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RESEARCH ARTICLE

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Evaluation of technological improvements in bundling units for the collection of eucalyptus logging residues on steep terrain in Spain

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Abstract

Aim of the study: The objective of this study was to evaluate recent technological improvements to forest bundlers: a new cutting device with shears and a mechanism which allows the bundling pressure to be changed by the driver.

Area of study: eucalyptus plantations in Northern Spain.

Material and Methods: Several time studies were performed in order to compare and calculate productivity depending on the machine: John Deere bundler working with the traditional chainsaw and Monra bundler equipped with the technological improvements of shears and adjustable bundling pressure.

Research highlights:

— Significant differences were found between cutting devices (shears and chainsaw) and between the Monra working at maximum pressure and at lower pressure.

— Shears were shown to be a more robust and reliable cutting device, with 1.02 cutting attempts per bundle compared to 1.55 with chain saw. The use of shears made the loading more efficient as it eliminates the need to shake the residues before feeding the bundler. A great advantage of this technological improvement is that it can be incorporated into other machines and thus improve bundling efficiency.

— In spite of this, working at standard bundling pressure, the productivity of the Monra bundler is only 3.2 per cent higher than that of the John Deere due to the fact that in the latter bundling is faster and it produces bundles with significantly more dry mass.

— For the Monra bundler, the option of producing lighter bundles further reduced productivity compared to when standard weight bundles are produced. However, it would be of interest to study the effect of the machine working at various pressures in order to optimize the work system. It is possible that working at higher pressures would have advantages in terms of increasing transport efficiency.

Keywords: bundler; time study; shear; cutting device; slash collection; forest biomass.

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Introduction

The use of biomass has gained more importance in recent years as a way to reduce both atmospheric CO_2 emissions and dependence on fossil fuels. The main aims of European energy policies are: security of supply, environmental sustainability and economic competitiveness. The objective of the European Union (EU) is to achieve a minimum quota of 20 per cent of energy from renewable sources in gross final energy consumption. Of particular relevance to the present work is the fact that of the 91.5 Mtoe of primary energy in the EU which comes from biomass, 5.4 Mtoe of this is accounted for by Spain (EurObserv'ER, 2015) and is mainly derived from the forestry sector.

At present the use of forest biomass in Spain represents about 5,500,000 green tonnes, although the potential available forest biomass from forest residues of final cuttings and from whole-trees in thinning operations is approximately 3,000,000 and 15,700,000 green tonnes per year respectively (IDAE, 2011). There is thus great potential for energy production from forest biomass.

One of the keys to development in this area is mechanization in the collection and transport of biomass, which needs to be combined with appropriate adaptation of the existing technology. The use of logging residues is costly, due to, in most cases, poor integration between timber and biomass supply chains, and because of the seasonality of production. The latter either creates supply and storage difficulties for the final consumer in power plants (Tolosana *et al*., 2010) or high capital costs per produced unit of biomass due to low level of machine use.

In general, slash has less than one fourth the density of solid wood (McDonald *et al.*, 1994) so the productivity of harvesting operations is reduced by the low density of the material, resulting in increased cost per tonne. Currently in the collection of forest biomass two machines are largely used to improve transport economy: chippers and bundlers. Biomass bundlers collect, compress and bind forest residues into cylindrical bundles that resemble logs (composite residue logs, CRLs), greatly simplifying biomass handling (Rummer *et al*., 2004) and meaning that subsequent operations (haulage, transport) can be performed with fully loaded conventional forwarders and trucks (Johansson *et al*., 2006), which simplifies the logistics involved. An additional advantage of this system over chipping is that bundles can be stored for long periods of time (Johansson *et al*., 2006; Steele *et al*., 2008), with only small dry matter losses in comparison to wood chips, which have a rather high dry matter loss per month.

Experiments with bundling started in Sweden and Finland in the late 1990s (e.g. Anderson & Nordén, 1996), and the following decade the local large scale use of bundlers supplied the Alholmen CHP plant in Finland. In the study area in Northern Spain there are currently about 15 units producing bundles for fuel, mainly working in eucalypt logging residue collection and providing biomass to a single large power plant with an annual consumption of 380,000 tonnes (87% of which is eucalypt logging residues: bark and bundles). This area of Spain is characterized by steep terrain, small property size, and long haulage distances, which make the collection of forest residues more difficult and expensive than usual.

Improvement in forest operations and evaluation of new machinery, such as the bundler, has become crucial, whatever the stand conditions or location of the exploitation. To this end, time studies are increasingly being used to assess and improve the productivity of machines employed in forest harvesting and so reduce costs. The productivity of a logging system depends on machine characteristics, stand factors (e.g. soil type, slope, stand density, tree size and species, and branch architecture) as well as on the operator's skill and motivation. A number of time studies of bundler productivity have been published (Andersson & Nordén, 1996; Cuchet *et al*., 2004; Kärhä & Vartiamäki, 2006; Patterson *et al*., 2008; Spinelli *et al*., 2011; Laitila *et al.*, 2013) and, specifically pertaining to Spain, by Sanz & Piñeiro (2003), Agudo (2010) and Sánchez-García *et al.* (2011). These studies have shown that the productivity of a bundler is related to the layout of residues (rows, piles or scattered), slash density, forest road density, type of residues, etc.

Delays in the system obviously have an impact on productivity. One of the main reasons for short term delays in bundler operations is the maintenance and malfunction of the chainsaw (Kärhä & Vartiamäki, 2006). As such, it is of great interest to investigate ways of reducing these delays, thereby increasing productivity and reducing costs. The latter is of prime importance since cost is one of the principal barriers to the wider acceptance of bundling.

The aim of this study was to evaluate bundler productivity in the collection of eucalypt logging residues, using two types of cutting device (chainsaw or shears), and the new possibility of selecting the pressure of compression in the bundling unit (with a maximum pressure of 250 kg/cm^2). The latter factor may have an influence on not only productivity, but also bundle quality.

Material and methods

This study was carried out in seven *Eucalyptus globulus* stands in Northern Spain. In the clear cuts, trees were felled manually with a chainsaw. Later, tree processing was carried out by a harvester and the haulage with a forwarder. The collection of residues was made by two bundlers: John Deere 1490D and Monra Enfo2000, the latter is a machine designed and built in a Spanish factory (Monra). The Monra Enfo2000 is a bundling unit only and so was mounted on a Dingo AD 2452 forwarder, which had an engine power of 141 KW) compared to the 134 KW of the John Deere 1490D bundler. Table 1 shows the description of the study areas, which were selected to be as homogenous and comparable as possible. The machines studied were operated by equally qualified operators in order to compare the machines with as little operator effect as possible. In each stand, various time studies were carried out and considered as replications.

Table 1. Descriptions of stands

Machine	Evaluation	Time Study	Stand	*n*	*S*	*slope*	*d*
Monra Enfo2000	shears / pressure 220 kg/cm^2 (M_S220)	1	Villa I	163	0.38	44	1,553
		2	Villa II	130	0.58	23	796
		3	Villa III	41	0.58	23	739
		4	Villa IV	130	0.22	42	912
	shears / pressure 250 kg/cm^2 (M_S250)	1	Cadavedo	99	1.70	35	522
		2		71	1.70	35	548
		1	Villabona	106	15.20	26	*
		2		150	15.20	26	2,501
		3		220	15.20	26	2,662
		4		197	15.20	26	2,660
John Deere 1490D	chainsaw / pressure 245 kg/cm^2 (JD_CS245)	1	Xove	46	4.99	15	*
		2		108	4.99	15	414
		3		61	4.99	15	331

Note: *n* number of bundles, *S* area of study (hectares), slope (in percentage), *d* distance travelled in each time study (*:GPS data not available).

The improvements evaluated were the new Monra cutting system with shears versus the traditional chainsaw cutting unit, and the possibility of using a lower bundling pressure in the Monra bundler. Three types of work technologies were evaluated:

i) a John Deere 1490D bundler with the chain saw cutting system at standard bundling pressure of 245 kg/cm^2 (henceforth, JD_CS245),

ii) a Monra Enfo2000 bundler with the shears cutting device and a standard bundling pressure of 250 kg/cm^2 (henceforth, M_S250), and

iii) a Monra Enfo2000 bundler with shears and working with a lower bundling pressure of 220 kg/cm^2 (henceforth, M_S220).

Based on prior analysis of the work of the bundlers, the bundler work cycle was divided into work elements, describing the start and the end of each one (Table 2). As two tasks can take place simultaneously in the bundler work cycle, for example bundling and movement, a priority order was established to assign the tasks during the time studies.

For the productivity analysis of the bundlers, thirteen detailed time studies were performed in seven different stands considering each time study as a replicate. During the detailed time study, the exact time elapsed in every basic activity of each cycle was recorded on a Trimble Nomad handheld computer. In addition, certain parameters which were assumed to have a large influence on cycle time were recorded (harvesting area, slope, disposal of residues, etc). In parallel with these detailed time studies, three work sampling studies were carried out to analyze infrequently occurring activities like repair and maintenance times for the three machines. Data collection was conducted using the UMT® time study software (LAUBRASS Inc. 2007). The duration of the different studies and the machine evaluated in each time study are shown in Table 3. A Trimble GPS receiver was mounted on machines to to calculate the distance travelled in each study.

In each stand, a sample of bundles were weighed and measured to ascertain their density and average weight. A sample disc was taken from every bundle and weighed. Each sample was weighed and then dried in an oven at 65ºC until no further weight loss occurred in order to obtain dry weight and thus calculate moisture content. With this data the oven dry tonnes (odt) collected in the stands were calculated.

After harvesting, the amount of residues left on the ground was estimated by weighing the remaining woody residues in four circular plots (radius equal to 3 m). A sample of residues (3 kg) was dried in an oven at 65º to measure the moisture content in order to obtain the dry weight of residues left in the forest.

Once the time study data was recorded, it was reviewed to eliminate errors and outliers (Olsen *et al.,* 1998). For each replicate average time per produced bundle was calculated and used in the subsequent analysis. To study the effects of machine type, data analysis was made using analysis of variance for all work elements except for moving, where analysis of covariance was used with distance travelled per bundle

Table 2. Description of work elements

Work element	Priority	Description
Loading	2	Begins when the boom moves to grasp the residues and ends when it puts them on the infeed deck
Bundling	1	Begins when the feed rollers start to compress residues in the bundling unit and ends when the cutting device starts its movement
Cutting	1	Begins when the cutting device starts its movement and ends when the bundle is dropped onto the ground
Moving	2	Movement of the machine between bundling positions. Starts when the wheels start to move and finishes when the wheels stop
Arranging slash	2	Handling of slash in preparation in order to ensure a full grapple load
Arranging bundles	2	Handling of bundles in preparation for haulage or avoiding bundles rolling away due to the slope
Getting access to forest road / Road access construction	2	Time to make good the access to the forest road from the stand
Rotation bundler	2	Time to position bundling unit. Begins when the driver rotates the bundler to start the bundling or manoeuvres onto the forest road
Maintenance time	1	Changing rope, refuelling etc.
Delays	1	Mechanical, operator or other delays
Others	2	All work elements that do not belong to the above categories

Tabla 3. Duration of the time studies

Evaluation	Time Study	Detailed Time Study (hh:mm:ss)	Work sampling (hh:mm:ss)
M_S220 (shears / pressure 220 kg/cm^2)	Villa 1	6:16:08	17:44:26
	Villa 2	4:30:37	
	Villa 3	2:14:15	
	Villa 4	4:31:14	
M_S250 (shears / pressure 250 kg/cm^2)	Cadavedo 1	3:47:13	25:11:37
	Cadavedo 2	2:24:58	
	Villabona 1	6:15:01	
	Villabona 2	7:02:59	
	Villabona 3	11:53:54	
	Villabona 4	11:18:31	
JD_CS245 (chainsaw / pressure 245 kg/cm^2)	Xove 1	2:07:49	17:26:08
	Xove 2	4:33:39	
	Xove 3	2:50:05	

as covariate. All analyses were made using proc GLM in the SAS/STAT® statistics software (SAS Institute Inc. 2004) and all p-values presented are from the type III tables. During the GLM procedure, differences in means were analysed with Tukey's HSD test.

The productivity was estimated by dividing the tonnes of residues (over dry tonnes, odt) or number of bundles (bundles per hour) produced by the total time and main work time.

Results

During the time studies a total time of 69 hours and 46 minutes was analysed using detailed time studies and 60 hours and 22 minutes with work samplings. Bundle characteristics for the three types of machine are shown in Table 4. The volume of bundles between different machines was similar, but there were significant differences in the dry weights.

Tabla 4. Study of bundles

Evaluation	Dry weight (kg)	Moisture content (%)	Diameter (cm)	Length (m)
M_S250	229a	0.79	78	2.44
M_S220	169b	0.33	78	2.44
JD_CS245	248c	0.47	75	2.60

Note: Different letters within first column indicate significant differences between groups (ANOVA, Tukey tests; p <0.05).

The amount of residues left in the forest varied between 9 and 16 odt/ha.

There were significant effects of machine type on the time consumption per bundle for certain work elements loading, cutting, and bundling (Table 5).

When producing standard bundles, the Monra bundler (M_S250) had a 9.4 per cent lower main work time per bundle than the John Deere bundler (JD_CS245) working at the same pressure, due to its more efficient loading of the slash and cutting of the bundles. The reason for this is actually due to the more robust cutting device (shears) on the Monra bundler, which allows the operator to load residues without shaking them to get rid of soil contamination and which is less prone to experiencing problems cutting the bundle: on average the Monra bundler made 1.02 cutting attempts per bundle, i.e. one bundle in 50 needs a second cutting attempt, in comparison to the John Deere bundler which made 1.55 cutting attempts per bundle, that is, more than every second bundle needed a second cutting attempt. On the other hand the John Deere is faster when bundling and the bundles contain significantly more dry mass (Table 4). Taking into account the higher dry mass of the John Deere bundles reduces the difference in production between the machines, expressed as odt per main work hour, to 3.2 per cent (higher in Monra bundler M_S250).

Producing light bundles reduces the production (odt per main work hour) of the Monra bundler (M_S220) by 11 per cent, although it is 17 per cent faster per bundle than when it is producing standard bundles (M_S250).

Tabla 5. Results of analysis of variance between work technologies

Element	John Deere JD_CS245	Monra M_S250	Monra M_S220	P machine effect	Covariate
Main work time					
Loading	43.7	27.9	20.0	0.0055	
Bundling	62.8	68.1	58.3	0.0037	
Cutting	26.3	19.8	17.5	0.0019	
Moving	12.5	15.9	13.5	0.481	m/Bundle
Main work time/bundle	145.3	131.7	109.2		
Complimentary work times					
Rotate bundler	0.6	2.0	2.7	0.110	
Arrange bundles	0.2	1.2	1.0	0.256	**
Move boom	0.0	0.2	1.7	0.0598	**
Planning	1.1	0.4	0.7	0.572	
Road access construction	0.0	1.6	0.6	0.176	*
Complimentary time/bundle	1.9	5.4	5.7		
Delay times					
Maintenance	17.7	20.0	20.9	0.952	
Delays	3.6	14.4	4.6	0.542	
Delay time/bundle	21.3	34.4	25.5		
Total effective time/bundle	147.2	137.1	115.9		
Bundles/hour	24.5	26.3	31.1		
Odt/main work hour	6.1	6.3	5.6		
Odt/hour	6.1	6.0	5.2		

Note: *: only dependent on stand conditions, **: highly dependent on driver & stand, m/bundle: distance travelled per bundle (distance/number of bundles). All times are in seconds.

The complementary work times (Table 5) are to a large extent dependent on site conditions, e.g. slope, or whether the machine was working in the stand itself or on an access road. Figure 1 shows the comparison between the percentages of different work elements in the work sampling. The John Deere bundler has a technical availability 90% of the main time, for the Monra at lower pressure (M_S220) this figure is 80% and at standard pressure it is 82%.The John Deere bundler spends about 29% of total time in bundling, while the Monra bundlers spend approximately 44% (M_S220 and M_S250). The proportion of time spent in loading is also higher for the John Deere bundler (around 39%, as against 14% for both Monra M_S250 and M_S220) due to the need for it to shake the residues to get rid of soil and stones as the chainsaw has problems cutting contaminated residues which the stronger shears of the Monra do not have. Differences in cutting time can also be observed, those of the John Deere bundler being higher (17% compared to 11% for both Monra work technologies). Other differences observed between work elements for the two machines probably depend largely on stand characteristics, layout of residues, operator, etc.

Discussion

The results obtained in this study point to an improvement in the cutting device for working with this type of residues: the more robust and reliable cutting device with shears allowing a more effective cutting and loading, due to increased efficiency and the reduced need to shake the residues. Although this work deals with handling hardwood residues rather than softwood, the shears would also be beneficial for this latter material as they need less maintenance than the traditional chainsaw unit.

The bundles produced were similar in size but not in weight. There are two probable causes for this; differences in the bundled material between the sites studied and the differences between the machines studied. To produce light bundles with the Monra (M_S220) reduced the amount of residues bundled per hour. It thus makes no sense to produce light bundles unless they have better storage properties or if, as occurred during this study, the machine owner is paid per bundle.

The productivity levels of both bundlers are similar to those found in Scandinavian studies, where, in good conditions, the Fiberpac bundler - which would become the John Deere bundler - produced 7.1 (Lofgren, 2004) and 8.5 odt per effective hour (E_0h) (Andersson & Nordén, 2000). In a follow up study the John Deere bundler produced 29.3 bundles per E_0h under summer and autumn conditions and 25.3 bundles per E_0h under winter conditions (Eliasson, 2011). It is important to note that softwood residues bundled in Scandinavia are less likely to interfere with the chain saw than the eucalypt residues bundled in the current study. However,

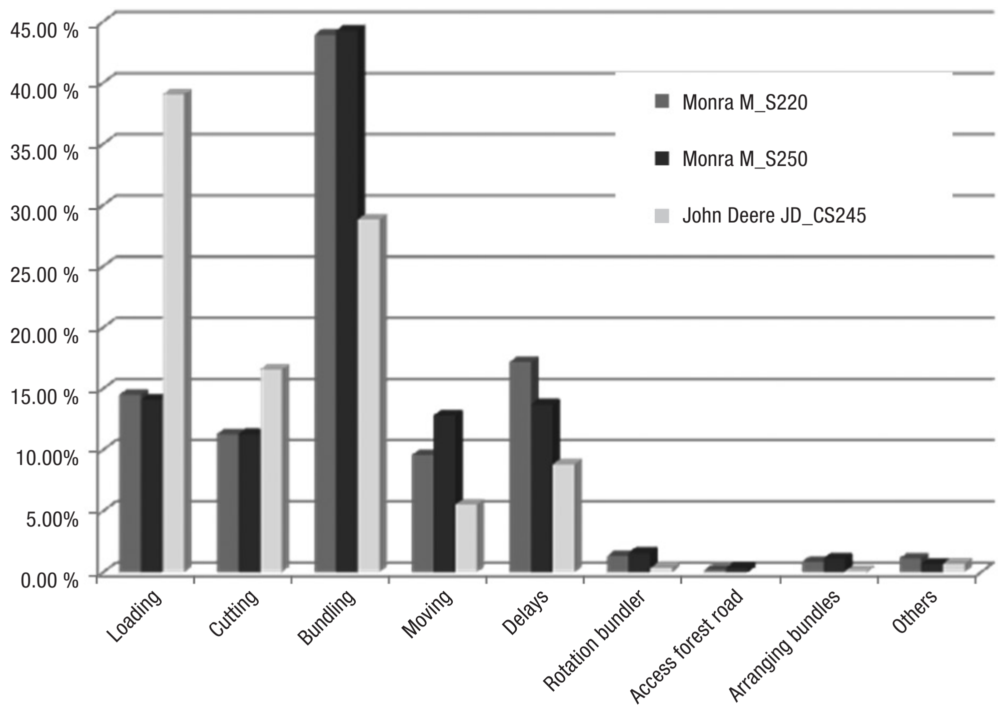

Figure 1. Distribution of work elements in percentages.

even when bundling mainly softwood residues delays due to the chain saw are not uncommon (Kärhä & Vartiamäki, 2006).

In this study, the Monra bundler demonstrated difficulties in doing two tasks simultaneously due to the low power of the forwarder. The forwarder did not have enough hydraulic power and sometimes it could not move the boom at the same time as carrying out other work elements (like bundling or moving) so this task was included in "Other work elements".

For a proper analysis of delay times a longer time follow up of the machines than the work samplings done here is needed. In a follow up study of almost one year in Sweden (Eliasson, 2011), 78 per cent of the work place time, excluding the time for relocations between sites, was work time.

The results of this study have relevance in not only similar scenarios with regard to slope, amount and type of residues, etc., but the effect of using the new cutting device would be expected to have a positive impact on productivity under other harvesting conditions. This would be of particular interest in scenarios where strength is important (because of the material being harvested) to avoid mechanical delays.

There is no consensus on the exact amount of residues than should remain on a site after biomass extraction (Abbas *et al*., 2011), as this varies with soil type. Finnish guidelines recommend leaving up to 30 percent of residues or the same amount of nutrients on the forest floor (Äijälä *et al*., 2005), whereas in Sweden it is considered advisable to leave at least 20 per cent of the residues on the site (SKOGSSTYRELSEN, 2008). Therefore, taking into consideration the amount of available residues in eucalyptus coppice in the north of Spain (between 17-35 t/ha of branches and leaves in stands in harvesting age) (Balboa, 2005), the amount of residues which remained on the stands during the study were considered suitable.

Conclusions

Three forest bundlers were evaluated in this study: a John Deere bundler (JD_CS245), a Monra bundler at standard bundling pressure (M_S250) and a Monra bundler at a lower bundling pressure (M_S220). Significant differences were found between cutting devices (chain saw vs. shears). Shears were shown to be a more robust and reliable cutting device, with 1.02 cutting attempts per bundle compared to 1.55 cutting attempts for the John Deere bundler with chain saw. The use of shears also makes loading more efficient, as it eliminates the need to shake the residues before feeding the bundler. In spite of this, the difference in productivity between machines working at standard bundling pressure is only 3.2 per cent higher in Monra bundler (M_S250), due to the fact that the bundling of the John Deere is faster and the bundles contain significantly more dry mass. For the Monra bundler (M_S220), producing lighter bundles reduced the amount of residues bundled per hour compared to when standard weight bundles were produced.

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