 Characteristics of the three forwarder work sites

Site	A	B	C
Country	Italy	New Zealand	New Zealand
Place	San Giovanni in Fiore	Paparoa Forest	Balmoral Forest
Province	Cosenza	West Coast	Canterbury
Elevation (m)	1150	280	230
Species	Calabrian Pine	Pinus radiata	Pinus radiata
Stand type	Plantation	Plantation	Plantation
Operation type	Selective cut	Clear-cut	Clear-cut
Total area (ha)	22	25	27
Density (trees/ha)	870	148	700
Site volume (m^3/ha)	630	300	405
Removal (trees/ha)	158	all	all
Removal volume (m^3/ha)	126	all	all
Average tree volume (m^3)	1.20	1.90	0.57
Average DBH (cm)	38	52	31
Average height (m)	26	38	29
Average slope (%)	25	5	5
Roughness	Medium	Medium (muddy/wet)	Low (clear, dry ground)

Table 2 Technical characteristics of the forwarders studied

Features	Measurement unit	Value	
		Model 1110E	Model 1910E
Power	kW	136	186
Transmission	–	IDM	IDM
Cylinders	N	6	6
Number of wheel	N	8	8
Wheel drive	N	8	8
Max speed of progress	km h^{-1}	24.5	21.3
Total weight empty	Tonnes	17.3	21.8
Max load capacity	Tonnes	13.2	20.2
Tire dimension	–	26.5–20	26.5–20
Std tire size rear			
Std tire size front		34–14	36–16/26.5–20
Boom	Model	CF5	CF8
Gross lifting torque	kNm	102	151
Maximum reach lengths	meters	8.5	8.5

Fig. 1 John Deere 1910E loaded in the radiata pine stand at Site C

a medium-sized John Deere 1110E with 136 kW engine power (Table 2). At work sites B and C, two large (21.8 t) John Deere 1910E eight-wheeled forwarders with 186 kW engine power and 20 t payload capacity were used (Fig. 1).

Work study

Each work cycle was divided into work elements and classified as productive time or delay time, following the terminology suggested by the IUFRO Working Group (Bjorheden et al. 1995). They were timed using a digital chronometer (i.e., 1 min = 100 units). The time study data were collected at site A during autumn of 2016, at B during the summer 2016 and at C in autumn 2017. Extraction of timber by forwarders has the characteristics of cyclic work. Each cycle (turn) consists of four main cycle elements namely, unloaded traveling, timber loading, loaded traveling and unloading of timber (Bergstrand 1985; Väkevä et al. 2001; Nurminen et al. 2006). The definitions used in this study are consistent with those used by Tiernan et al. (2004), Cavalli et al. (2009) and Sanchez-García et al. (2016).

Travel empty

Begins when work starts or after unloading of logs at landing, the forwarder has to return to the work zone unloaded.

Loading

Begins once the forwarder is at the side of the logs to be loaded, displacement stops and crane arm begins to move or seat begins to turn in order to begin loading. It includes the time spent after the forwarder finishes loading the logs from one pile and moves to the next pile, until the forwarder is fully loaded.

Travel loaded

Once the bunk of the forwarder is full, it begins to move with the load to the landing.

Unloading

At landing, the forwarder uses the crane to unload the logs from its bunk. This activity includes small displacements required at landing in order to complete the unloading.

Complementary work times

Action involves the crane and/or the machine, other than loading, unloading and displacement such as handling logs (at landing, stand or in the forwarder bunk), planning or accessing forest road.

Delays in harvesting operations are characterized as periodic (Spinelli and Visser 2008). They include operational, mechanical or personal delays. They were recorded during the study and a utilization rate calculated for the study period, but the study focus is on the productive elements. The study period is not long enough to provide a meaningful long-term utilization estimate.

For each cycle, the total number of logs in the bunk was counted, identified and recorded as a function of the dimension (large saw timber and small assortments–pulpwood) to calculate the volume of each load. At site A, it was possible to measure each log prior to loading. At site B, a sample of loads was measured, the remainder estimated based on accurate log counts in the bunk to avoid unnecessary impact on productivity. At site C more than 50 logs were measured in the stock-piles to provide an average log volume for the main assortments. In each case the volume of each log was calculated using Huber's formula by multiplying the average cross-sectional area of the stem by length (Philip 1994; Macrì et al. 2016). Extraction distances were measured with a laser rangefinder and the gradient was assessed with a Suunto clinometer.

Statistical analysis

Delay-free time models were formed using the data of all three case studies for both individual elements and the complete cycle time. Regression analysis with variable transformation was used for modeling forwarding in which the time could be explained with the independent variables (i.e., number of logs, total volume payloads, slope, distance of loading and forwarding distance). Two block factors were introduced to identify site differences: WC (West Coast) for B site and CA (Canterbury) for site C.

An F test was conducted to examine the goodness of fit of regression models and to test the co-significance of the coefficients. Each coefficient of the work phase models was also tested separately with a *t* test. If the test results indicated *p* values larger than 0.05, the null hypotheses were rejected and the differences in cycle times were assumed to be from random variation.

Cost

The machine's costs were calculated as described by Miyata (1980). The production costs were calculated based on fixed cost (investment, depreciation and interest) and variable cost (repair and maintenance, petrol oil and lubricants and wages). Total hourly machine cost is the sum of fixed and variable cost. The purchase prices and operator wages required for the cost calculations were obtained from catalogues and accounting records (Forme 2015). A salvage value of 20% of the purchase price was assumed with an economic life of 8 years for all forwarders. Cost calculations were based on the assumption that companies worked the whole year except the rainy season when the harvest areas in Southern Italy are not normally accessible. Spinelli et al. (2011) considered a total 180 working days in the year, at

Table 3 A summary of the variable recorded at the three different forwarder study sites

Variables	Work sites								
	Site A			Site B			Site C		
	Min	Average	Max	Min	Average	Max	Min	Average	Max
Total travel distance (m)	290	729	1560	100	650	1400	240	665	1640
Loading distance (m)	25	54	90	10	10	10	30	83	270
Number of logs (n°)	20	20	39	25	35	43	52	77	119
Average log volume (m^3)	0.27	0.36	0.53	0.35	0.42	0.54	0.15	0.25	0.47
Total payload volume (m^3)	8.3	10.1	10.8	11.4	14.3	17.6	8.4	14.8	18

Table 4 Descriptive statistics of forwarder work element times, in minutes and percentage of total delay-free cycle time

Work sites	Work phase	Average (min)	Min (min)	Max (min)	%
A	Travel empty	3.3	1.15	6.4	9.8
	Loading	13.3	7	22	40.1
	Travel loaded	5.8	2.45	15.2	17.5
	Unloading	10.8	5	14,3	32.6
	Total cycle time	33.2	22	51.5	100
B	Travel empty	4.9	1.07	9.95	20.4
	Loading	8.6	2.67	13.9	35.6
	Travel loaded	5.0	1.06	10.5	20.7
	Unloading	5.6	2.89	8.06	23.3
	Total cycle time	24.2	17.0	62	100
C	Travel empty	3.0	1.1	6.45	13
	Loading	10.2	5.04	28.3	44.9
	Travel loaded	3.4	1.15	7.2	14.7
	Unloading	6.3	3.22	11.4	27.5
	Total cycle Time	22.8	29.3	58.2	100

an average of eight scheduled working hours per day (equals 1440 h year^{-1}), and was adopted in this study.

Results and discussion

The time studies covered in total 73.4 h; of which 29.2 h were recorded at site A, 28.5 h at site B, and 15.7 at site C. Within this time, the forwarders completed 159 forwarding cycles (50 for site A, 69 for B and 40 for C, respectively) and extracted 6884 logs with a total volume of about 2078 m^3. Basic study data regarding total travel distance for the cycles, the number of logs and the total payload (volume) are presented in Table 3. Only short delays were measured during all three different studies, giving 97, 93 and 93% utilization rates, for sites A, B and C, respectively. While such high levels of utilization indicate very reliable machines and efficient systems, long-term utilization rates are likely to be much lower (Spinelli and Visser 2008).

The mean time consumption per cycle was 33.2 min at site A, 24.2 at B and 22.8 at C, respectively (Table 4). At site A, the higher average cycle time was in part due to the longer average distance, but also the relatively poor road network. Furthermore, the larger-scale clear-cut at sites B and C facilitated the pre-bunching of logs by the harvester, which concentrated them in a smaller area.

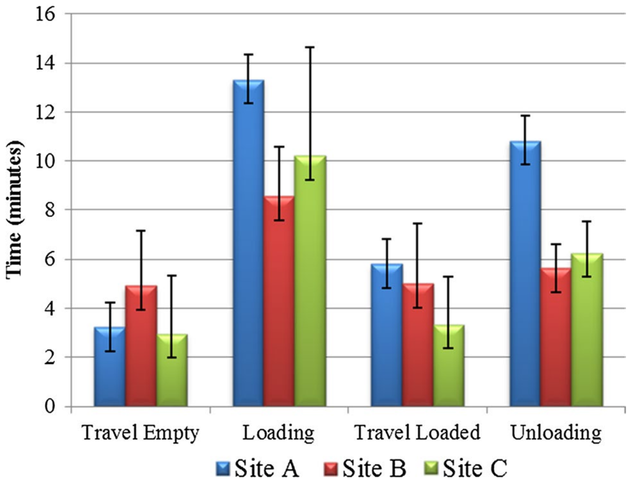

Fig. 2 Share of operations under analysis within work time

Figure 2 shows the ratio of the time elements for the total work time at each site. Site A differed significantly for the loading and unloading elements to both sites B and C. Loading at site A took over 40% of the total time. Loading time was lowest at site B as the logs were pre-bunched (shoveled) to the extraction corridor.

By adding the distance for the travel empty and loaded, and dividing it by the distance travelled within that element, it is possible to establish average travels speed. The average speed for travel empty was 6.68 km/h at site A, 3.77 km/h at B and 6.90 km/h at C, respectively. For travel loaded the average speed was 3.75 km/h at site A, 3.68 km/h at B and 6.17 km/h at C, respectively. For the relatively flat sites B and C, this shows that unloaded and loaded speeds are very similar and indicate modern forwarders have enough power and that speed is limited by terrain roughness. This is indicated by the average speed at the rough and muddy site B being much slower than site C. Site A shows the effect of slope on speed, whereby unloaded downhill was almost twice as fast as loaded uphill.

Different models to predict work element times were evaluated using linear regression and selecting the independent variables by stepwise regression. The number of valid observations collected during the tests was large enough to develop a reliable model for predicting cycle time (Proto et al. 2016b). While regression equations for each individual site yield models that explain more of the variation, the data from all three locations were combined to provide more robust models.

A travel time equation was developed (Eq. 1), whereby travel time includes both unloaded and loaded travel. This is because a forwarder might travel a shorter distance and load over an extended distance and then travel back from the furthest point. However, the forwarder might also travel out to the furthest point and load on the way back, or as common at site C complete a circuit to avoid having to turn or reverse. The distance (Dist) in the equation is the total distance travelled. The equation shows the effect of poor ground conditions at the West Coast (WC—site B) slowed the machine significantly; whereby the travel time at the Canterbury (CA—site C) was similar to that in Calabria.

$$\text{Travel (min)} = 3.64 + 0.007 * \text{Dist} + 2.89 * \text{WC} - 2.24 * \text{CA} \\ \left(F = 86.9; p < 0.01; R^2 = 0.79\right) \tag{1}$$

Equation 2 shows the regression model for loading time. While the model is significant for the data from the three sites, one surprising component is the negative effect of load size (Vol). It would suggest that the larger machines loading at sites B and C were faster than the smaller machine at site A. However, the other factor is that the logs were more spread out at site A; the bunched logs at site B reduced the average cycle time by almost 3 min.

$$\text{Loading (min)} = 18.02 - 0.457 * \text{Vol} - 2.90 * \text{WC} - 0.98 * \text{CA} \\ \left(F = 28.3; p < 0.01; R^2 = 0.59\right) \tag{2}$$

Equation 3 for unloading shows a very similar effect as Eq. 2 for loading. It does show that the larger machines at both sites B and C unloading onto a large landing were much faster than unloading the smaller forwarder in the more constrained site in Calabria (site A).

$$\text{Unloading (min)} = 13.43 - 0.25 * \text{Vol} - 4.17 * \text{WC} - 3.39 * \text{CA} \\ \left(F = 102.8; p < 0.01; R^2 = 0.81\right) \tag{3}$$

While the regression models for the individual time components are significant and informative in helping explain the results for this study, they should be used with caution to predict time elements at other sites as they are confounded by site and machine factors between the three sites.

Equation 4 provides a regression model for the total cycle time and combines the characteristic of the individual elements in Eqs. 1–3. Overall it shows that the larger-scale clear-cut operations in New Zealand (sites B and C) are faster that the smaller-scale operation in Calabria, despite having to load approximately 50% more volume.

$$\text{Total cycle time (min)} = 36.09 + 0.012 * \text{Dist} - 1.10 * \\ \text{Vol} - 2.75 * \text{WC} - 4.23 * \text{CA} \\ \left(F = 66.6; p < 0.01; R^2 = 0.79\right) \tag{4}$$

The average productivity of forwarding at site A was 18.9 m^3/PMH, at site B 37.1 m^3/PMH, while at C 42.7 m^3/PMH. Figure 3 shows the relationship and variability between average forwarding distance and productivity. While the cycle time models already show a difference,

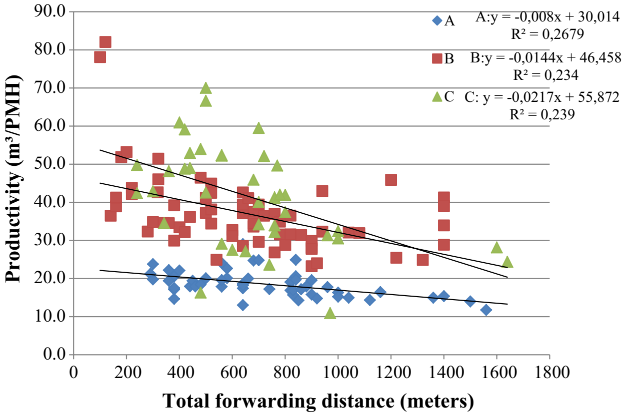

Fig. 3 Relationship between average distance and productivity for forwarding at the three study sites

when factoring in the larger payloads, productivity at sites B and C are considerably higher.

Equation 5 shows the productivity model for delay-free productive machine hours (PMH). For this model, all parameters are logical with a reduction in productivity with distance (Dist), increase with payload volume (Vol), a decrease with poor track conditions at site B (WC) and the highest productivity on the good dry flat terrain at site C (CA).

$$\begin{aligned} \text{Prod}\left(m^3/\text{PMH}\right) &= -11.2 - 0.015 * \text{Dist} + 3.95 * \text{Vol} \\ &\quad + 0.47 * \text{WC} + 3.71 * \text{CA} \\ &\left(F = 74.36; p << 0.1; R^2 = 0.82\right) \end{aligned} \tag{5}$$

The Calabrian productivity range is consistent with results from a study of forwarding carried out in Northern Spain that resulted in a productivity of 6–15 t/SMH (Spinelli et al. 2003). Other productivity studies resulted in the range of 8 to over 20 t/SMH, depending on the model and working conditions (Gulberg 1997; Saunders 1996; Horvat et al. 1999). The results are also consistent with Sever (1988), Valenta and Neruda (2004) and (Raymond 1989) who all showed that the most important factor influencing forwarding productivity was the extraction distance and load volume. The effect of site has also been identified by Tufts (1997) and Tufts and Brinker (1993) that showed productivity was also affected by the average assortment volume (i.e., number of pieces in the load) and quantity and concentration of timber on a felling site.

Interestingly, slope was not found to be a significant predictor of a forwarder's productivity, but this may have been due to the fact that the forwarders were equipped with tracks to accommodate for wet soil conditions (Williams and Ackerman 2016). In other studies (e.g., Bergstrand 1985; Kellogg and Bettinger 1994; Nurminen et al. 2006) the forwarding productivity depended on the number of loaded assortments, and the productivity also varied between different assortments. Within this study there was no significant difference identified between log assortments.

Fixed and hourly operating costs for productive machine time of the forwarder are reported in Table 5. At site A the extraction costs were calculated to be €4.55/m^3, at site B €2.85/m^3 and at site C €2.50/m^3. The calculated costs were consistent with Jiroušek et al. (2007) who showed forwarder extraction cost depends on the type of the vehicle used (i.e., its nominal carrying capacity) and that forwarders of higher carrying capacity achieve lower costs per product unit and higher productivity.

Table 5 Calculation of hourly costs for the two John Deere forwarders used in the case study for forwarding in Southern Italy and New Zealand

Parameter	Value	
	1110E	1910E
Purchase price (€)	265,000	432,000
Salvage value (€)	86,400	86,000
Economic life (year)	8	8
Scheduled operating time (h)	1440	1440
Annual depreciation (€)	26,500	43,200
Interest cost (€)	12,058	19,656
Taxes and insurance (€)	13,780	22,464
Total fixed cost (€ h^{-1})	36.35	59.25
Total variable cost (€ h^{-1})	50.7	47.5
Total labor cost (€ h^{-1})	20	13
Total cost (€ h^{-1})	87.1	106.7

Conclusions

Time consumption, productivity and costs of forwarding were calculated for two different models of forwarder, a John Deere 1110E and a John Deere 1910E based on data collected at three different sites. Forwarder productivity in cut-to-length forest harvesting systems is strongly positively correlated with the volume of payload and negatively with the average extraction distance. Even when considering the higher operating cost of the larger machines, the much higher productivity rates at the plantation clear-cut New Zealand sites resulted in significantly lower unit extraction cost.

The data provided show a clear opportunity for southern Italian sites adopting higher levels of mechanization, even if conditions such as steeper terrain, limited infrastructure or longer forwarding distance will negatively impact productivity. The data provided should help facilitate improved logging planning and consequently achieving cost competitiveness of the system for harvesting Calabrian pine.

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