Biomass Recovery from Spanish pine plantations mechanized thinnings residues. Effects of biomass piling methods and top diameters.

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Abstract:
The goals of the new RES policy in Spain mean a very strong increase in the use of agricultural and forest biomass ($5.5 \cdot 10^6$ tonnes·y^{-1} from present to 2020). One of the focussed forest resources have been the almost 5 million hectares of conifer plantations needing thinnings, that traditionally have produced only pulpwood, mostly by fully mechanized logging methods. A time-study of timber harvesting and logging residues recovery in a Pinus spp. mixed planted stand located over a gentle terrain in central Spain has been designed. The first explanatory factor selected has been the way of piling the branches and tops, using the forest harvester to bunch them along the striproad sides while processing the timber or leaving them on the striproad centre and using a 175 HP bulldozer with a raking implement to pile them up afterwards. The second factor considered was the top diameter, being 8 and 10 cm the compared values. These working methods were followed by the timber and biomass hauling off with forest forwarders, and the biomass processing at landing using a self-propelled shredder machine. The productivity of timber harvesting was larger when leaving the biomass on the striproad centre and when felling and processing until the smaller top diameter. Biomass hauling off was significantly more productive when it was pilled by the bulldozer. The unit cost of biomass recovery ranged from 29.7 € to 31.5 € per green tonne (at 51% of moisture over humid weight). In addition, the timber and biomass yield – per hectare - in each case was measured, and also the recovery efficiency, that was always very high. A global cost balance for only timber harvesting or combined logging with biomass recovery was performed, based in the net income per hectare for every studied case. Considering the present (2009) market prices in Spain, timber and biomass harvesting – recovering residual biomass – was economically preferable to timber harvesting only for these delayed thinning operations on gentle terrain.

Keywords: Pinus plantations, Residual forest biomass, Harvesting techniques, Work study, Spain

1 Introduction

In Spain, Renewable Energies (REs) contributed to a 9.4% of primary energy consumption in 2009, being the goal for 2020 a share of 20.1%, after the new PANER (REs National Action Plan 2011-2020, IDAE 2010). REs had a share of the Spanish electricity production in 2009 of 24%, being the objective for 2020 to reach a 36% contribution. Biomass and biogas are supposed to grow up at a yearly rate between 7 and 13% from 2009 to 2020. The energy use of forest and agricultural products or residues, besides woody crops, are supposed to reach an additional consumption of $5{,}5 \cdot 10^6$ tonnes·$year^{-1}$, as a result of the correspondent fostering measures This aims would require huge efforts to mobilize every biomass sources, particularly woody biomass.

The total afforested or reforested area during the period 1940–1984 was 3.383.291 ha (Gómez and Mata, 1993). After Valbuena-Carabaña *et al.* (2010), the conifer afforested or reforested surface in Spain during the dictatorship of General Franco (1940–1975), the democratic period before the competences transfer to the Regional Governments (1976–1982) and the Autonomic period previous to the Common Agricultural Policy (1983–1993) reached a surface of $2.937 \cdot 10^3$ hectares, while the afforested surface on marginal agricultural lands - funded by the European Common Agricultural Policy - from 1994 to 2008 reached $657 \cdot 10^3$ hectares (both conifer and broadleaves, data from 2003 and 2004 are missing). Still in this last period, accordingly to the same official source (MMARM, 2011), the additional plantations on forest lands reached 746 $\cdot 10^3$ hectares afforested and $173 \cdot 10^3$ hectares reforested, the last frequently on surfaces affected by forest fires. These data also comprise both conifers and hardwoods, and the figures from 2003 and 2004 are missing as well.

As a result, if *Pinus pinaster* and *P. radiata* plantations on private lands are summed up, almost 5 million hectares of the Spanish forest land are covered with conifer plantations. Although a considerable proportion of the public surface corresponds to protective stands where the management intensity is very low, there is a huge potential for biomass production from early thinnings. These commonly delayed treatments produce a considerable part of the pulpwood consumed in Spain, but the potential production is very high if compared to the present extractions. A new market that would increase forest biomass demand would be a chance for developing new forest management systems or recovering traditional ones using new technologies and/or work systems.

Whole Tree System (WTS) is widely used for harvesting biomass from small trees coming from selective thinning, mainly using multi-tree harvesters followed by forwarders both in Nordic countries (Ala-Fossi 2005; Kallio & Leinonen 2005; Kärhä 2007) and North America (Adebayo *et al*. 2007). In Southern European countries, there are some references about WTS applied to plantation thinnings (Laina *et al*, 2008; Spinelli & Nati, 2009; Canga *et al*., 2009 a & b; Tolosana, 2009). As a conclusion, WTS in thinnings can be cost effective to supply biomass for energy when the whole tree is chipped, but its profitability is strongly dbh-dependant, so biomass use would strongly compete with pulpwood harvesting.

Another possible option is the harvesting of residual biomass after the thinning operation has been performed. In general, profitability of residual biomass collection is strongly conditioned by the integration between timber and biomass harvesting systems – residuals must remain bunched in piles or strips, and as clean as possible, what is easier if felling and processing are fully mechanized -, by the residuals weight per hectare – the greater amount of residuals, the better – and by the size of the branches and tops – the greater size, the better (Spinelli, 2007; Tolosana, 2009).

In the case of early thinnings, even when they were strongly delayed, these factors can hardly make profitable the residuals harvesting for biomass. Nevertheless, there are some reasons that can make interesting this work method, significantly the interest on avoiding the competence among pulpwood and biomass as final wood uses.

In the case of mechanized thinnings, the main factors affecting residuals harvesting productivity and cost could be the way of residuals bunching and the residuals size and amount per hectare, closely related to the top diameter used for the mechanized crosscutting.

This study has then two principal aims:

- Developing a methodology for comparing logging work systems when different yields of various products impede to compare productivities or unit costs. As an example of application, a case-study of mixed shredded biomass and roundwood has been analyzed, studying their profitability related to two factors: biomass bunching method and top diameter.
- Comparing two methods of bunching the biomass, using the harvesting head to leave the residuals stripped along the strip road sides (method S) or leaving the residuals on the strip road center, as it is most common in mechanized cut-to-length harvesting system – CTL -, and using afterwards a medium sized bulldozer to pile the residuals on bunches (method C), before their extraction using a forest forwarder.
- Comparing two top diameters used by the harvesting head to separate tops from wood logs, 8 cm (Ø8) and 10 cm (Ø10).

2 Material and Methods

2.1 Dasometric characterization

A mixed artificial stand containing *Pinus sylvestris*, *P. nigra* and *P. Pinaster* on a plain to slightly sloped terrain was selected in *Castilla y Leon* Region. 18 permanent circular plots with 10 m radius were measured (every dbhs and a sample of heights) before and after thinning, in order to characterize the silvicultural treatment. Initial stand average dbh was 19.8 cm, being the correspondent basal area 42.5 $m^2 \cdot ha^{-1}$. After the thinning, 470 out of the initial 1,251 trees·ha^{-1} were removed, representing a 37.6% of the initial tree number and a 23.8 % of the initial basal area. The share of the removals among the diameter classes reflects the thinning "from below" type, as represented in Fig.1.

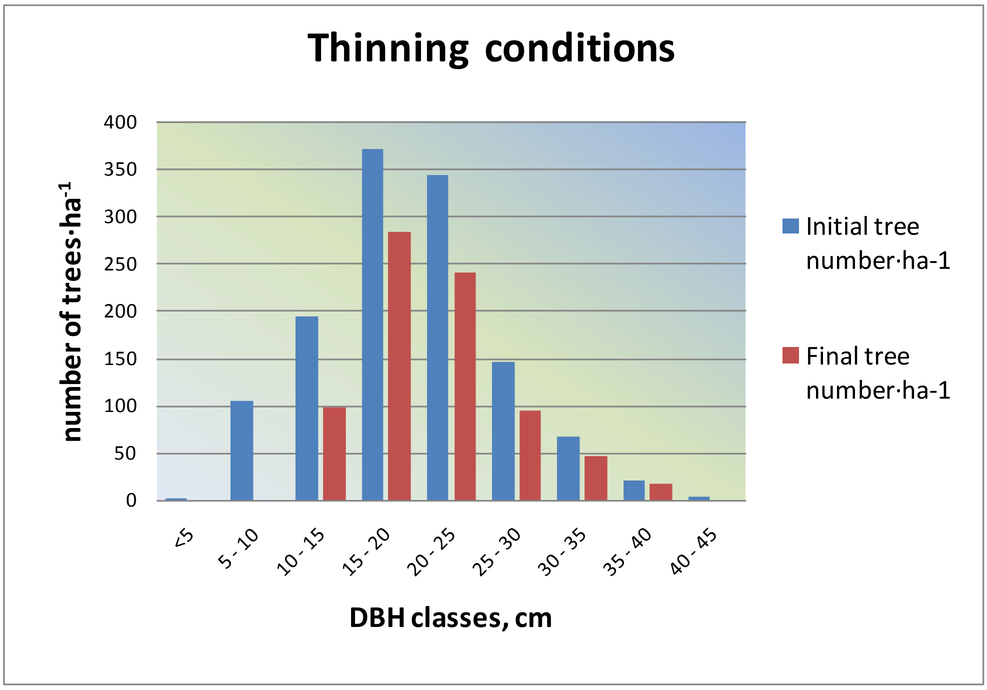

Figure 1: Thinning average intensity

2.2 Logging systems and machinery

The harvesting method was always a fully mechanized Cut-to-Length (CTL) system. Roundwood destination was a particleboard factory, a fencing poles fabrication unit and a sawmill for packaging. Branches and tops were crushed for energy use. In the Table 1, the main characteristics of the used machinery are summarized.

In the harvested area, strip roads were opened following the maximum inclination when terrain was undulated, and with a separation of 17.5 m between them.

Table 1: Utilized machinery

Operation	Machine type - mark / model		Power (kW)	Payload/other features
Felling - Processing	Forest harvester	Timberjack 1270 C	160	----
		John Deere 1270 D	160	----
Timber hauling-off	Forest forwarder	Dingo 6x6	89	16 m^3
Biomass hauling-off	Forest forwarder	Timberjack 1410 D	129	17 m^3
Biomass bunching (System C)	Bulldozer	Fiat-Hitachi fd 175	140	Raking front implement
Crushing	Schredder	Hammel VB 950	522	

2.3 Time and productivity study

Work operations were divided into work phases, in order to study the work distribution in each case. For the work elements classification, IUFRO standards were adopted (Bhöjerden & Thompson, 2000) following the table formats developed by the European Concerted Action AIR3-CT94-2097 (De Menthiere, 1995).

The time-study methods were different depending on the task type: for wood and biomass forwarding, the continuous control method was the procedure adopted, using a Psion Workabout® hand-held computer with the purpose-designed software Kronos 3.0® (Ambrosio & Tolosana, 2007). In case the operations were not cyclical – for example, biomass bunching by bulldozer or biomass shredding - and in the felling and processing case, the "stopwatching" method was chosen: the controller registered, when a chronometer beeped, the work phase performed. In this case, intervals of one hour were defined, and the treated surface and/or the volume or weigh extracted were measured, treating each controlled hour as a "treatment repetition" for each combination of harvesting method x top diameter.

The controlled time for each operation is shown in Table 2.

Table 2: Controlled time for the different harvesting operations

Operation	Control method	Attendance controlled time (hours)	Attendance controlled time (work days)
Felling - Processing	Discontinuous (stopwatch)	94	7
Timber hauling-off	Continuous	30	3
Biomass hauling-off	Continuous	33	4
Biomass bunching (System C)	Discontinuous (stopwatch)	17	2
Crushing	Discontinuous (stopwatch)	18	3

The surfaces corresponding to the four work methods and top diameters were marked and the treated surface was control by GPS each controlled day, this allowed the production control from the different treatment combinations. The productivity control was performed in different ways depending on the operation: if it dealt with logs, they were counted and a sample on each stratum was measured; if it had to do with tractor loads, their number was registered, and either the number of loads or the bulk biomass volume of each load was measured.

In every studied combination, the biomass percentage left on the terrain was measured, by weighing the biomass left in several 2x2 m^2 square plots in each stratum.

Bulk density and moisture of the different raw biomass and shredded material were sampled and measured by weighing the net content of recipients of known volume. Subsamples of biomass were oven dried to determine moisture content.

2.4 Costs and income estimation, treatment comparison

Machines and operators hourly costs were estimated using classical methods (Miyata, 1981). Once work time is defined as the common basis for calculations, hourly cost and productivity have been expressed regarding to work time. It allows estimating the direct unit cost on a production basis (timber o.b. m^3, biomass green tonne). Transport costs were estimated as 12.7 €·green $tonne^{-1}$ for shredded biomass and 9.0 €·green $tonne^{-1}$ for timber, corresponding to the good access conditions and short transport distances to the mills (30 km).

As long as the wood harvesting efficiency and cost may be affected for the elementary operations performed to manage the residuals, and the biomass production depends on the residuals collection efficiency, possibly affected by the bunching method as well, the direct productivity or unit cost comparison among work methods were not easy.

Furthermore, top diameters also affect to the pulpwood and biomass productions and also to the collection efficiency or productivity of both products, so the direct productivity or unit cost comparison was neither easy for this factor.

Besides, both products have different market prices, so the comparison among the different combinations of both factors has been based on a methodology based upon the comparison of the global cash-flow balance – considering incomes and expenses under the present Spanish market scenario, on a *per hectare* basis.

As they were neutral to the final balance, no stumpage price was considered for timber or biomass, while a 15% of indirect and fixed cost plus a 12.5 % of contractor profits were added to the direct estimated costs.

3 Results

3.1 Biomass and wood production

The biomass and wood production for the different treatments top diameters were significantly different: greater top diameter (Ø10) resulted in 33.2 o.b. $m^3 \cdot ha^{-1}$ of roundwood and 32.6 green tones of branches and tops·ha^{-1}. The treatments with smaller top diameter (Ø8) yielded 42.1 o.b. $m^3 \cdot ha^{-1}$ of round wood and 18.6 green tones of branches and tops·ha^{-1}. The green weight corresponds to the average moisture content of 51.3 % (humid basis).

The differences among treatments regarding the residuals amount left on the terrain were not statistically significant, being the average reduced (925 kg·ha^{-1}, equivalent to a 3.9% of the biomass average removal).

3.2 Time and productivity analysis

Felling and processing

As an average for every treatment, direct productive time accounted for 59.3% of attendance time. The longest productive operations were felling and processing, both reached the 44.4% of attendance time, while average biomass management accounted for 7.0% of attendance time. Indirect productive time was 19.8% of attendance time, while not productive time reached 20.8%, because of the long time needed for workers' lunch out of the work site.

The time invested in branches and tops management was significantly different among the alternatives C and S. If the residues were left, as usual, in the strip road center (method C) this operation accounted for a 5.6% of total attendance time, while the figure reached the 10.6 value if the residual biomass was bunched along the strip road sides (method S) using the harvesting head.

When the combinations of top diameters and working methods were compared, the results obtained are shown in Figure 2 and Table 3: On the one hand, the felling and processing productivity in roundwood m^3·productive h^{-1}, of the Method S (strip road side piling of branches and tops using the harvesting head) was always less than the productivity of the strip road center piling of biomass (Method C) with statistically significant differences. On the other hand, the felling and processing productivity in rounwood m^3·productive h^{-1} was greater for the Ø8 top diameter than for the Ø10 alternative, also with statistically significant differences at 95% level. So the most productive processing option was CØ8, while the less productive one was SØ10.

No statistically significant differences were found among areas with different slopes, from plain terrain (0%) to undulate terrain (10.5%).

Table 3: Multiple Range Tests for Roundwood Productivity (Felling&Processing), m^3•productive $hour^{-1}$ by Combination of Biomass Piling Method (S/C) x Top Ø, cm

Biomass Work Method (S/C)x Top Ø, cm	Count	Mean	Homogeneous Groups			
S_Ø10	30	8.32	X			
S_Ø8	12	10.70		X		
C_Ø10	16	12.66			X	
C_Ø8	52	16.44				X
Contrast	Difference		+/- Limits			
C_Ø10 - C_Ø8	* - 3,77785		1,05033			
C_Ø10 - S_Ø10	* 4,34144		1,24225			
C_Ø10 - S_Ø8	* 1,96245		1,76158			
C_Ø8 - S_Ø10	* 8,11929		1,28061			
C_Ø8 - S_Ø8	* 5,7403		1,78883			
S_Ø10 - S_Ø8	* - 2,37899		1,90785			
Method: 95,0 percent LSD (* denotes a statistically significant difference).						

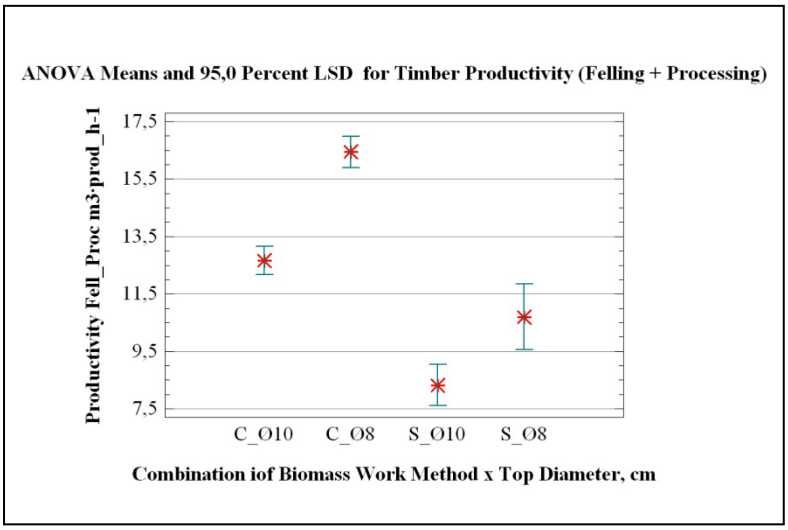

Figure 2: Roundwood productivity of felling and processing vs. combination of Biomass Piling Method (C/S) x Top Diameter, cm

Wood forwarding

Direct productive time rate was high (78.3% of attendance time), even when not productive time accounted for 14%, because of the time consumption in having lunch out of the work site. Loading operation was the longest one (35% of attendance time), followed by off-road transport (27%).

Average productivity was 14.9 m^3·attendance $hour^{-1}$ (17.6 per work site hour and 19.0 per productive hour).

The ANOVA applied to the loading times showed statistically significant differences between the undulate and the plain type of terrain, so different regression lines were tried to fit for the productive cycle time in plain and undulate terrain. The correspondent equations were [1] for plain terrain (p=0%) and [2] for undulate terrain (p=10.5%)

Productive Time (s·$cycle^{-1}$) = -69.25 + 1.41·LoadingDist + 62.23·NrGripLoads + 1.29·2:HaulingDist [1]

Where LoadingDist is the strip road length in which the forwarding is being loaded, in m; NrGripLoads is the number of wood grips needed to complete the load on each cycle, and HaulingDist, m, is the average distance driven during the off-road transport, half the whole empty and loaded distance driven through the strip roads. Statistics of the fitting showed an adjusted R^2 = 79% and an average absolute error = 221 s·$cycle^{-1}$.

Productive Time (s·$cycle^{-1}$) = 348.25 + 1.82·LoadingDist + 44.52·NrGripLoads + 1.73·2·HaulingDist [2]

Where all the variables have the same meaning and units that in [1], while the adjusted R^2 was 94% and the average absolute error was 123.5 s·$cycle^{-1}$.

These equations were converted into work site time functions through the ratio work site time to productive time, and then converted into productivity equations using the payload of the forwarders as an additional variable, and then simplified using the formula [3] and substituting the variable NrGripLoads by its average value, 32,4 grip loads·$cycle^{-1}$, after studying its short variation range along the sampled cycles.

LoadingDist(m) = Payload(m^3)/[WoodRemoval(m^3·ha^{-1})·StripRoadSeparation(m)·10^{-4}]=P/(R·S·10^{-4}) [3]

So the productive time equations [1] and [2] were transformed in the productivity equations [4] and [5], respectively for plain and undulate terrain.

$$Prod(m^3 \cdot workhour^{-1})=[3{,}600 \cdot P(m^3)]/\{1{,}944.5+1.52 \cdot P(m^3)/[R(m^3 \cdot ha^{-1}) \cdot S(m) \cdot 10^{-4}]+1.39 \cdot 2 \cdot HaulingDist\} \quad [4]$$

$$Prod(m^3 \cdot workhour^{-1})=[3{,}600 \cdot P(m^3)]/\{1{,}788.9+1.97 \cdot P(m^3)/[R(m^3 \cdot ha^{-1}) \cdot S(m) \cdot 10^{-4}]+1.87 \cdot 2 \cdot HaulingDist\} \quad [5]$$

Branches and tops bunching using bulldozer

In the biomass management method "C" (where branches and tops were left on the strip road center after the round wood processing with the harvesting head), a bulldozer was used to bunch the residual biomass. After time study, the data obtained from the stopwatching control method and the production control on the bunches density and loose volume, no statistically significant differences were found between the productivity in plain or undulate terrain, or between the productivity where the top diameter was 10 cm or 8 cm.

Therefore, the average productivity was adopted as the reference, being its value 28.63 green tonnes·E_0 hour^{-1}. Density of bulldozed residuals was 149 kg·loose m^{-3} – in front of 124 when piled by the harvesting head - and the moisture content was the same in both cases, 53.1% over humid basis.

Branches and tops biomass forwarding

Productive work time accounted for a 81.2% of attendance time, very close to the figure from round wood forwarding. No significant differences were found between the plain and undulate terrain in this case, but, when analyzing productive times, loading and unloading times were significantly different between the residuals management methods C (branches and tops left on the strip roads center and bulldozed afterwards) and S (branches and tops left along the strip roads sides using the harvesting head).

In both cases, the productive times were significantly shorter for the method "C", because of the bigger degree of biomass concentration and greater biomass density after its bulldozing.

Because of this reason, fitting different time equations for both methods was decided, and the difference between regression lines test confirmed the decision was right. The two obtained equations were [6] and [7], correspondent respectively to the methods S and C.

$$Productive\ Time\ (s \cdot cycle^{-1}) = 1{,}023.9 + 8.92 \cdot LoadingDist + 0.93 \cdot 2 \cdot HaulingDist \quad [6]$$

Where LoadingDist is the strip road length in which the forwarding is being loaded, in m, and HaulingDist, m, is the average distance driven during the off-road transport, half the whole empty and loaded distance driven through the strip roads. Fitted equation showed an adjusted R^2 = 89% and an average absolute error = 58.2 s·cycle^{-1}.

$$Productive\ Time\ (s \cdot cycle^{-1}) = 771.9 + 4.48 \cdot LoadingDist + 2.67 \cdot 2 \cdot HaulingDist \quad [7]$$

Where all the variables have the same meaning and units that in [6], while the adjusted R^2 was 78.5% and the average absolute error was 205.0 s·cycle^{-1}.

After transformation of variables and simplification very similar to the roundwood forwarding equations case, the following productivity equations, [8] and [9] were obtained for the biomass management methods S and C.

$$Prod(t \cdot E_0hour^{-1})=[3{,}600 \cdot BP(t)]/\{1{,}095.6+9.5 \cdot BP(t)/[BR(t \cdot ha^{-1}) \cdot S(m) \cdot 10^{-4}]+0.99 \cdot 2 \cdot HaulingDist\} \quad [8]$$

$$Prod(t \cdot E_0hour^{-1})=[3{,}600 \cdot BP(t)]/\{771{,}9+4.48 \cdot BP(t)/[BR(t \cdot ha^{-1}) \cdot S(m) \cdot 10^{-4}]+2.67 \cdot 2 \cdot HaulingDist\} \quad [9]$$

Where all the variables and units are similar to the used for the roundwood forwarding case, except t (green tones), that are the units chosen to evaluate the biomass forwarding productivity, the biomass payload BP and the biomass removals BR. The payload is one of the most important factors; roughly a green tonne of payload increment implies a green tonne per E_0 hour of productivity increment. In the Figure 3, the influence of biomass removals and hauling distance are shown for both methods.

Biomass shredding

Biomass shredding productivity was time-studied, and the average value was 140.4 loose $m^3 \cdot E_0$ $hour^{-1}$, equivalente to 36.51 green tonnes·E_0 $hour^{-1}$. The most remarkable result of the time analysis was the high percentage of machine stops because of the extra heating.

No statistically significant differences were found between the shredding of biomass coming from the different top diameters areas or from the different biomass management studied systems. Average shredded biomass density was 260 kg·loose m^{-3}, while moisture content was 51.3 % (humid basis).

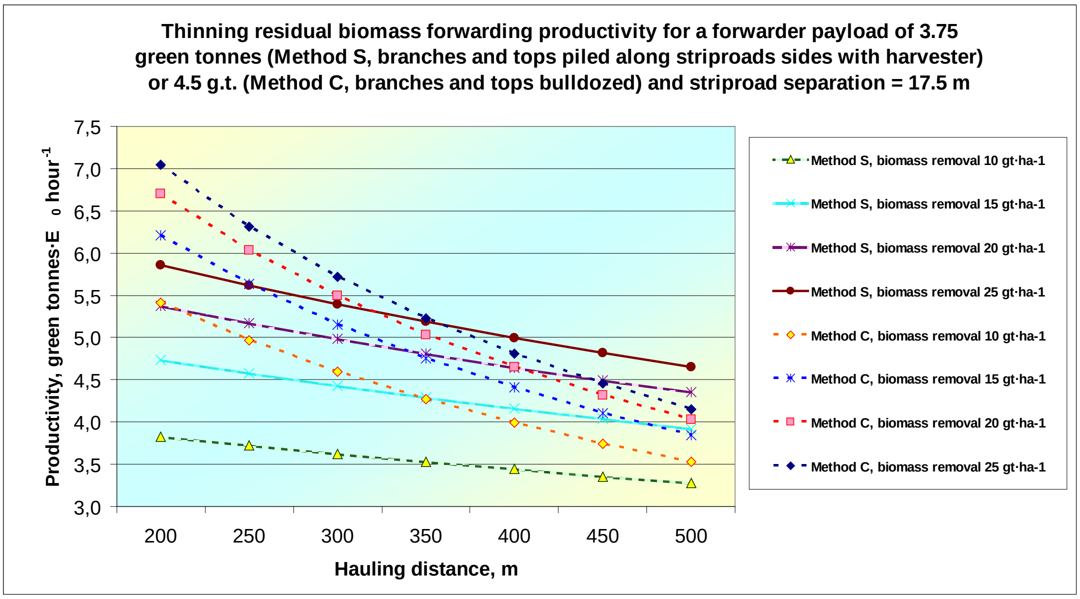

Figure 3: Biomass forwarding productivity in front of hauling distances, biomass removals and biomass management method.

3.3 Cost estimation.

The estimated hourly costs estimated for the different machines used in the trials have been estimated, on the basis on the registered data about prices, fuel and oils consumption, etc. during the study (2009, September and October) and are presented in the Table 4.

Table 4: Estimated machinery hourly costs

Machine	Hourly cost (€·E_0 hour^{-1})
Forest harvester	66.15
Forwarder (timber hauling off)	45.17
Forwarder (biomass hauling off)	52.85
Bulldozer	37.99
Shredder	122.01

The average productivity and unit direct costs of every operation, both regarding roundwood and biomass, are presented in Table 5 for every studied alternative - combination of Biomass management method (S/C) x Top diameter (Ø8/Ø10) -.

Table 5: Productivities (roundwood o.b. m^3·E_0h^{-1} or biomass green tonnes ·E_0h^{-1}) and unit direct costs (€·m^{-3} or €·green tonne^{-1}) of roundwood and biomass harvesting for the studied alternatives

		Alternative (Biomass Management method x Top Diameter)							
		SØ10		SØ8		CØ10		CØ8	
Product	**Operation**	**Prod, m^3·E_0h^{-1}**	**Unit cost, €·m^{-3}**	**Prod, m^3·E_0h^{-1}**	**Unit cost, €·m^{-3}**	**Prod, m^3·E_0h^{-1}**	**Unit cost, €·m^{-3}**	**Prod, m^3·E_0h^{-1}**	**Unit cost, €·m^{-3}**
Round wood	**Felling & Processing**	3.93	16.83	5.42	12.20	7.61	8.69	9.77	6.77
	Forwarding	17.58	2.57	17.58	2.57	17.58	2.57	17.58	2.57
	Transport	------	9.00	------	9.00	------	9.00	------	9.00
	TOTAL	------	28.40	------	23.77	------	20.26	------	18.34
Product	**Operation**	**Prod, t·E_0h^{-1}**	**Unit cost, €· t^{-1}**	**Prod, t·E_0h^{-1}**	**Unit cost, €· t^{-1}**	**Prod, t·E_0h^{-1}**	**Unit cost, €· t^{-1}**	**Prod, t·E_0h^{-1}**	**Unit cost, €·t^{-1}**
Shredded biomass	**Bunching w/bulldozer**	------	-----	------	------	28.63	1.33	28.63	1.33
	Forwarding	4.71	11.22	4.71	11.22	6.22	8.50	6.22	8.50
	Shredding	36.51	3.35	36.51	3.35	36.51	3.35	36.51	3.35
	Transport	------	12.70	------	12.70	------	12.70	------	12.70
	TOTAL	------	27.27	------	27.27	------	25.88	------	25.88

To compare these costs on a common basis, the production of roundwood and biomass corresponding to each alternative must be considered. This permits to estimate the *per hectare* cost of each studied method and, if the prices of the different products are known, the *per hectare* incomes can also be estimated, so it is possible the economic comparison among the studied alternative on the basis of the *per hectare* balance.

The unit costs in Table 5 have been increased in a 15% to have into account the indirect and relocation costs, and in an additional 12.5% as an estimate profit percentage for the contractor who performs the harvesting operations. In the final balance, the stumpage price for the extracted roundwood and biomass has not been considered, because it should be constant for the different work systems, as long as the result of the silvicultural operation is the same for the forest owner.

The considered prices for roundwood depend on the final use: if it were particleboard, the market price in Spain in the considered moment was 30 €/green tonne, being the average price 50 €/green tonne when the destination is poles and sawnwood for packaging. Basing on the wood destination in the studied site, for the top diameter of 10 cm, the roundwood percentage utilized for particleboard has been estimated in 40%. The additional roundwood obtained when the top diameter is 8 cm has also particleboard as destination. The shredded biomass price has been estimated as 42 €/green tonne.

The *per hectare* balance is presented in Table 6.

Table 6: Costs, incomes and per hectare balance for each studied work method.

		Alternative (Biomass Management method x Top Diameter)			
		SØ10	**SØ8**	**CØ10**	**CØ8**
Production ($m^3 \cdot ha^{-1}$ /green tonnes$\cdot ha^{-1}$)	**Roundwood**	33.21	42.16	33.21	42.16
	Biomass	32.60	18.60	32.60	18.60
Unit cost (€$\cdot m^{-3}$ / €$\cdot$green tonne^{-1})	**Roundwood**	34.00	28.02	23.50	21.03
	Biomass	31.50	31.50	29.70	29.70
Cost (C, €$\cdot ha^{-1}$)	**Roundwood**	1,129.10	1,181.31	780.40	886.62
	Biomass	1,026.90	585.90	968.20	552.42
	Roundwood +Biomass	2,156.00	1,767.41	1,748.70	1,439.04
Incomes (I, €$\cdot ha^{-1}$)	**Roundwood**	1,394.82	1,666.58	1,394.82	1,666.58
	Biomass	1,369.20	781.20	1,369.20	781.20
	Roundwood +Biomass	2,703,84	2,447.68	2,764.02	2,447.68
Global Balance: Incomes – Costs (I – C, €$\cdot ha^{-1}$)		**547.84**	**576.91**	**1,015.32**	**905.28**

First of all, it is remarkable that, despite the high costs related to the residuals collection in first thinning, the balance is always positive. This means that there is enough margin to pay a stumpage price for the roundwood and biomass and even to afford additional costs or to get additional profits.

If the global balance is compared, under the Spanish market conditions, the most profitable option to produce roundwood and biomass sequentially from a delayed thinning on a conifer plantation as the studied one, is the system with top diameter of 10 cm and in which the branches and tops were left on the strip road center and, after the roundwood forwarding, bunched with a bulldozer equipped with a raking implement and then loaded in another forwarder for its extraction.

4 Discussion and conclusion

These kind of silvicultural treatments are considered to be not profitable for residual biomass collection, most likely adequate for WTH system or CTL for energy wood (Suadicani, 2003; Bergstrtand *et al*., 2007; Spinelli, 2007; Tolosana, 2009; Spinelli & Magagnoti, 2010).

The residual biomass recovering case studied dealt with branches and tops collection in a gentle terrain conifer plantation delayed thinning. In Nordic Countries, the preferred harvesting systems when trees small to medium-sized – early thinnings – are the whole tree system, sometimes with different piling systems (Kärhä, 2011).

In Spanish conditions, as the feed – in - tariffs or the alternative market-dependant green premium added to the market price only subsidize electricity production with forest biomass coming from energy crops or from felling residuals, thinning products used to produce electricity should not be paid, unless a traceability system could ensure the separate use of roundwood and felling residuals (Tolosana, 2009).

The scarce residual biomass yield from thinnings could be a decisive economic constraint for residual collection (Kalio & Leinonen, 2005; Spinelli, 2007). Anyway, certain changes in the conventional timber and residues harvesting operations should be needed to improve the economic balance, in order to get a denser biomass accumulation in strips or piles. The adequate management of the residuals using the single-grip harvesting head is essential to improve operational productivity in residuals collection in regeneration fellings (Nurmi, 2007), although the felling and processing time for roundwood can be increased, as an average, in a 20% (Tolosana, 2009). In any case, the appropriate biomass piling is essential for an optimized forwarder loading and biomass recovery efficiency (Suadicani, 2003; Tolosana, 2009).

Tolosana (2009) describes the collection and crushing of residuals from silvicultural fire preventive treatments – cleaning, pruning and debrushing – in a Spanish mixed conifer and hardwood uneven stand on plain terrain. The residues were piled inside the stand as part of the treatment, so the considered operations were only residues collection with a front grapple that loaded them in a rigid basculating truck which, after hauling them off, unloaded the material at landing, where the same front loader finally fed a Doppstadt AK-430 grinder. The total cost, including relocation and indirect cost as well as transport cost to a 30 km distance, was 40.3 €•green tonne^{-1}. These fire preventive treatments are needed but may not be profitable, while the collection of the piled residuals produced in these operations, once they have been performed, can be cost-competitive in gentle terrain.

Regarding the residuals forwarding, the importance of the identified factors affecting productivity – payload, hauling distance, roundwood or biomass removals - have been widely recognized (Kallio & Leinonen, 2005; Nurmi, 2007; Spinelli, 2007, among others), being remarkable as a specific factor the positive influence on forwarding productivity of the denser biomass bunching using the bulldozer with the raking implement if compared to the biomass piling using the harvesting head.

Main conclusions of this work are the positive economic balance of residuals collection in this kind of delayed thinning on gentle terrain, and the better economic result of choosing a greater top diameter and of bunching the residual biomass with a bulldozer with raking front implement if compared to piling it along the strip roads sides using the harvesting head.

Further studies should consider the possible negative environmental effects of removing the residuals, particularly when the medium sized bulldozer is used for bunching them. Also the influence of the tried bunching methods on the biomass quality and price (because of the probable greater sand content when it has been piled with bulldozer) must be taken into account in future studies to refine the economic evaluation.

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