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 tonne capacity John Deere 1110E, (2) a clearcut on the West Coast of New Zealand with a larger 19 tonne capacity John Deere 1910E, and (3) a larger clearcut operation in Canterbury, New Zealand with two John Deere 1910E forwarders. An elemental time and motion study was used resulting in 73.4 hours of detailed data, with 159 cycles extracting 2,241 m3 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 tonnes 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 (0.59m3). 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 /m3. 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.

Factors Affecting Forwarder Productivity

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Abstract

Modern forwarders are an efficient extraction option for timber harvesting operations. 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 tonne capacity John Deere 1110E, (2) a clearcut on the West Coast of New Zealand with a larger 19 tonne capacity John Deere 1910E, and (3) a larger clearcut operation in Canterbury with two John Deere 1910E. The studies used an elemental time and motion study approach resulting in 73.4 hours of detailed data, with 159 cycles extracting 2241 m3 of timber. Productivity models were created for all three sites as well as one combined model. Distance and payload were significant factors for all models, and in the combined model the sites were also significant. That indicates that other factors not recorded, or a combination of factors, significantly influence the overall productivity. Average cycle time was 33.2, 24.2 and 22.8 min respectively, and average productivity 24.6, 37.1 and 42.7 t per productivity 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 ($0.59m^3$). Travel speed was slowest at the West Coast site showing the effect of wet and difficult terrain, with travel empty speed being just 1.0 km/min compared to 1.9km/min at the other two sites. Productivity at the two clear-cut operations were significantly higher than the selective cut, compounded by the use of the larger capacity forwarders at the clearcut sites. The unit cost of forwarder extraction ranged from €2.55 to €3.60 /m^3, showing that forwarders are very cost effective.

1. Introduction

The economy of New Zealand is highly dependent on primary industries such as agriculture, fishing and forestry. In recent years the forest industry contributed NZ$4.5 billion (14%) of gross domestic product (GDP). Planted forests constitute 1.74 million hectares (7% of New Zealand's total land area). Radiata pine plantings total 1.56 million hectares (90%), with Douglas-fir plantings in second place with 110,000 hectares (6.3%). Radiata pine trees are harvested at an average age of 28 years and the average clear fell yield is 473 m^3 per hectare (New Zealand Forest Owners Association 2011). Individual trees average 2.3 m^3 in volume for saw logs and 1.6 m^3 for structural timer. In New Zealand, the primary harvesting operations of felling, extraction, processing, and loading are conducted by logging crews under varied forest settings, with distinct stand and terrain variables, using machines that vary with type, make, and power ratings (Jiroušek et al. 2007). One of the common harvesting systems in pine plantations is the combination of mechanical felling and processing with forwarding.

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; Maesano et al. 2014). 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). Forests in southern Italy are important in terms of forest production, having the largest percentage forest cover of all regions of the country, even though the highest concentration of woodlands occurs in the northern regions of Italy. The 1.5 million ha forest area in southern Italy consist mainly of mature beech, chestnut, Corsican pine, and silver fir forests (INFI 2005). These forests can provide a significant resource for the economy of the entire Mediterranean basin; an objective that could be attained with better and more efficient mechanization of forest operations (Istat 2013). However, the current level of mechanization is low (Zimbalatti and Proto, 2009b), while the dynamic international wood market has led to more efficient timber extraction technologies that reduce time and labour required for harvesting (Cavalli et al. 2014; Moneti et al. 2015). The most common work method 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 (e.g. winches, hydraulic cranes, log grapples, etc.). This level of mechanization for timber extraction has to date been adequate due to the characteristics of the forest ownership and the small dimensions of many forest enterprises (Proto and Zimbalatti, 2015).

In both nations one of method commonly used is CTL (Cut - to - Length). This system offers several advantages, notably the smaller size of landing area that is required and minimal damage to the logs during handling and transport. Mechanized CTL timber harvesting methods have become widely used in many industrialized European countries such as Sweden (ca. 98%), Ireland (ca. 95%) and Finland (ca. 91%) compared to motor-manual harvesting (Karjalainen et al. 2001). The CTL system requires less labour, less road construction, and fewer landing areas than the other ground-based systems (Bettinger and Kellogg 1993). The mechanized cut-to-length (CTL) system consists of felling, delimbing and bucking trees into logs of specified lengths at the stump. Logs are then transported to a landing by a forwarder (Spinelli et al. 2004). Over the years, the system has become increasingly mechanized and it is now based on harvester and forwarder machine combination. The forwarders operate under a variety of working environments, that are often very different from those for which the machine was originally intended (Spinelli et al 2004).

Many forwarder classifications are already known; forwarders are classified by netmass, load capacity or gross mass (vehicle + load, (Porsinsky 1997)). The latest forwarder classification found in literature is based on their loading capacity (payload), from light (<10 t), medium (10 t – 14 t) and heavy forwarders with the load capacity over 14 t (Brunberg 2004).

Timber extraction from forest to landing which is called primary transportation is one of the most time-consuming and expensive parts of harvesting activities (Mousavi 2009).

In work observation studies, the work cycle to forward a load to roadside is often divided into separate work elements, for instance: Driving empty, Loading, Loading drive, Driving loaded and

Unloading (including unloading drive) (Bergstrand 1985; Väkevä et al. 2001; Nurminen et al. 2006). Another complication is that in work observation studies forwarding is generally divided into separate work elements, but the number and definitions of work elements can vary considerably, as no generally acknowledged nomenclature is used (Andersson 2015).

Productivity of the 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). One of the problems arising is the definition and determination of the mean distance of timber forwarding. Some authors consider that the distance of timber forwarding is the distance between the roadside landing and the point in the felling site when the bunk of the forwarder is half loaded with timber (Kuitto et al. 1994; Nurminen et al. 2006). Accordingly, the mean distance of timber forwarding would be equal to the sum of travel distance of unloaded vehicle and half the travel in timber loading i.e. the travel between the loading points (Suvinen 2006; Väkevä et al. 2001).

One of the most important factors influencing machine cost calculations is the annual use and utilization rate of forest machinery. Annual utilization rate is the ratio of productive to scheduled machine hours. Machine utilization is affected by different factors such as: technical reliability of the machines, weather and road conditions, logistics, proportion of set-up time, and the workers. Such information can support strategic and operational decision making processes within a company, especially accurate costing for new investments (Holzleitner et al. 2012)

The aim of this study was is to analyze operational time consumption for estimating the productivity of two different models of forwarders (John Deere 1910E and 1110E), in three different sites (two in New Zealand and one in Southern Italy) and show general trends of productivity in relation to common factors in harvesting operations and to determine the operation cost for harvesting for different forwarders.

2. Materials and methods

2.1 Site description

The times of the work phases were recorded separately in three different test worksites, indicated with letters A, B and C respectively.

The forest at site A was a stand of *Calabrian Pine*, at an altitude of 1,200 m above sea level. The study was conducted in a selective felling site that was 22 ha in size, with S-E exposition. The forest area was classified as I class for roughness, while the slope is between III and IV class in accordance with terrain classification of UK Forestry Commission (1995). The density of the forest is generally uniform; small gaps are 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). Site characteristics are described in Table 1. The forest in New Zealand at site B was located on the West Coast of the South Island. The forests in New Zealand at site B and C were both stands of radiata pine, at an altitude of 280 m and 230 m above sea level, respectively. The site represented West Coast forestry activities quite well, being predominantly wet and muddy. The forest was split into a gridded pattern by well constructed roads that were suitable for log trucks. In between this grid pattern was general cutover operations, where a bucket digger would cut tracks through the cutover for the forwarder to extract the timber. These tracks became quite muddy and often had to travel over wet guts and ditches which slowed the machine down considerably as the machine was not using chains or band tracks. The study observed a combination of loaded and unloaded travel along the well formed logging roads and the tracks through the cutover. The machine would very rarely venture off these tracks. Both study sites involved clearcut operations that were 25 and 27 ha in size. The terrain class could be described as 1.

Table 1. Characteristics of three 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	High forest	Plantation	Plantation
Operation Type	Selective cut	Clearcut	Clearcut
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	1.9	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)

2.2 Machines used

In site A, the forwarder studied was a medium sized John Deere 1110E with 136 kW maximum engine output. The forwarder's basic technical parameters which may affect its productivity, include: a 12 t load rating, length 9,475 mm, height 3,700 mm and width 3,106 mm; which are considered constant. The cross-sectional area of the log bunk is 4.3 m^2. At work sites B and C, two large (21.8 tonnes) John Deere 1910E eight-wheeled forwarders with 19 tonnes payload capacity and 186 kW engine power, were used during the study (Figure 1). Both forwarders were brand new before the study. They each had a hydrostatic-mechanical transmission, rotating and levelling cabin, crane with a maximum reach of 8.5 m, 6.2 m^2 load-area and 0.52 m^2 grapple area. Payload (PL, load capacity) is one of the most important exploitation characteristics of forwarders.

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

2.3 Productivity

According to Harstela (1993), productivity is the ratio between output (volume of wood) and input (time). In this study, time was measured using the repetition-timing method to determine the total forwarding cycle times (Spinelli and Magagnotti 2012; Nikooy et al. 2013). 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 (Bjorhedenet al. 1995) and timed using a digital chronometer (i.e. 1 min = 100 units), Tag-HeuerMicrosplit™. In addition to the productive cycle time, delay time was also measured. The time study data was collected during autumn of 2016

(Italy) and during the summer 2016 and autumn 2017 (New Zealand). Extraction of timber by forwarders has the characteristics of cyclic work. Each cycle (turn) consists of four main cycle elements (unloaded traveling, timber loading, loaded traveling and unloading of timber), plus work pauses or time consumptions whose character is not cyclic, but periodic.

In order to determine the productivity of the forwarder, the operating cycle of the machine has been divided in several elements (Cavalli et al. 2009; Tiernan et al. 2004; Sanchez et al. 2016) as below:

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 involving 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;

Refuel time: The portion of the service time used to refuel the machine; such as transporting to refuel, refuelling, etc.

Delay time and others: Operational delay, technical delays, and personal delay were recorded.

The time study data consisted of 159 forwarder cycles (50 for site A, 69 in B and 40 in C, respectively).

During forwarding operations the machines were constantly monitored, the various work stage were observed using a time and motion study, and the various distances were recorded. The total number of logs assortments were counted, identified and recorded as a function of the dimension (large saw timber and small assortments – pulpwood) before being transported and were counted to calculate the volume of each load in order to obtain a good estimate of the total volume carried. This proportion may refer to the total volume in a given stand or, alternatively, in a given load. Thus, there are no generally acknowledged rules for classifying assortments. In this 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). Elevation was measured using a handheld GPS while the gradient was assessed with a Suunto clinometer, PM-5/360 PC. Extraction distances were measured with a laser rangefinder, PRO 1 M and GPS (Nikon Forestry Pro laser range finder and Garmin 60csx & 62s GPS in New Zealand).

2.4 Statistical Analysis

Two different techniques were adopted to construct a model for time and productivity. A delay-free time model was formed separately for each time element and the model for total time formed by combining the element models. Regression analysis with variable transformation was used for modelling 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 was rejected and the differences cycle times were assumed to be from random variation.

2.5 Cost

The machine's costs were calculated as described by Miyata (1980) and by using the COST model proposed by Ackerman et al. (2014). 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 of labourers). 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. 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. As reported in others study (Spinelli et al 2011) were considered a total 180 working days in the year, at an average of 8 scheduled working hours per day (equals 1440 hr / year).

3. Results

The time studies covered in total 73.4 hr; of which 29.2 hr were recorded at site A, 28.5 hr at site B, and 15.7 at site C. Within this time, the forwarders completed 159 forwarding cycles and extracted 7,337 logs with a total volume of about 2,241 m^3. Basic study data regarding total travel distance for the cycles, the number of logs and the total payload volume is presented in table 2.

Table 2 - Main results of time studies between forwarder models.

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
Numer of logs (n°)	25	37	46	25	35	43	52	77	119
Average volume (m^3)	0.27	0.36	0.53	0.35	0.42	0.54	0.15	0.25	0.47
Total volume payloads (m^3)	10.3	13.2	15.75	11.45	14.3	17.64	8.4	14.85	18

Cycle times for each machine were split into the time elements: Travel empty, loading, travel loaded and unloading and delay time when present. Considering all forwarders, Table 2 shows the descriptive statistics of work element times in forwarding of logs and the percentage of time spent in each work element time in relation to total time. At site A, 97% of cycle time and at site B and C 93% of cycle time, forwarders were involved in productive work elements, specifically moving empty, loading, moving loaded and unloading. The mean time consumption per cycle was 33.2 minutes at A, 24.2 at B and 22.8 at C, respectively. Descriptive statistics of main influential variables for all machines are presented in Table 3.

Table 3 - Descriptive statistics of work element times, in minutes and percentage of total time of cycle time without delay time

Work Sites	**Work phase**	**Average**	**Min**	**Max**	**Dev St**	**%**
A	Travel Empty	**3.3**	1.15	6.4	1.2	9.8
	Loading	**13.3**	7	22	2.65	40.1
	Travel Loaded	**5.8**	2.45	15.2	2.12	17.5
	Unloading	**10.8**	5	14,3	2.26	32.6
	Total Cycle Time	**33.2**	22	51.5	5.98	100
B	Travel Empty	**4.9**	1.07	9.95	2.24	20.4
	Loading	**8.6**	2.67	13.95	1.98	35.6
	Travel loaded	**5.0**	1.06	10.52	2.44	20.7
	Unloading	**5.6**	2.89	8.06	0.95	23.3
	Total Cycle Time	**24.2**	17.03	62	9.57	100
C	Travel Empty	**3.0**	1.1	6.45	2.35	13
	Loading	**10.2**	5.04	28.3	4.42	44.9
	Travel loaded	**3.4**	1.15	7.2	1.93	14.7
	Unloading	**6.3**	3.22	11.38	1.27	27.5
	Total Cycle Time	**22.8**	29.24	58.2	5.74	100

By taking the distance for the travel empty and loaded element, 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 1.85 kph at A, 1.02 kph at B and 1.91 kph at C, respectively. For travel loaded the average speed was 1.5 kph at A, 1.06 kph at B and 1.71 kph at C, respectively.

Figure 2 shows the shares of particular elements of times within the work time. The diagram revealed legible differences between the stand A and the other two sites in terms of duration of most of the operations under analysis. Forming a load on this site took over 40% of the work place time. In Site B the time was in less because the logs were pre-bunched (shovelled) to the extraction corridor. Whereas, differences between travel empty and travel loaded varied less based on site. Delays that occurred during the logging operations were not serious and they were fixed by the forwarders operator as they emerged, due to which their impact on the course of works was insignificant.

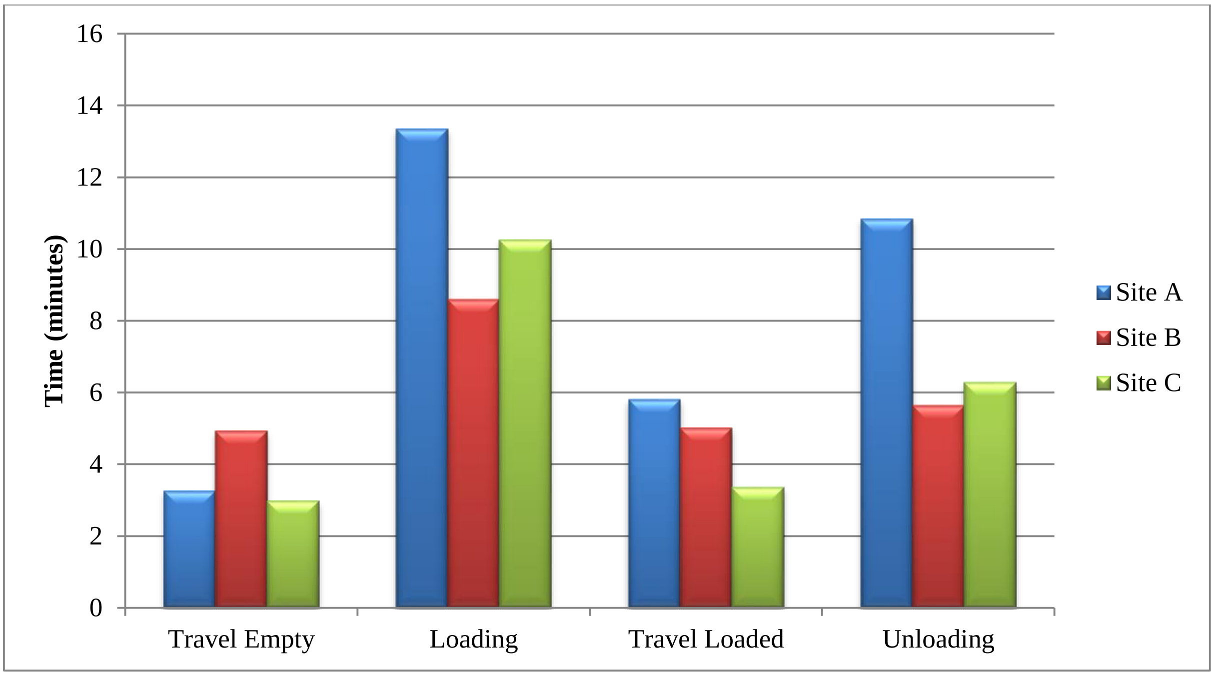

Figure 3. Share of operations under analysis within work time

Different models to predict work element times (Locomotion (travel empty + travel loaded), loading, unloading and total time) were evaluated using linear regression and selecting the independent variables by step-by-step regression. The equations finally proposed and goodness-of-fit statistics of each model are presented in Table 4. All parameters were significant at the 5% level. Variance analysis revealed statistically significant differences in mean duration of a forwarding cycle between the stands under investigation (p>0.05). Taking into account that in this type of equation the common value of R^2 is relatively high; the time consumption models explained a high percentage of total variability. Main work time could be calculated as the sum of individual times estimated employing the models fitted (Equations 1–4 in Table 4), so it is possible to develop a productivity model following equation.

Table 4 - Equations finally proposed and goodness-of-fit statistics of each model work

Work Elements	**Equation**		**F**	***p***	**R^2**
Locomotion	Eq.1	T_{Loc} = 3.64+0.007*Dis+2.89*WC-2.24*CA	86.96	0.000	0.79
Loading	Eq.2	T_L = 17.64-0.325*Vol-4.4*WC-2.56*CA	27.01	0.000	0.58
Unloading	Eq.3	T_U = 13.57-2.06*Vol-4.98*WC-4.22*CA	101.8	0.000	0.81
Total Time	Eq.4	Total Time = 36.15+0.12*Dist-0.84*Vol-6.32*WC-7.96*CA	63.6	0.000	0.78

Where:

Dist – Forwarding distance;

Vol – Total volume payload;

WC = 1 when West Coast Site, otherwise = 0;

CA = 1 when Canterbury Site, otherwise = 0.

The model of multiple regression function presented in the above table explained the variability in duration of the elements of forwarding cycles, which was reflected by the values of coefficient of determination R^2, about (59 - 73%). The values of β coefficients obtained in the analysis indicated that the total forwarding distance had the greatest impact on the skidding cycle duration, followed by the total volume and site. The factors with the weakest influence on the forwarding cycle time in the above-mentioned model, were the conditions under which the timber was extracted. In stand B, where the mean cycle time was the lowest; Distance of load, Number of logs, slope and distance did not have a significant contribution.

Total effective time was converted into delay-free productivity (P) and gross effective productivity:

P = (Total Volume for cycle * 60 / Total Time) / total time   Eq.5

The productivity model was calculated with the significant variables of the equation of the total cycle time.

Prod (m^3 per effective hour) = -11.4 - 0.015*Dist + 3.52*Vol + 6.1*WC + 10.5*CA

The variables included in the model of productivity were: forwarding distance, total volume payloads and work sites.

The model in question explained more than 80% of the variability in productivity of forwarding cycles (R^2=0.82). The F test (74.36) revealed that the model was statistically significant; though there must have been other independent variables that affected the productivity of skidding in its successive cycles. The values of standardized β coefficients of regression indicated that the volume of payloads had the strongest impact on productivity, followed by the forwarding distance. Sites related factors affect the productivity of forwarding much significantly. The number of valid observations collected during the tests was large enough to develop a reliable model for predicting cycle time (Proto et al. 2016).

The average productivity of forwarding at Site A was 24.2 m^3/SMH and 24.6 m^3/PMH, respectively. In contrast, at Site B, the average hourly productivity was 35.2 m^3/SMH and 37.1 m^3/PMH, while in Canterbury (Site C) the average productivity was 41.4 m^3/SMH and 42.7 m^3/PMH. Figure 2 shows the relationship between average forwarding distance and productivity.

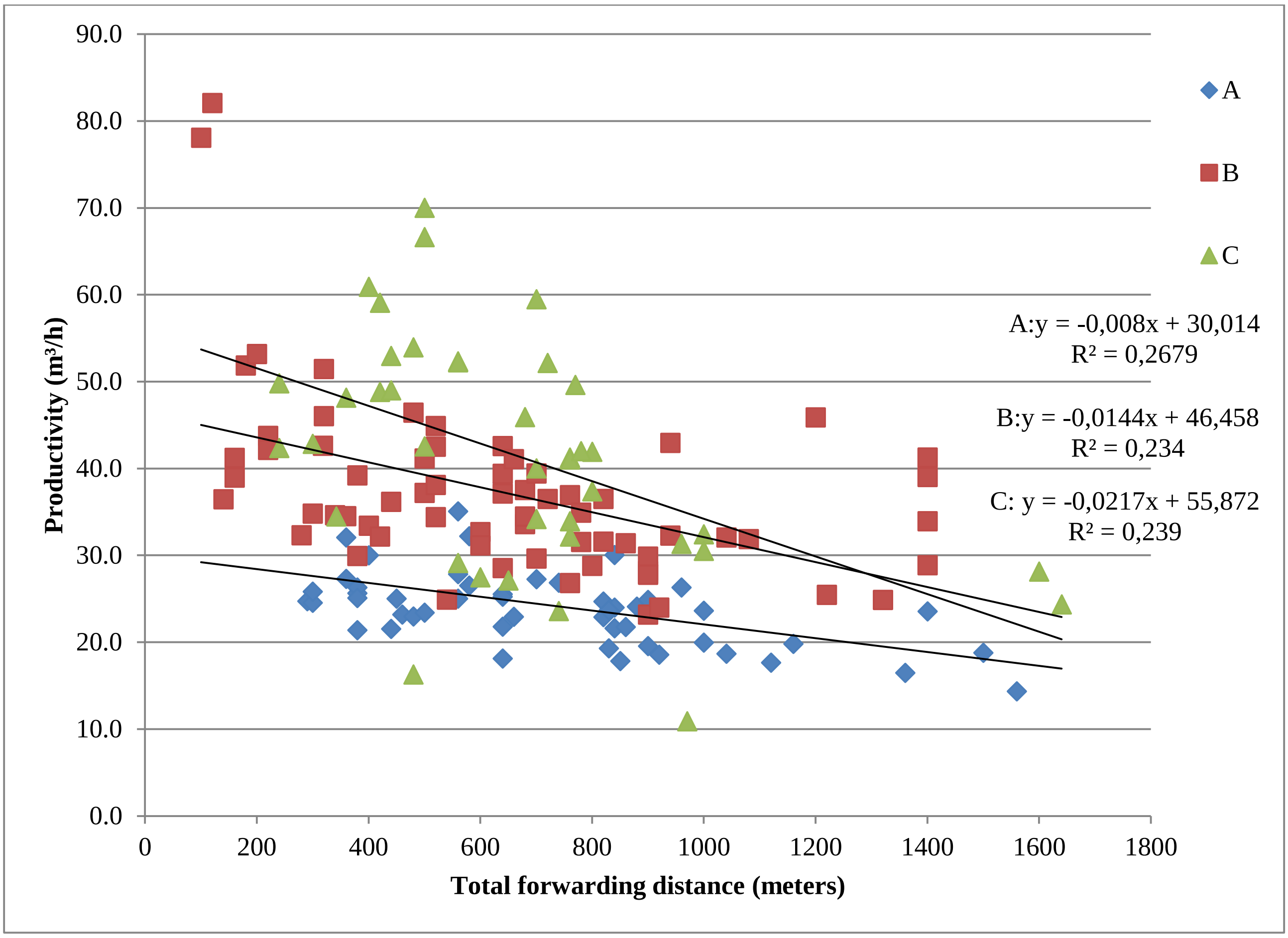

Figure 2 - Relationship between average distance and productivity

Both sites compare favorably with results from a study of forwarding carried out in Northern Spain; that resulted in a productivity of 6 to 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 (Gullberg 1997; Saunders 1996; Horvat et al. 1990). The number of valid observations collected during the tests was large enough to develop a reliable model for predicting cycle time (Proto et al. 2016).

Fixed and hourly operating costs of the forwarder are reported in Table 5. At Site A the extraction costs were calculated to be € 3.60/m^3, € 3.00/ m^3 at site B and € 2.55/m^3 at site C. Considering only the forwarder productive time (i.e. €/PMH), the extraction costs were € 3.50/m^3 at site A, € 2.85/ m^3 at site B and € 2.50/m^3 at site C. Delay times increased the operating cost by 3 to 4 % for all sites and production cost increased when both forwarding distance increased and load volume decreased.

The increase of each variable on this machine; with exception to number of logs and average volume, causes an increase in cost. Only with increasing the annual utilization PMH or scheduled operating time (days/year), does forwarding cost per cubic meter decrease.

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 (y)	8	8
Scheduled operating time (h)	1,440	1,440
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 labour cost (€ h^{-1})	20	13
Total cost (€ h^{-1})	**87,1**	**106,7**

4. Discussion

On average, the work elements travel empty, loading, travel loaded and unloading collectively account for over 95 % of the forwarding time consumption when extraction distances are 500 to 600 m (one-way), although the time consumption for these work elements can be influenced by work planning. The transportation only work elements (i.e. travel empty and travel loaded) jointly account for just 13 to 20 % of the time consumption. Time consumption for transportation only work elements depend on the extraction distance and driving speed, which in turn are mainly determined by geophysical factors. Forwarder efficiency is affected by numerous factors. In the clear-cut stands (B and C), the mean duration of a forwarding cycle was the same (the differences detected appeared to be statistically insignificant), and accounted for ca. 22 - 24 minutes, which corresponded to similar values quoted in the existing literature. The most important factor influencing the efficiency of timber forwarding is the extraction distance (Sever 1988). With the increase of extraction distance, the impact of the load volume on the vehicle productivity is also increased (Raymond 1989). Productivity is also affected by the average assortment volume (i.e. number of pieces in the load) and quantity of timber on a felling site, which is less favourable in thinning operations (Tufts 1997; Tufts and Brinker 1993). As rule, forwarding productivity is calculated from productivity standards based on the mean volume (payload) and forwarding distance. Owing to this, these two factors were considered a priority for timber forwarding as well. Forwarder efficiency depends on the type of the vehicle used (i.e. its nominal carrying capacity) as forwarders of higher carrying capacity achieve lower costs and higher productivity per product unit (Jirousek et al. 2007). The model presented in this study is therefore in accordance with past studies. As mentioned prior, in this study, the distance moved while travelling in-field fully loaded is the most representative value of the total, one-way travel distance because the machine would pick up logs while travelling through the compartment and then return fully loaded along the same path to the unloading area situated at the roadside. As reported in a previous study (Valenta, Neruda 2004), the operational conditions and statistical analyses indicated that forwarding distance and volume of payload, have the most significant impact on forwarder operator productivity. Due to a great number of variables determining the duration of forwarding and its productivity, a multiple regression analysis is often used for modelling these properties. This study covered an elaboration of models that described the cycle time and the productivity of forwarding cycles within the productive work time, based on a extraction distance, number of logs per load, and volume of payload. Those variables were used for developing a productivity model. The models also included other variables defining the silvicultural treatment performed and stand conditions encountered on a certain felling site. The latter is a variable hardly ever used for modelling of work time and productivity, which is mainly due to the fact that studies on productivity of forwarding are usually conducted in stands with limited variability in stand conditions. Nevertheless, the field research discussed in this paper was carried out in three stands managed within different silvicultural treatments and distinctly different stand conditions, which enabled the authors to include the variable in question into modelling. Interestingly, slope was not found to be a significant predictor of the forwarder's productivity; but this may have been due to the fact that the machine was equipped with tracks to accommodate for heavy rain conditions (Williams and Ackerman 2016). In other studies (e.g. Bergstrand, 1985; Kellogg and Bettinger, 1994; Nurminen et al., 2006) the forwarding productivity depends on the number of loaded assortments, and the productivity also varies between different assortments. Comparative research of skidding/forwarding machines carried out in stands of small coniferous trees showed that, in terms of costs, figures speak in favour of timber forwarding, as forwarder productivity was twice the productivity of a skidder with winch (Li et al. 2006).

5. 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. Forwarder productivity in cut-to-length forest harvesting systems is strongly correlated to the volume of payload and the average extraction distance, and is expected to increase with increases in the payload, but decrease with the increase in average extraction distances.

At site A, particularly where there were difficult working conditions (e.g. steep terrain, limited infrastructure, long forwarding distance), these results will be of great practical help in terms of improving logging planning, and consequently for performing and achieving cost competitiveness of the system for harvesting Calabrian pine.

Due to the fact that larger machines have higher productivity, the costs are decreasing with larger machines. From the economic point of view the larger forwarders could be recommended for clear-cutting operations.

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