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A Long-Term Follow-Up Study of Slash Bundling in Fast-Growing Eucalypt Plantations

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Abstract: The Authors conducted a long-term follow-up study of a John Deere 1490 forwarder-mounted bundler owned by a Portuguese company and used for bundling logging residues from fast-growing eucalypt plantations located in Portugal and Spain. The study spanned 7 years, from 2011 to 2016. During this time, the machine clocked over 11,500 h and produced more than 200,000 bundles or 75,000 green tons of biomass. Bundle length was commonly 2.4 m, and bundle mass averaged 350 kg. Overall, the database contained 1752 daily records. Bundling productivity averaged 19 bundles per productive machine hour (meter hour, excluding all major delays). Mechanical availability was very high and averaged 93%. Utilization commonly ranged between 65% and 75%. Use and productivity showed a predictable seasonal trend and a slight decline over time. The latter might be due to wear, but also due to the increasingly challenging conditions faced by the company as the average worksite size sharply decreased from 2011 onwards. While almost extinct elsewhere, bundling seems to thrive in the Iberian plantations, possibly due to the industrial character of both eucalypt farming and bioenergy generation in the region. That allows the reaping of all integration benefits offered by bundling, while the cost of setting up a parallel biomass chain is minimized. Furthermore, bundling seems the ideal technique for efficient residue recovery where slash yields are low and roadside storage space is limited: these are the typical constraints of industrial eucalypt plantations, where planted area is maximized (=little landing space) and the largest possible proportion of the tree mass is turned into pulpwood (=relatively low residue yield).

Keywords: harvesting; biomass; productivity; downtime; utilization

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Citation: Spinelli, R.; Magagnotti, N.; Assirelli, A.; Martins, J.P.; Mihelič, M. A Long-Term Follow-Up Study of Slash Bundling in Fast-Growing Eucalypt Plantations. *Forests* **2021**, *12*, 1548. https://doi.org/10.3390/f12111548

Academic Editor: Pete Bettinger

Received: 17 October 2021
Accepted: 5 November 2021
Published: 9 November 2021

1. Introduction

In its natural state, logging residue is not dense enough for efficient handling: it requires compaction, which is normally achieved by either comminution or packing. The former has always been the reference method, immensely popular since the late 1970s. In contrast, packing has struggled to assert itself as a viable residue processing technique, despite an early start and a continued general interest [1].

The benefits of packing are clear to all, and they include: improved handling quality, simplified logistics, and trouble-free storage [2–4]. However, most technical solutions proposed over the past decades have failed to reach the profitability level required for widespread adoption.

The progress of packing technology is marked by recurrent ups and downs. The latest distinction was at the beginning of the new millennium, when at least five different manufacturers developed commercial slash bundler models. By 2003 over 700,000 bundles were being produced annually in Finland [5], and by 2005 Finnish logging companies had already deployed 30 bundlers, mounted on medium size forwarders, in order to manufacture their bundles directly on the cutover and accrue the benefits of compaction as early as possible along the supply chain [6]. This aroused the interest of European, American, and Australian stakeholders, who commissioned a number of trials and pilot projects [7–12]. However, all this anticipation did not develop into the global success expected by many, and ten years later slash bundling had faded away as a large business opportunity with some notable exceptions.

The main such exception is represented by the fast-growing eucalypt plantations of the Iberian region. In 2015, 15 bundlers were working in Spanish eucalypt plantations and today their numbers seem to be stable or even growing [13]. An additional seven units are working full time in the Portuguese plantations today [14]. The Iberian fleet is likely the largest in operation to date and it does not seem to be shrinking—in fact, it may be experiencing a slow but steady expansion. What is more, this fleet has been in continued operation for over a decade, starting just a short time after bundling first affirmed itself in the Nordic region.

The Iberian experience is most interesting for at least two reasons: first, because it can bring to light those factors that make bundling successful in the long run, as it represents the only instance where this technology has survived in numbers until now; second, because it can offer reliable long-term performance data about slash bundling technology deployed in commercial operations, given that some units are now over 10 years old and have accumulated some 20,000 m hours.

Better knowledge of the Iberian experience can help define when bundling can represent a competitive option to slash processing and how it should be deployed for maximum efficiency. A few studies deal specifically with the use of bundlers in this region, but they confirm that the productivity levels achieved under the conditions of Iberian eucalypt plantations are not substantially different from those achieved in the rest of Europe—with softwood or hardwood logging residues. However, these are all short-time productivity studies that fail to capture those long-term trends that may contain the answer to prolonged success. As a matter of fact, the rich literature on bundling is entirely composed of short-term studies. The only notable exceptions deal with machines deployed in Nordic Europe [6,15] and in the Alps [16], but these regions present peculiar vegetational, environmental, and economic conditions that may not properly represent the work environment encountered by other bundlers elsewhere in Europe and in the rest of the World, especially when fast-growing plantations are concerned.

Therefore, the goal of this study was to gather and analyze long-term usage data for a bundler representative of the fleet deployed in Iberian eucalypt plantations. Information was sought about usage level and patterns, utilization, productivity, fuel consumption, relocation frequency, and main sources of downtime. The results of this study may be of general interest to forest managers and engineers that aim at obtaining more knowledge about available biomass processing technologies, and of special interest to all stakeholders in fast-growing eucalypt plantations, especially in the Southern Hemisphere.

2. Materials and Methods

The device in this study is a John Deere 1490 bundler. This is the most popular among several bundler models using the same packing principle, based on two compacting grapples (one fixed and the other mobile), a wrapping device and a cutting system. The machine can be mounted on a trailer, a truck, or a forwarder, but the latter is by far the most common. For that reason, the study focused on a forwarder-mounted John Deere 1490 (Figure 1). The machine selected for the study was installed on an 8-wheel John Deere forwarder powered by a 136 kW engine and equipped with a CF5 loader. The machine had been modified by replacing the chainsaw cutting unit with a two-blade shear system very much resembling a giant cigar scissor. The total weight of the complete unit (bundler, loader, and base machine) was 23 t.

Figure 1. The John Deere 1490 bundling unit observed in this study.

The machine selected for the study belonged to Biolose, a Portuguese company based in Alverca do Ribatejo and operating in Portugal and Spain exclusively on fast-growing eucalypt plantations. The study material was the daily work data recorded by machine operators at the end of their work shift and delivered to management for production control purposes. Such data were manually noted in the machine logbook, every time the machine was used. The main entries were: date and place, hour and minute at the beginning and at the end of the shift, hourmeter reading at the end of the shift, number of bundles produced, selected bundle length, liters of fuel added to the tank, and number of twine rolls used during the day. The record also contained the duration and the cause for any major downtime events. Records covered the period from September 2009 to August 2017. The machine that was used had 3617 h on its meter at the beginning of the study. After August 2017, management changed the recording practice so that available records did not contain the same level of detail that was present in the data collected until then. Therefore, the analysis was conducted only for the 7 years of data that contained all the required information, without trying to adapt later records into a format they were not designed for. It was felt that 7 years and almost 11,500 metered hours would represent a long enough interval, and that combining and analyzing a heterogenous dataset would have generated more doubt than it was worth.

Overall, the database contained 1752 daily records. These were intersected with the company delivery log that contained information about the total weight of the bundles delivered to the factory each month, based on the factory weighbridge tickets. The main issue with reconciling bundler and delivery records lays with the fact that deliveries may occur several weeks—if not months—after the bundles have been manufactured, and therefore some reconciliation error is inevitable. For that reason, a match was attempted for several observation periods (month or year) in order to test the right time span for which delays in bundle deliveries would not cause excessive error, as would be denounced by flagrant inconsistencies in bundle mass estimates. Weighbridge tickets reported fresh weight as delivered and were not associated to any estimates of wood moisture content.

Data analysis started with the extraction of descriptive statistics, crucial to determining general reference values for productivity, utilization, and material consumption (fuel and twine). Furthermore, time series analysis (decomposition) was used for checking the presence of seasonal or multi-annual trends.

Distribution analysis was conducted on the frequency of main delays, after categorizing all delay descriptions into homogeneous pre-defined classes. That allowed for the determination of the importance of different types of delay, so that future work may define and address their root causes. As a matter of fact, daily records did contain descriptions of the main causes for downtime, but they generally failed to indicate exactly how much downtime could be attributed to each of them. Even when the record contained only one major descriptor, it would have been inaccurate to attribute all the downtime in that record solely to the mentioned event: almost all records contained some downtime and many did not indicate any relevant events, which implied that preparation, minor delays, and general attrition would account for at least some of the downtime in all records. For that reason, the analysis of downtime focused on the frequency of noted causes, rather than on the actual time associated with any of them. In fact, the database contained about 100 recorded delay events per year, for the period between 2010 and 2015. This was a rather stable figure that did not change much from one year to the other. In contrast, the number of recorded delay events suddenly dropped to 38 in 2016. This was caused by a change in recording practice, rather than a real reduction in the number of delay events, given that utilization rates did not increase from 2015 to 2016. For that reason, the analysis of delay event frequency was limited to the period between 2010 and 2015. In that instance, χ^2 (chi-square) analysis was used to see if the frequency distribution of the main delay types would change between years.

Data were also aggregated by worksite, intended as one or more daily records attributed to a single location different from the location associated with the records just before and after. That was done in order to determine worksite size, expressed in terms of permanence (days and hours) and yield (bundles). The surface area of a worksite was estimated by multiplying bundle yield by mean bundle weight and then dividing the resulting figure by an expected recoverable residue load between 15 and 30 t ha^{-1}, respectively defined as the low and high estimates [17].

Given that bundle length was occasionally extended from the standard 2.4 m to 3.0 m, the size and significance of the bundle length effect was tested with non-parametric statistics, namely the Mann–Whitney U-test, which was most suitable to the non-normal, unbalanced dataset at hand.

For all analyses the significance level was $\alpha < 5\%$.

3. Results

The machine meter read 3617 h at the beginning of the study on 22 September 2009 and 15,288 h at the end of it on 3 August 2017. Overall, the study started with a machine that had just completed its break-in period and ended with the same machine quite well used, even though the machine was still in good use three years later with over 20,000 h on its clock. Overall, the study covered 11,449 metered hours or 16,308 scheduled (shift) hours. Annual usage varied from 1350 to 1630 metered hours, with an average value at 1492. The corresponding shift time was between 1968 and 2253 scheduled hours per year, with an average at 2130. During that period, annual usage was relatively stable, with a possible small decrease of metered hours over time, possibly resulting from a marginal expansion of downtime (Figure 2).

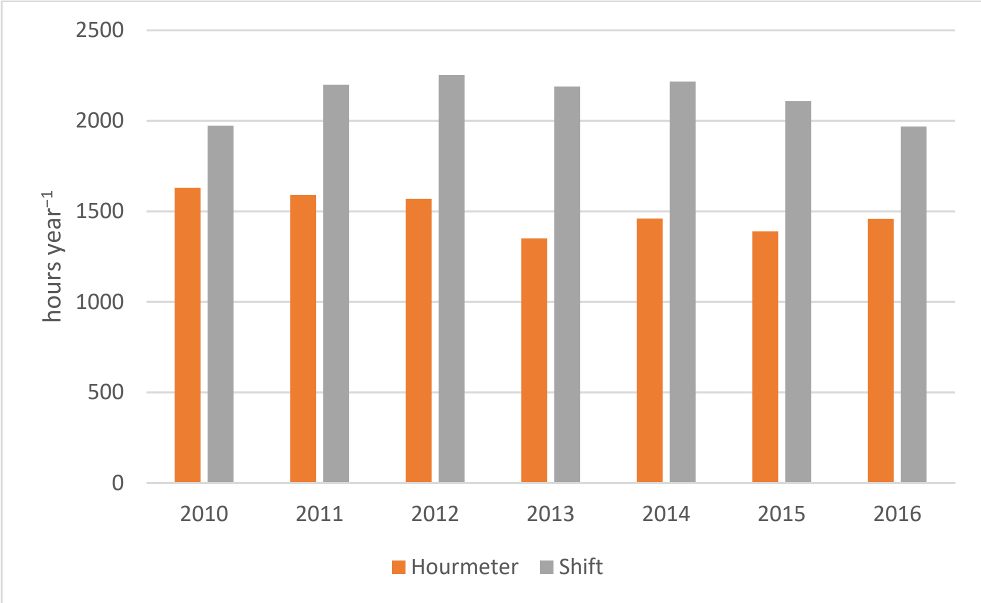


Figure 2. Annual use in shift hours and meter hours.

Monthly use varied most commonly from 16 to 20 days, the average shift lasting about 9 h 30 min (Table 1). Mechanical availability was very high and averaged 93%. Utilization commonly ranged between 65% and 75%, with an average at 70%.

Table 1. Monthly use statistics (*n* = 94).

	Mean	Median	Lower Quartile	Upper Quartile
Workdays month^{-1}	18.2	19	15.7	20.7
SMH day^{-1}	9.5	9.6	9.1	9.9
Mech. Availability %	92.8	94.4	89.5	96.1
Utilization %	70.0	69.8	65.1	74.9
Bundles month^{-1}	2365	2453	1831	2900
t month^{-1}	745	727	579	912
L Diesel month^{-1}	1883	1911	1440	2326
Rolls twine month^{-1}	57.3	56	30.5	84.1

Note: SMH = Scheduled machine hours, including delays (shift time).

Productivity ranged typically between 12 and 15 bundles SMH^{-1} (scheduled machine hour, including all delays), or between 14 and 19 bundles PMH^{-1} (productive machine hour, excluding all delays) (Table 2). Expressed as delivered weight, that corresponded to an average of 4.6 t SMH^{-1}, or 6.6 t PMH^{-1}. Bundles would achieve a mean delivered weight of 345 kg each, but variability was quite high. Fuel consumption averaged 0.8 L bundle^{-1} and was estimated between 2.4 and 3.8 L t^{-1}. A roll of twine was enough to pack between 30 and 70 bundles—most often 50.

Table 2. Productivity and fuel/twine consumption.

	n	Mean	Median	Lower Quartile	Upper Quartile
Bundles PMH^{-1} *	1616	20	19	16	23
Bundles SMH^{-1} *	1606	14	14	11	18
Bundles PMH^{-1}	94	17	20	14	19
Bundles SMH^{-1}	94	14	14	12	15
t Bundle^{-1}	94	0.345	0.294	0.266	0.425
t PMH^{-1}	94	6.6	6.0	5.2	8.0
t SMH^{-1}	94	4.6	4.1	3.6	5.6
L Diesel PMH^{-1}	94	16	15	13	18
L Diesel SMH^{-1}	94	11	11	9	13
L Diesel Bundle^{-1}	94	0.8	0.8	0.7	0.9
L 1 Diesel t^{-1}	94	3.1	2.4	2.4	3.8
Bundles roll^{-1}	94	53	41	29	77

Note: SMH = scheduled machine hours, including delays (shift time); PMH = productive machine hours, excluding delays (machine hour meter time); * extracted from daily records—in contrast all the other statistics were extracted from monthly records (summed daily records); roll = roll of twine.

If bundle length was increased by 25%, from 2.4 m to 3.0 m, productivity in bundles per hour decreased by 30% (Table 3). By the same token, diesel consumption per bundle increased from 0.9 to 1.3 L. These changes were statistically significant. Other performance indicators also showed measurable changes, but the analysis demonstrated they were deprived of statistical significance.

Table 3. Performance indicators for manufacturing 2.4 m vs. 3 m long bundles.

	Median	Median	*p*-Value
Bundle length	2.4	3.0	
Observations	42	34	
Bundles PMH^{-1}	21.5	15.4	<0.0001
Utilization %	86	89	0.3145
L Diesel PMH^{-1}	16.7	16.7	0.2769
Bundles L Diesel^{-1}	1.3	0.9	0.0001
Bundles roll^{-1}	38.5	34.9	0.0585

Notes: *p*-Value according to the Mann–Whitney non-parametric unpaired comparison test; Observations = days; PMH = productive machine hours excluding delays (in this case equal to machine meter hours); roll = one full roll of twine.

Monthly usage, production and utilization showed a slowly decreasing trend over time, with a marked seasonal pattern. Activity peaked in the early Spring (April–May) and Autumn (September–October) and dropped in December and especially in August at the time of traditional holidays, which in the Summer corresponded with the period of highest heat, discomfort, and fire hazard, when operations would be paused anyway (Figure 3). Decomposition analysis allowed modelling the long-term descending trend and the seasonal pattern as distinct components of the movement derived from their combined effects (Table 4).

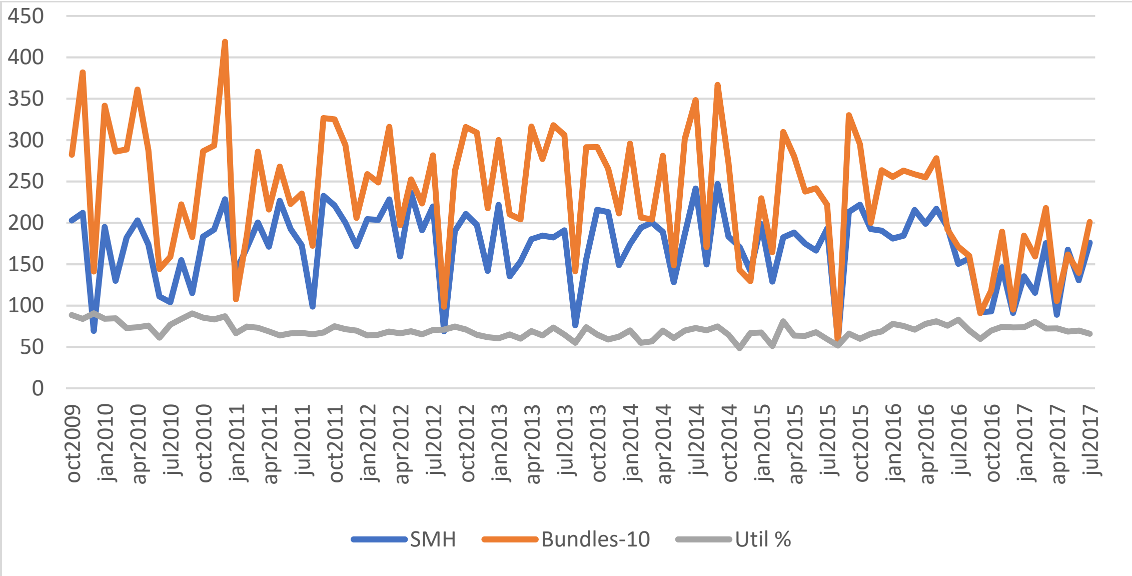


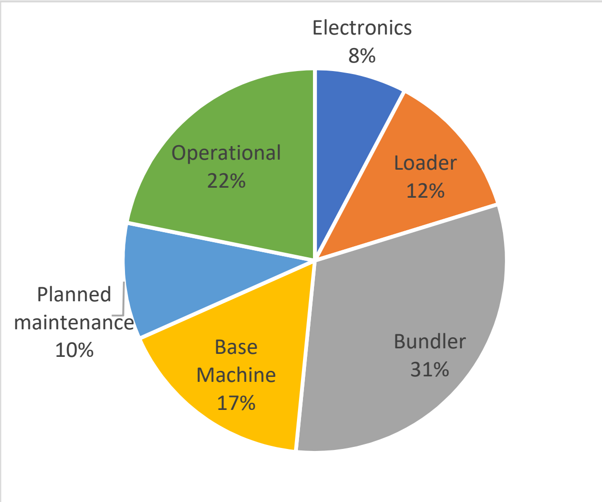
Figure 3. Monthly graph of scheduled hours, bundle production, and utilization rate.

Table 4. Main statistics from the decomposition analysis of the time series.

Trend Equation Y = a − b × Month			
Y	SMH month^{-1}	Bundles month^{-1}	Utilization %
A	182.02	2776	73.21
B	−0.095	−8.228	−0.093
Seasonal indices			
January	1.011	1.026	0.972
February	0.959	0.798	0.954
March	1.089	1.116	0.975
April	1.020	1.117	1.029
May	1.133	1.033	0.985
June	1.013	0.986	1.031
July	1.102	1.028	0.974
August	0.479	0.602	0.989
September	1.106	1.176	1.113
October	1.151	1.192	1.025
November	1.069	1.083	0.959
December	0.866	0.841	0.991
Accuracy measures			
MAPE	18.84	25	9.54
MAD	27.22	468	6.50
MSD	1327.24	388,578	65.27

Notes: MAPE = mean absolute percent error; MAD = mean absolute deviation; MSD = mean square deviation.

Defined as non-productive time, downtime represented on average 30% of the total worksite (scheduled) time. Over 20% of the total number of downtime events recorded between 2010 and 2015 was represented by operational delays (Figure 4 left), notably: relocation, planning, reconnaissance and interference with other machines, teams, or people (often visitors). Another 10% was planned maintenance. The remaining 68% was unplanned maintenance of some machine component that had broken down. The bundling unit alone accounted for over 30% of all events, and that only included failures in the mechanical and hydraulic components, because malfunctions in the electronics were recorded separately. Among the causes of delays referring specifically to the bundling unit, over half concerned the compacting device, and 25% the cutting device (Figure 4 right).



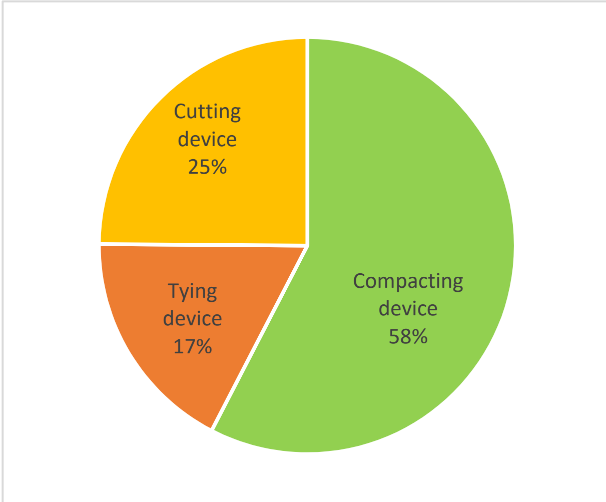


Figure 4. Reported causes for downtime: frequency of events for the whole machine (**left**) and the bundling unit only (**right**).

The analysis pointed at a significant decrease in the frequency of delay events associated with electronics malfunctions over the time between 2010 and 2015. Conversely, the same period witnessed to an increase in the frequency of delay events associated with planned maintenance and—especially—operational causes (Table 5).

Table 5. Downtime events by year and attribution.

Year	Electronics		Loader		Bundler		Base Machine		Planned		Operational		All
	Count	%	Count	%	Count	%	Count	%	Count	%	Count	%	Count
2010	19	18	15	15	32	31	29	28	3	3	5	5	103
2011	18	15	16	13	40	33	20	17	9	7	18	15	121
2012	2	2	17	17	38	37	10	10	14	14	22	21	103
2013	5	5	5	5	24	26	17	19	13	14	27	30	91
2014	4	4	12	12	22	22	20	20	12	12	30	30	100
2015	1	1	14	12	42	37	10	9	11	10	36	32	114
All	49	8	79	13	198	31	106	17	62	10	138	22	632

Between September 2009 and July 2017, the machine covered 160 work sites. In fact, the database contained 118 unique sites, because the same site could be visited more than once over the study period, even in the same year. One site was visited 15 times during the whole study period. More often, however, the same site would be visited two or three times. Repeat visits were due to the fact that plantations of different ages could be available on the same site, and they would be harvested in consecutive years. In other cases, logistical and/or organizational reasons may have dictated changing site before harvesting was completed and then coming back to it shortly after. Overall, permanence on a worksite averaged two work weeks and about 100 scheduled hours (Table 6).

Table 6. Worksite statistics (n = 160).

	Mean	Median	Lower Quartile	Upper Quartile
Days site^{-1}	11	9	7	15
SMH site^{-1}	102	85	60	144
Bundles site^{-1}	1390	1074	752	2029
L Diesel site^{-1}	1002	770	562	1442
ha site^{-1} (low est.)	25	20	14	37
ha site^{-1} (high est.)	13	10	7	18

Note: ha site^{-1}—low and high estimates are based on a harvest residue yield of, respectively, 15 and 30 t ha^{-1} [17].

A single site would yield approximately 1400 bundles, but the lower quartile was half that much: one could take this value as the minimum reasonable figure for effective operation, even though 5% of the sites yielded ≤150 bundles each. After 2011, the number of sites covered in a year increased, while the average permanence on site and the mean number of bundles yielded from each site decreased (Figure 5).

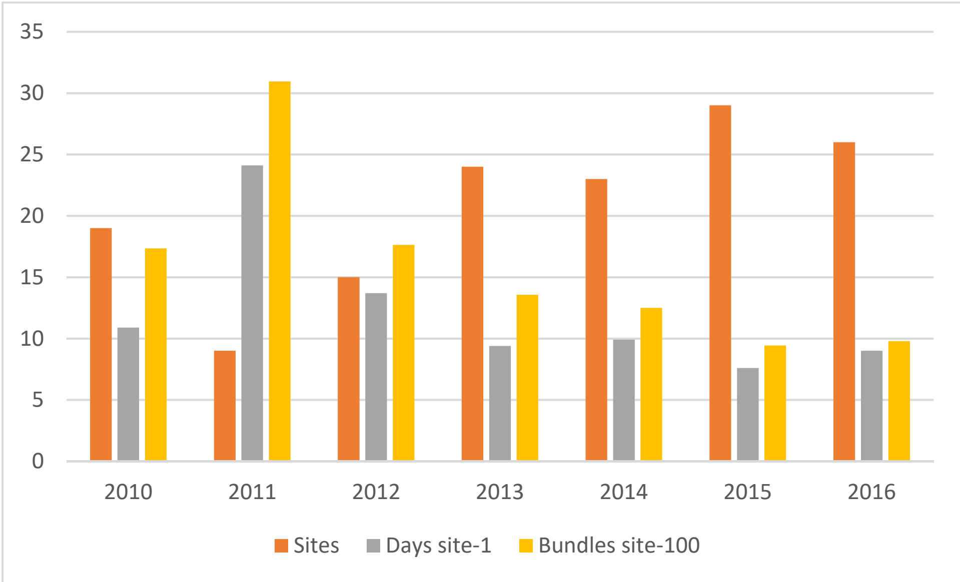


Figure 5. Main worksite statistics from 2010 to 2016.

4. Discussion

4.1. Study Limitations

Before elaborating on the important findings of this study, it is fair to point at its main limitations, so that results are interpreted correctly and with due caution. The first and obvious limitation is the exclusive reliance on company records, collected for purposes other than scientific investigation and with variable accuracy. In particular, company records may be flawed by omission, approximation, and transcription errors derived from rushed or incomplete compilation, and from the variable care and understanding of the multiple operators entering each individual daily log. That was the case of the delay event descriptions in 2016, which became abruptly scarce, compared with the same descriptions made in the previous years. Nevertheless, the sheer amount of data is likely enough for random errors to compensate—a notion that seems confirmed by the fundamental consistency of the figures extracted from the database. Flagrant inaccuracy would have been denounced by large variations in the database and by recurring outliers—neither of which was observed.

A further limitation of this study concerns bundle weight and bundle weight reconciliation. While the financial interest associated with meticulous accounting makes it unlikely that delivery records were less than accurate, ticket weights were not associated with moisture content records and therefore interpretation of these data was complicated by the variability introduced by the inevitable fluctuation in moisture content, due to seasonal variations and to the variable delays between bundling and delivery. Sanchez-Garcia et al. [13] do report very large moisture content variations for bundled eucalypt slash in Spain, and that warns us about cautious interpretation of the mass figures in this study—not because they are likely incorrect, but rather because they may reflect the inevitably large variability in moisture content that characterizes eucalypt slash. Operators estimate water mass fraction to be as high as 50% in winter with rainy weather, if the bales are processed and loaded out within a week from tree felling, or as low as 25% in the dry season, if the bales are left in the woods for two months [14]. As a general reference, however, one might adopt a moisture content between 30% and 35%, which was also used by Sanches-Garcia et al. [18] and best represents the effect of a generally dry climate and of the widespread practice of leaving eucalypt slash to dry at least 15–20 days before introducing the bundler [19]. This figure would also be consistent with user specifications [20]. In any case, dividing the total delivered mass by the total number of bundles, one obtains a mean bundle weight of 345 kg, which is fully within the range indicated in all previous studies, and very close to the mean figures offered by most of them (Table 7).

Table 7. Comparison with the results of previous studies of forwarder-mounted bundlers.

Study Reference	Duration (SMH)	Country	Species	Machine Model	Bundle Length (m)	Productivity Bundles PMH^{-1}	Productivity Bundles SMH^{-1}	Utilization %	Bundle Weight (kg)
[21]	7	Finland	Spruce	JD 1490	3.0	26	-	-	465
[15]	2952	Sweden	Spruce	JD 1490	3.0	28	22	78	-
[6]	78	Finland	Spruce	JD 1490	3.2	18	-	-	418
[21]	79	France	Poplar, pine	JD 1490	2.4–3.0	12–24	9–20	78	340–430
[12]	-	Germany	Mixwood	JD 1490	3.2	-	16	-	-
[11]	-	USA	Softwood	JD 1490	2.6–5.0	12–24	-	-	230–530
This study	16,308	Portugal	Eucalypt	JD 1490	2.4	20	14	70	345
[22]	36	Spain	Eucalypt	Monra	2.5	24	21	89	370
[13]	9	Spain	Eucalypt	JD 1490	2.6	25	21	87	470
[13]	53	Spain	Eucalypt	Monra	2.4	26	21	79	260
[10]	7	Australia	Eucalypt	Pinox	-	12–18	-	-	410–570
[9]	116	Chile	Eucalypt	Monra	2.5	22–26	19–22	84	250–310

Notes: SMH = scheduled machine hours, including delays; PMH = productive machine hours, excluding delays.

Concerning bundle mass reconciliation with bundling time data, the best thing would have been to conduct it on a site basis rather than a monthly basis. However, delivery records were made available on a monthly basis due to privacy reasons, and therefore reconciliation could only be made in that way. Therefore, it was inevitable that this operation suffered from the error caused by the time lag between bundling and delivery. That definitely excluded attempting reconciliation on a daily basis, and even the monthly basis adopted here was likely too short for the effective dampening of mass allocation errors. For that reason, monthly production figures and trends are best discussed in terms of bundles rather than tons—and that is what was done throughout the paper. If one wants to get an appreciation for the equivalent mass figures it may be best to simply convert bundle figures by multiplying with the average bundle weight. On the other hand, overall mass figures are most likely correct and can be taken at face value.

Finally, an obvious limitation of this study lies with the inclusion of one single machine. For that reason, readers must be warned about the risks of generalizing the findings of this study, especially if they wish to extend them to bundling machines that present widely different technical characteristics or mechanical conditions. On the other hand, the machine covered in the study was considered representative of the larger Iberian bundler fleet and belonged to the most popular type and model on the global market. Furthermore, the study machine was operated by several drivers along the course of the study. These were all professional operators with similar training and competence, but each must have had his own individual skills, abilities, and limitations. Therefore, the inclusion of multiple drivers allowed accounting for the random variability introduced by operator effect, which has a strong impact on the performance of all machines, including slash bundlers [16].

4.2. Comparison with Previous Studies

Despite the inevitable limitations described above, this study offers solid, reliable figures that are largely corroborated by the results reported in the existing scientific literature. Table 7 summarizes the results of previous studies conducted on forwarder-mounted bundlers, of the same model as covered in this study or similar ones. Table data are organized in two groups: studies conducted on eucalypt plantations (bottom half) and studies conducted on other stand types (top half). The results of this study are positioned in between to facilitate immediate matching.

There is general agreement among all main indicators, which corroborates the results of this study. Widespread consistency also suggests that a bundler is a bundler, and in relatively stable conditions it will perform approximately the same regardless of region and stand type.

There are, of course, differences in some important details, such as bundle length, which is generally shorter in eucalypt plantations (2.4–2.6 m vs. 3.0–3.2 m for the others). This reflects the common practice of crosscutting eucalypt stems into 2.4 m lengths for crosswise loading on forwarders and trucks. One of the main benefits of bundling is the full integration between roundwood and biomass supply chains [23], and therefore bundle length must match the dominant log length. In that specific regard, the bundle length comparison conducted in this study offers some interesting insights. Our results show that extending bundle length to 3 m may offer a productive advantage. However, eucalypt trees are generally processed to very thin log diameter specifications (<8 cm) and the resulting tops are too weak for building solid bundles if their length is further extended from the 2.4 m standard: longer bundles are not coherent enough and may fall apart during handling and transportation. That was also noted for other hardwood (i.e., oak sp.) slash in previous bundling studies [21].

The table also shows the large variability in bundle weight discussed just above. Even when limiting observation to Iberian eucalyptus, mean bundle weight ranges from 260 kg to 470 kg—and the mean value from this study falls right in the center at 345 kg.

Our figures only deviate from those in the table when it comes to utilization, which is markedly lower in this study than in all other quoted studies. Rather than a weakness, this might be one of the main strengths of this study, which covered a much longer period than all the others. Short-term studies generally fail to account for all downtime and tend to overestimate utilization [24]. If so, the multi-year span that characterizes this database is likely to guarantee superior accuracy: a good appraisal of long-term bundler utilization might be one of the major contributions offered by this study.

4.3. Specific Considerations

The accuracy of our utilization estimates might be further confirmed by the capacity of this study to detect their seasonal and multi-annual trends, both of which follow reasonable trajectories. There is no need to elaborate here on seasonal trends that have already been discussed when the data were first presented, except for a short note on the obvious fact that these trends are specific to the climatic and social conditions in the study region. Since they are connected to the alternance of dry and wet periods, and to festivities that belong to tradition, one may not expect these trends to automatically repeat in other climatic regions or cultures. Therefore, adoption of the forecasting models in Table 4 must be done with some caution. In turn, the multi-annual declining trend in utilization, use, and production might depend on a number of reasons, besides machine wear. In particular, one may surmise a worsening of external work conditions, including the steady reduction of parcel size and the parallel increase of relocation frequency recorded in the study. Similarly, it is possible that economic conditions became more challenging over time and that decreasing quotas and/or bundle prices were a component cause for declining utilization. Nevertheless, the long-term decline in utilization is moderate: the model estimates it at seven percentage points in 6 years, i.e., slightly more than one percentage point per year. The very same considerations are valid for work hours and production, which present similar declining trends.

If at all, one may wonder about the role of learning, which should have caused all main performance indicators to improve rather than decline [16,25]. One possible explanation is that the mechanical and/or economic challenges were stronger than learning could compensate for, and therefore the resulting tendency was downward, though mitigated by the effect of learning. The other explanation is that the study began when the machine had already clocked over 3000 h, by which time the steepest ramp of the learning curve was already in the past.

Closely connected to utilization is downtime, which our study probed in terms of recorded event frequency. The analysis showed at least three very interesting trends. First, the frequency of delay events attributed to failures in the electronic system decreased very sharply after the first two years of observation, when the original Timbermatic T-900 measurement and control system was replaced with a simpler TMC monitor (EPEC): the latter transmits less information to the operator, but is much faster at startup and, above all, it is much more reliable.

Conversely, the frequency of operational delays (reconnaissance, relocation, interference, etc.) increased steadily over time, which may support the hypothesis of increasingly challenging work conditions such as the reducing parcel size and the resulting increase of relocation frequency. Finally, the fact that the number of events attributed to the bundling unit is over twice as large as that attributed to the base machine or to the loader highlights the very different degree of technical maturity between the three equipment types. Obviously, the base machine and the loader are much more mature and are built in immensely larger numbers than the bundling unit, which can still be improved to a much larger degree than the other two. In that regard, it is interesting to note that over half of the delay events attributed to the bundling unit are specifically associated with the compacting system, which suffered from several types of hydraulic and mechanical malfunctions. Previous studies attribute a high frequency of malfunctions to the older chainsaw-type cutting system [21] and point at its replacement with a shear system to alleviate such problems [13]. This study may indicate that fitting a shear system in place of the older chainsaw actually achieves the intended result—as far as these are limited to reducing downtime and do not include extending work capacity to contaminated material: if it is true that a shear can handle contaminated slash, it is also true that the dirt eventually packed with the slash bundles will cause problems downstream along the chain, in terms of increased chipper maintenance and high ash content. Dirt must therefore be shaken off the slash before bundling, whenever present.

Finally, a short comment on annual usage. It is interesting to stress that a very high annual use (over 2000 SMH year^{-1}) was consistently achieved without double-shifting—which is not a popular practice in Southern European forestry [26]. Neither was shift length overly long, seldom exceeding 10 SMH day^{-1}, which is a rather common shift length for specialized biomass machinery in Southern Europe [27]. In contrast, high utilization was achieved by a keeping a steady work pace and avoiding prolonged interruptions, even in the face of unfavorable seasonal conditions. This was made possible by the industrial character of the Iberian eucalypt business and the good mobility of the bundler model covered in this study. Otherwise, work could have been halted by strong seasonal fluctuations of product demand or by the inability of the machine to cope with adverse site or weather conditions. Since that was not the case, maintaining a high usage level was possible without suffering the drawbacks typical of shiftwork [28].

4.4. General Considerations

Coming from the technical to a more general level, this study also offers valuable insights. First, it confirms the capacity of properly conducted short-term time studies (few days) to accurately reflect productivity levels, given that the output figures obtained from this long-term study closely match those reported in several short-term studies of the same machine type under the same conditions. That is the fundamental assumption about time studies, which has seldom received the independent scientific confirmation finally offered here. At the same time, this study also confirms the main limitation of short-term time studies: their tendency to significantly overestimate utilization [24].

Furthermore, the study suggests a direct relationship between lot size and utilization—which is indeed a reasonable assumption. If that is true, then the tendency to place legal restrictions on clearcut size [29] will have an impact on machine utilization and overall performance, which must be considered in all supply chain costing exercises.

Finally, the original question of this study: what makes bundling thrive in Iberia, after it was outcompeted almost everywhere else—at least for now? Certainly not its production capacity, because none of the Iberian studies points at a productive advantage, but they all report similar productivity figures to those found in studies conducted elsewhere, whether short- or long-term. The same can be said for annual usage, which is higher in Iberia than in the Alps [16] but equal or slightly smaller than in Nordic Europe, where bundling has also been largely discontinued. Thus, the supposedly higher usage level allowed by industrial plantation forestry is unlikely to be a factor.

If higher productivity and/or usage are excluded, then the explanation must reside with some other advantages that are most often associated with bundling [30]. First of all, most of the biomass produced in Iberia supplies large power plants that favor centralized chipping, for its superior cost-efficiency. At the same time, delivery to a large, centralized facility implies relatively long transportation distances, which excludes moving loose slash. In such circumstances, bundling makes much sense, and it also represents the industrial option that requires the lowest capital commitment at the harvest end of the chain [31]. Once a bundler is acquired, there is no need to buy a chipper and a dedicated chip transportation fleet: slash is converted into "composite residue logs" and moved around with the same extraction and transportation equipment used for conventional roundwood (which also explains the 2.4 m bundle length). Therefore, bundling might be favored by industry structure, with a strong emphasis on the receiving plant side and a much smaller investment on the supply side.

Apart from this, the specific conditions of Iberian eucalypt plantations may also play a role in determining the success of bundlers. In particular, plantation management requires quick removal of the biomass to facilitate resprouting or recultivation, while the sites offer relatively little space for stocking the biomass. Even where storage space is available, the high wildfire hazard prevents the building of large piles as well as extended roadside storage—regardless of quantity. Bundling allows packing more biomass in the same landing space and loading it on any available log truck, which facilitates logistics.

Bundling might also be favored by another typical characteristic of Iberian eucalypt plantations: their low residue yield. This has been estimated at 15–30 t ha^{-1} [30], which is almost half as much as reported for some of other common stand types [32]. Low residue loads are likely the result of a very intense stand utilization aimed at maximizing pulpwood yield, so that as little as possible is left on the cutover. Forwarder productivity is strongly affected by biomass concentration [19,33] and its scarcity greatly expands loading time. Introducing a bundler allows concentrating loads and may dramatically boost forwarder productivity at little additional own cost, because the bundler can move to reach its next grapple load while the compactor is still processing the previous one. If the biomass were already concentrated, the driver would need to stay idle and wait for the compactor to digest a grapple load before introducing the next one—little time is gained by concentrating the slash for the forwarder-mounted bundle, and little is lost if some distance must be covered by the bundler to reach relatively sparse slash.

In any case, the success of bundling—and that of logging residue collection in general—depends on the careful management of the harvesting operation as a whole. In particular, close cooperation must be achieved between the teams engaged with roundwood processing and the bundling team: the former must arrange the residue in clean organized piles for the latter to operate efficiently.

5. Conclusions

Spanning over 7 years, this study offers authoritative corroboration to most of the figures reported in earlier short-term studies. It shows that the work conditions found in Iberian eucalypt plantations do not result in any significant increase of machine productivity, usage, or utilization. One may speculate on the reasons why bundling technology has affirmed itself under those conditions, while failing elsewhere. A most likely candidate is the industrial character of both eucalypt farming and bioenergy generation in Portugal and Spain, which allows for the reaping of all integration benefits offered by bundling, while the cost of setting up a parallel biomass chain is minimized. Furthermore, bundling seems the ideal technique for efficient residue recovery where slash yields are low and roadside storage space is limited. These conditions are common to many eucalypt plantations worldwide: in that sense, Iberia is not just the "Galapagos of Bundling" where we can observe an otherwise extinct species, but rather the place where bundling has shown its true potential, for eventual replication wherever the same conditions are met.

Author Contributions: Conceptualization, J.P.M., A.A. and R.S.; methodology, software and validation, R.S., N.M. and M.M.; formal analysis and data curation, R.S., M.M. and A.A.; writing—original draft preparation, R.S. and N.M.; writing—review and editing, All Authors; supervision, A.A.; funding acquisition, A.A. and M.M. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Italian Ministry of Agricultural, Food and Forestry Policies (MiPAAF), AGROENER project (Decree n. 26329, 1 April 2016). http://agroener.crea.gov.it/. Additional support was provided by the Pahernik foundation—University of Ljubljana. https://www.uni-lj.si/news/news/6498/.

Acknowledgments: The Authors acknowledge the support of J. L. Carvalho (The Navigator Company, Lisboa, Portugal) in making the contacts and encouraging the team to conduct a study on the subject of bundling.

Conflicts of Interest: The authors declare no conflict of interest.

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