Analysis of Productivity and Cost of Forwarding Bundles of Eucalyptus Logging Residues on Steep Terrain

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Abstract

The objective of this study was to evaluate the productivity and costs of two Spanish forwarders, models Dingo AD-8468 and AD-2452, in the hauling of bundles of residues after Eucalyptus globulus *clear cuts on steep terrain in Northern Spain. In addition, various models to predict time consumption for the main work elements and productivity were fitted including several independent variables previously selected using stepwise regression.*

Finally, the models explain between 83% and 97% of variability. Since the equations are based on simple variables (depending on each individual equation this was either velocity empty and loaded, slope loading, distance empty/loading/loaded or load per cycle), they will be a helpful and easy to use tool to assist in forest management planning. Productivity was 6.75 odt/PMH for the Dingo AD-8468 forwarder and 11.56 odt/PMH for the Dingo AD-2452. Cost per tonne for the Dingo AD-8468 was 6.77 €/odt compared to 3.94 €/odt for the Dingo AD-2452.

Keywords: forwarder, time study, bundles, Eucalyptus globulus*, displacements, GPS, steep slope*

1. Introduction

As noted by the European Union, the welfare of its citizens, the competitiveness of industry and the overall functioning of society depend on safe, secure, sustainable and affordable energy. EU energy policy objectives for 2020 are consequently ambitious, and indeed, the commitment continues beyond this date, aiming to reduce member state CO_2 emissions by almost 40% by 2050 (CEC 2011) and to resolve obstacles and difficulties in developing actions to achieve these goals.

A key problem is the high dependence on energy from outside the EU. One of the priorities established by the European Parliament in May 2013 was, therefore, to increase the diversification of the EU's energy supply, particularly renewable energy options, and develop local energy resources to ensure energy security, i.e. a drive towards member states making better use of their own energy resources (EP 2013).

Within the broad field of renewable energy, in recent years biomass has taken on great importance because of the potentially critical role it is assumed to play in mitigating the effects of climate change (Viana et al. 2010). Also, according to recent reports from the Commission of the European Communities (CEC 2005, 2008), biomass has many advantages over conventional energy, in particular, its resilience to short-term climate changes, the fact that it promotes and strengthens regional economic structures and provides alternative sources of income for farmers. However, there are complex issues to consider, such as the sustainability of production practices and the efficiency of bioenergy systems (IPCC 2014).

Currently, the supply chain costs of forest biomass (extraction, pretreatment, forwarding and trucking) are considerable obstacles to the development of its bioenergy use, given that they are higher than for other fuels like petroleum or natural gas. To counter this situation would require guaranteed biomass sales, equipment adapted to the needs of forest biomass processing, and changes in operational procedures that can minimize these costs and integrate conventional timber harvesting systems and forest biomass harvesting systems.

The main factors that influence the total supply chain cost of forest biomass are the type of logging, the size of the area to be harvested, amount of resources, slope, infrastructure (i.e. harvesting and permanent tracks), impediments in the terrain (e.g. rocky outcrops) and the transport (forwarding and trucking) distance between the supply and demand point. Furthermore, due to these factors, there is not one single optimum harvesting system for all regions or all conditions. It is, therefore, essential to carry out studies of different operational systems, considering various conditions and types of forest and focus on the optimization of productivity and costs so as to make this type of forest biomass profitable.

In the Iberian Peninsula, where currently *Eucalyptus* spp. stands cover approximately 1,125,000 ha (ENCE 2009), cost and productivity studies are essential to evaluate the viability and improve the efficiency of the harvesting of logging residues for energy purposes. Such harvesting not only provides a means for mobilizing a biomass resource, which would otherwise be »wasted« and would provide no income to the forest owner, but it is also an important intervention, both to reduce forest fire hazard and to improve access to the forest.

In the north of Spain, *Eucalyptus globulus* stands are typically managed as coppice and harvested in clear cuts with the cut-to-length system (CTL), the felling being done manually and the processing mechanically, resulting in large amounts of residues, including bark left on the ground. Once the residue material had been collected together in the forest, the first difficulty encountered in its manipulation is its low density, which complicates and raises the price of its mobilization. For this reason, collection technology is often based on chipping the residues on-site to reduce size, or in creating compact bundles on-site to increase the density of the units for transportation. Bundling of residues was launched commercially in the study area at the beginning of 2007, and currently there are about 15 units producing bundles for fuel, mainly working with eucalypt logging residue collection and providing biomass to a single large power plant, whose consumption of such residues grew from 340,000 oven dry tonnes (odt) to a current level of 420,000 t after a recent expansion.

Bundling has a great advantage over chipping in that it simplifies the logistics and storage of the biomass, especially when supplying fuel on a large scale to power plants (Johansson et al. 2006). These advantages initially made the bundling system a positive choice in Nordic countries (Kärhä and Vartiamäki 2006, Gustavsson et al. 2011, Eliasson 2011, Laitila et al. 2013), and also in Southern European countries (Agudo 2010, Spinelli et al. 2011, Sánchez-García et al. 2015). However, bundling system costs must be analyzed in-depth, since, following such evaluations in Nordic countries, the tendency has changed to using chip systems rather than bundling. Nonetheless, in the area of Spain under study in this work, both professional opinion and technical studies (Sánchez-García et al. 2015) consider bundling to be an economically competitive technique in local *Eucalyptus* stands, which generally present some very particular conditions for forestry, e.g. steep terrain, small sized forest plots, and long haulage distances, making the collection of forest residues more difficult and expensive than in other scenarios. One advantage is that forwarding of bundles can be carried out with the same machinery that was in use in harvesting timber.

The aim of this study was to determine the productivity and costs of two Spanish forwarder models (a Dingo AD-2452 and a Dingo AD-8468) in the hauling of bundles of residues from *Eucalyptus globulus* logging operations to a landing point. These specific forwarders, characterized by being small and light, have been designed and built by a factory in the north of Spain (www.dingoma.es) specifically to work under difficult conditions commonly found in this area, such as steep slope and narrow tracks. The study involves a time and cost study of each forwarder, and includes the fitting of equations to predict work element times and productivity as a function of different independent variables such as slope, distances and velocity.

2. Material and methods

2.1 Data collection

The productivity and cost study of forwarding of eucalyptus bundles was carried out in 2 zones, and distributed in a total of 4 different stands (Table 1) cho-

Table 1 Description of study sites

Zone		1		2	
Coordinates UTM	$x_{min} - x_{max}$	733,586 – 733,768		623,091 – 623,478	
	$y_{min} - y_{max}$	4,814,643 – 4,814,858		4,832,966 – 4,833,262	
Altitude, m	Max	250		190	
	Min	70		60	
Stand		1	2	3	4
Total area, ha		0.38	0.58	0.22	4.99
Age, years		44.3	23	41.8	15.0

sen to be as similar and thus as comparable as possible. Operators were skilled and had similar qualifications and experience in order to minimize operator effects in the study. In the clear cuts, the collection of residues was made by two bundler models: a Monra Enfo 2000 (zone 1) with a cutting device using shears and a John Deere 1490D (zone 2) with chainsaw cutting device. The bundles were forwarded to the roadside landing with the two Spanish forwarder models; a Dingo AD-8468 (zone 1) and a Dingo AD-2452 (zone 2). At the landing, bundles were stacked side by side and then transported on standard timber trucks to the end-use facility.

For the productivity analysis, four detailed time studies were performed. Each work cycle was divided into work elements (Table 3) and to avoid later mistakes, the work elements were clearly and concisely defined, setting the start and finish points.

Data acquisition was conducted using the specific time study software UMT® (LAUBRASS Inc 2007). The time spent in each work element of the forwarder work was recorded on a Trimble Nomad handheld computer. A total of 14 hours and 24 minutes (26 cycles) were timed in the four different stands.

In addition, certain parameters known to have a great influence on cycle time were also recorded (number of grabs and bundles per cycle, harvesting area, slope, disposal of residues, etc) and a GPS model XH Trimble Explorer was mounted on top of each forwarder to georeference its position on a continuous basis (every second), in order to obtain the slope, distance and velocity travelled as independent variables for each displacement (either empty, loading or loaded).

Table 2 Specifications of forwarders

Zone		1	2
Forwarder model		Dingo AD-8468	Dingo AD-2452
Configuration		6x6	6x6
Load size, tonnes		8.5	13.5
Engine model		DEUTZ BF6L 914	DEUTZ TCD 2012 L06
Power rating (Diesel), kW		89	141
Max. velocity km/h of displacement		40.0	
Max. velocity of work, km/h	1000 rpm	0.8	
	2500 rpm	20.0	
Operative range of crane, m		7.5	9.1
Box size	Length, mm	3600	4100
	Width, mm	2100	2500

Oven dry tonnes (odt) were calculated using data from a previous study of bundler productivity performed in the same stands, that is, an average weight of bundles of 169 kg and 187 kg for zone 1 and zone 2, respectively.

2.2 Study of productivity and cost: model adjustment

The timing data were reviewed to eliminate errors and outliers (Olsen et al. 1998) and then, time study data and additional data (influential parameters) were

Table 3 Description of work elements for forwarders hauling bundles of eucalyptus residues

Work element	Description
Moving empty	Begins when work starts or after unloading of bundles at landing, the forwarder has to return to the work zone unloaded
Loading	Begins once the forwarder is at the side of the bundles 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 bundles from one pile and moves to the next pile, until the forwarder is fully loaded
Moving loaded	Once the box 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 bundles from its box. 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 bundles (at landing, stand or in the forwarder box), 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.
Delays	Mechanical, operator or other delays
Others	All work elements not covered by the above categories

Table 4 Specifications of forwarders

Data	Dingo AD-8468	Dingo AD-2452
Investment, Euro	168,000	186,000
Service life, years	8	8
Maintenance and repair cost, €/h	6.01	6.65
Fuel cost, €/h	13.22	20.98
Lubricant cost, €/h	4.36	6.92
Driver cost, €/h	12	12
Total yearly utilization, SMH/year	2000	2000

combined into a single data set using proc SQL from SAS/STAT® (SAS Institute Inc 2004), and grouped by cycle number. The same procedure was then carried out to combine the GPS data with this timing data, using time (hours, minutes, seconds) as the common variable such that the accurate position of the forwarders was obtained at all times during the timings. The paths were analyzed using ArcGis 9.2, (ESRI 2006) filtering errors (for GPS precision or point clouds caused by a machine stop) and including points on the forest roads, where no points were recorded due to GPS signal loss. The point shape was transformed into polylines with XTools Pro tool of ArcGIS 9.2 (ESRI 2006), joining points included in the same work element and the same cycle. In this way, the slope, distance and velocity travelled by the machine (empty, loading or loaded) in each cycle were calculated.

Productivity for each forwarder was estimated per hour by dividing the tonnes of residues extracted (odt, oven dry tonnes and gt, green tonnes) or number of bundles, by productive hour (PMH, Productive Machine Hour).

Machine costs were estimated with the method described by Miyata (1980) and employing the utilization rates according to Spinelli et al. (2004). The main cost assumptions, obtained directly from the company, are presented in Table 4.

Different models were fitted by regression analysis to predict time consumption of the main work elements, using the influential parameters measured as independent variables. A dummy variable was used to take into account the model of forwarder as an independent variable. To select the variables to include in each model, step-by-step regression was used, implementing the stepwise command of the REG procedure of SAS/STAT® (SAS Institute Inc, 2004). The best models were selected using goodness-of-fit statistics (R^2 and RMSE) and graphical analysis, as well as taking into account the simplicity of the selected model. In addition, a model that combined the models of work element times was developed to predict productivity.

3. Results and discussion

3.1 Study of productivity and cost

Considering both forwarders, Table 5 shows the descriptive statistics of work element times in hauling of bundles and the percentage of time spent in each work element time in relation to total time. For 93% of cycle time, forwarders were involved in main work times, specifically moving empty, loading, moving loaded and unloading. The mean time consumption per cycle was 33 minutes and 13 seconds.

Table 5 Descriptive statistics of work element times, hh:mm:ss and percentage of total time,%

Work element times	*N* cyles	Avg.	Min	Max	Std. Dev.	%
Moving empty	22	0:07:06	0:02:37	0:16:39	0:04:16	21.36
Loading	22	0:09:44	0:05:35	0:15:56	0:03:24	29.28
Moving loaded	22	0:07:46	0:02:29	0:14:22	0:03:32	23.36
Unloading	22	0:06:01	0:03:12	0:09:18	0:02:29	19.05
Complementary work times	16	0:01:18	0:00:06	0:04:05	0:01:23	2.86
Refueling	1	0:10:22	0:10:22	0:10:22	0:00:00	1.42
Delays	4	0:04:43	0:01:09	0:13:08	0:05:42	2.58
Others	1	0:00:39	0:00:39	0:00:39	0:00:00	0.09
Cycle time	22	0:33:13	0:23:34	0:48:27	0:06:49	100.00

Table 6 Descriptive statistics of load per cycle, distances travelled, slope and velocity

Descriptive parameters by model machine		*N* cyles	Avg.	Min	Max	Std. Dev.
Dingo AD-8468	Load/cycle, odt	13	3.51	2.70	4.22	0.47
	Load/cycle, gt	13	4.95	3.82	5.96	0.66
	Distance empty, m	11	1467.31	940.69	2316.52	555.07
	Distance loaded, m	11	1129.02	258.21	1543.77	403.41
	Distance between load piles, m	10	64.21	19.37	146.74	44.52
	Slope empty, %	11	15.18	9.28	23.94	6.14
	Slope loaded, %	11	14.12	11.14	17.74	2.18
	Slope between load piles, %	10	14.42	3.35	37.74	10.17
	Velocity empty, km/h	11	10.50	6.40	15.67	3.25
	Velocity loaded, km/h	11	6.73	1.07	8.92	2.16
	Velocity between load piles, km/h	10	2.00	1.25	3.27	0.64
Dingo AD-2452	Load/cycle, odt	9	5.92	5.23	6.73	0.46
	Load/cycle, gt	9	11.53	10.20	13.11	0.89
	Distance empty, m	9	334.85	133.67	480.04	118.70
	Distance loaded, m	9	385.23	257.64	517.91	75.51
	Distance between load piles, m	9	117.24	61.17	274.44	66.67
	Slope empty, %	9	15.04	8.52	20.94	4.192
	Slope loaded, %	9	15.15	9.70	23.67	4.07
	Slope between load piles, %	9	15.21	8.38	22.35	4.08
	Velocity empty, km/h	9	4.66	2.57	6.06	1.03
	Velocity loaded, km/h	9	5.12	4.53	6.23	0.53
	Velocity between load piles, km/h	9	1.79	1.33	2.42	0.28

Descriptive statistics of main influential variables for both machines are presented in Table 6.

The main results of the time study are shown in Table 7. The differences between empty and loaded moving times are due to the different topography and forwarding distances involved in the two work zones. These times were higher in zone 1, where the forwarder (Dingo AD-8468) worked on zig-zagging tracks with greater slopes (see Table 1) making manoeuvring more difficult, and distances being longer (see Table 6). In contrast, in zone 2, the forwarder (Dingo AD-2452) worked within the forest due to good conditions and low degree of slope.

Time consumption in moving between loadings in zone 1 (Dingo AD-8468) was lower because the bundles were grouped and located only at the sides of the track, whereas in zone 2 the bundles were grouped but distributed across the whole area due to the more suitable topography. This is in accordance with McNeel and Rutherford (1994), who reported that this time parameter is strongly influenced by the distribution of bundles, and is lower when bundles are in groups of an optimum size.

Regarding loading and unloading times, they are longer or the Dingo AD-2458 (around 40%) due to the larger box size, which allows a greater load per cycle according to the study of Jiroušek et al. (2007) and its larger crane allows it to have a greater working radius, meaning that an increased number of bundles can be collected from the same point (Laitila et al. 2009).

In this study, the productivity for the Dingo AD-2452 forwarder working in zone 2 was 11.56 odt/PMH

Table 7 Main results of time studies between forwarder models

Variables	Dingo AD-8468	Dingo AD-2452
Moving empty, min	8.94	4.43
Loading, min	7.20	13.38
Moving loaded, min	9.94	4.61
Unloading, min	4.36	8.21
Main work time/cycle, min	31.11	30.63
Complementary work times, min	1.59	0.46
Delay times, min	5.90	1.15
Other times, min	0.66	–
Cycle time, min	34.79	30.96
Productive time (PMH), min	32.58	30.83
Non-productive time, min	7.18	1.15
gt/PMH	9.52	22.51
Odt/PMH	6.75	11.56
Bundles/PMH	39.94	61.78
Bundles/cycle	21	32
€/PMH	47.11	52.86
€/SMH	39.99	44.98
€/odt	6.77	3.94
€/gt	4.79	2.02

PMH – Productive Machine Hour
odt – oven dry tonnes
€ – euros
gt – green tonnes

and for the Dingo AD-8468 forwarder working in zone 1, it was 6.75 odt/PMH. The difference is due to the lower load size and more difficult topography in the latter scenario. This is in accordance with the work by Jiroušek et al. (2007), where the productivity of a forwarder increased with improvement in harvesting area conditions, since this implies better track conditions and better accessibility to collect the bundles.

The number of bundles extracted per cycle was very close to the results obtained by other authors (see Table 7). Eriksson (2008) recorded 25 bundles extracted per cycle with a size of forwarder similar to the Dingo AD-2452, and Laitila et al. (2009) obtained 24 bundles per cycle (minimum 8 bundles, maximum 31) using a similar machine. Also, Kärhä et al. (2010) obtained 22 bundles per cycle, with a smaller forwarder that had similar technical characteristics to the Dingo AD-8468.

Assuming a utilization rate of 70%, the hourly cost of the Dingo AD-8468 and Dingo AD-2452 was 39.99 €/SMH and 44.98 €/SMH, respectively. These results were very closer to those obtained with similar forwarders by Spinelli et al. (2004), i.e. 38.6 €/SMH and 57.4 €/SMH, but slightly below those obtained by Agudo (2010), i.e. 62.91 €/SMH, for a forwarder with similar characteristics to the Dingo AD-2452. Cost per oven dry tonne varied between 3.94 to 6.77 €/odt (see Table 7).

3.2 Model adjustment

Different models to predict main work times (moving empty and loading, loading and unloading) 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 8. All parameters were significant at the 5% level.

Table 8 Equations finally proposed and goodness-of-fit statistics of each model

Work element times	Equation		RMSE	R^2
Moving empty, min	Eq. 1	$t_{\text{moving empty}} = 4.633 - 0.5274 \times V_{\text{empty}} + 0.00677 \times D_{\text{empty}}$	0.77	0.97
Loading, min	Eq. 2	$t_{\text{loading}} = 11.15 - 0.06635 \times S_{\text{loading}} + 0.02381 \times D_{\text{loading}}$	1.51	0.83
Moving loaded, min	Eq. 3	$t_{\text{moving loaded}} = 10.53 - 1.844 \times V_{\text{loaded}} + 0.01066 \times D_{\text{loaded}}$	1.15	0.91
Unloading, min	Eq. 4	$t_{\text{unloading}} = 1.569 + 0.5726 \cdot L_{\text{cycle}}$	0.58	0.92

RMSE – Root Mean Square Error
R^2 – Coefficient of Determination
t – time (minutes)
$V_{\text{empty/loaded}}$ – velocity when the machine is empty or loaded (km/h)
$D_{\text{empty/loading/loaded}}$ – distance travelled when the machine is empty, loading, or loaded (meters)
S_{loading} – slope (percentage)
L_{cycle} – load hauled per cycle (green tonnes)

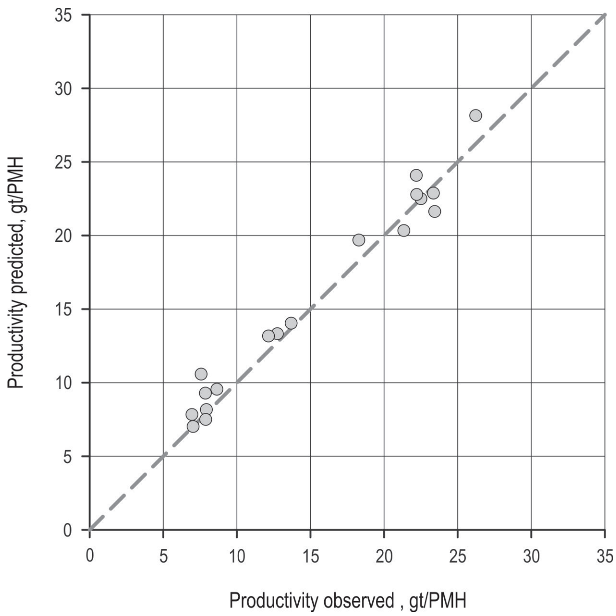

Fig. 1 Plot of predicted values against observed values for the productivity equation (Eq. 5)

Taking into account that in this type of equation the common value of R^2 is around 0.5 (Olsen et al. 1998), the time consumption models explained a high percentage of total variability (between 83 and 97%). Main work time could be calculated as the sum of individual times estimated employing the models fitted (Equations 1–4 in Table 8), so it is possible to develop a productivity model following Equation 5.

$$Productivity = \frac{60 \cdot L_{cycle}}{t_{moving\ empty} + t_{loading} + t_{moving\ loaded} + t_{unloading}} \left[\frac{gt}{PMH}\right] \quad (5)$$

Where:

L_{cycle} load hauled per cycle (green tonnes)
t time in minutes.

Plot of the values predicted (gt/PMH) from the productivity equation (Eq. 5) against the observed values are shown in Fig. 1.

4. Conclusions

Productivity and costs of forwarding bundles of residues on steep terrain were calculated for two different models of forwarder, a Dingo AD-8468 and a Dingo AD-2452. Productivity in oven dry tonnes per productive time was 6.75 odt/PMH and 11.56 odt/ PMH for the Dingo AD-8468 and Dingo AD-2452, respectively.

Total hourly cost of the Dingo AD-8468 was 39.99 €/SMH and 44.98 €/SMH of the Dingo AD-2452. Equations were developed to predict different work element times as a function of independent variables ($V_{empty/loaded}$, velocity; $D_{empty/loading/loaded}$, distance travelled; $S_{loading}$, slope; L_{cycle}, load hauled per cycle) depending on the equation, which represented between 83% and 96% of total variability. A productivity equation was developed based on main work element times as the sum of individual times employing the model fitted. These equation can also be used to calculate costs (€/gt) using the costs in €/SMH and the specific utilization rate.

Under difficult working conditions, such as in the study area (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 of eucalyptus logging residues collection. Since specific terrain conditions of forest harvesting operations have such a significant effect on this type of machine (forwarder), these equations should be extended to include various other scenarios.

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