

Replacement of steel cable with synthetic rope in mountain logging operations in *Castanea sativa* Mill. coppice stands

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Abstract

Aim of the study: The objective of this study was to evaluate skidding from stump area to roadside with a tracked skidder (Caterpillar 3DG XL) using two different types of cable (steel or synthetic).

Area of study: NW of Spain.

Material and methods: A time study was performed to calculate productivity for the two types of cable and two regression models were fitted to predict the productive and cycle time of the tracked skidder.

Research highlights: An increase of 12.53% in productivity (m³/SMH) and improvements in working conditions using synthetic rope were found.

Key words: Chestnut; synthetic rope; time study; tracked skidder.

Introduction

The mechanization of wood harvesting operations has intensified since the 1990s, driven by a need to reduce production costs and increase productivity in order to improve competitiveness and working conditions (Bramucci & Seixas, 2002; Lopes *et al.*, 2007). Moreover, the forestry sector has an obvious interest in the sustainable management of resources, reducing the negative effects of logging on the environment and maintaining profitability. The complicated process of wood harvesting is influenced by several factors (operator skill and experience, terrain, slope, skidding distance, etc.) some of which may lead to operational problems and inefficient work (Lopes *et al.*, 2007). The timber extraction system employed in harvesting operations accounts for a large percentage of the operational costs and there are many different systems available; crawler tractors, skidders, forwarders, cable yarder systems etc., the choice of which is heavily influenced by the prevailing ground conditions at the site. In Asturias (Northern Spain), the average slope gradient on chestnut skid trails varies between 30 and

75% (moderate to very steep following the classification for terrain difficulty made by Kantola & Harstela (1988)), which makes the extraction of forest products an even more difficult, risky, expensive and time-consuming operation than it is usually. In this context, improvement in forest operations has become crucial. As a result, time studies are used to assess and improve the productivity of machines employed in forest harvesting.

The use of skidders for timber extraction is very common and there have been numerous studies of the productivity of these machines in Europe (Spinelli & Baldini, 1992; Sabo & Poršinsky, 2005; Marenče & Košir, 2008; Spinelli & Magagnotti, 2012), America (Kluender & Stokes, 1996; Wang *et al.*, 2004; Spong & Wang, 2008; Becker *et al.*, 2011) and Asia (Behjou *et al.*, 2008; Barari *et al.*, 2011; Lotfalian *et al.*, 2011; Mousavi, 2012).

In stands where there are steep slopes and trees of large diameters, the skidder is often the most effective machine to use despite a high initial cost (Behjou *et al.*, 2008). In contrast, other studies have suggested that although the adapted tractor has a lower pulling power, its low cost and smaller size are more appropriate for use in sites of particular environmental interest (Huyler & LeDoux, 1991; Spinelli & Baldini, 1992). In Astu-

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Received: 06-11-13. Accepted: 30-01-14.

Table 1. Stand locations and characteristics

Stands	Stand 1 (Melandreras 1)	Stand 2 (Melandreras 2)	Stand 2 (Vegafriosa)	Stand 4 (Las Vegas)
Total area (ha)	1.83	1.27	4.19	3.03
Altitude (m)	600	150	550	
Slope (%)	54.39	58.05	72.54	67.33
Skidding way	Uphill	Uphill	Uphill	Uphill
UTM coordinates (X, Y)	736712.85, 4780517.83	736768.41, 4815625.34	726401.71, 4782204.58	736136.35,

rias, tracked and wheeled skidders are very often employed on steep slopes and both are considered suitable.

Traditionally, steel cable has been used for all types of winching in timber harvesting owing to its strength, durability and longevity (Hartter *et al.*, 2006). However, there are difficulties associated with its use due to its weight and lack of flexibility, both of which contribute to operator fatigue, increasing the possibility of occupational health risks and/or accidents (Pilkerton *et al.*, 2001; Hartter *et al.*, 2006). Furthermore, its use increases the likelihood of puncture damage to operators, especially on hands and arms (Spong, 2007). The potential for synthetic rope, produced from high density polyethylene, to replace steel cable in timber applications, has been demonstrated and it is considered to:

- Improve operators' working conditions: for the same diameter, the synthetic rope has the same strength and a ninth of the weight of steel cable, besides which its high flexibility facilitates operations and increases speed (Pilkerton *et al.*, 2001; Spong, 2007).

- Reduce operator fatigue: logging is an extremely demanding job in terms of workload and cardiovascular demand, and the use of synthetic rope reduces the difficulty of several aspects of logging work (Pilkerton *et al.*, 2001, 2004a b). Several studies (Pilkerton *et al.*, 2003, 2004a; Spong, 2007; Magagnotti and Spinelli, 2012) have shown the ergonomic benefits and operational effectiveness of the use of synthetic rope with skidders compared to steel cable.

- Reduce of environmental impact: synthetic rope is much lighter, making the extraction of timber easier, causing less damage on the stand (Spong, 2007) and reducing the abrasion of and damage to the soil (Golsse, 1996; Lapointe, 2000; Hartter *et al.*, 2006).

- Improve skidding economy and productivity: On average, for the same diameter, synthetic rope costs

between 4 and 6 times more than conventional steel cable. However, this is offset by the fact that synthetic rope results in higher productivity (Pilkerton *et al.*, 2001, 2004b; Magaud & Villette, 2008), a fact confirmed by this study.

The overall objective of this paper is the time study and performance analysis of a tracked skidder (Caterpillar D3G XL) in skidding from stump area to roadside in chestnut clearcuts, fitting equations to predict the productive time per cycle and the total time per cycle from different operational variables. Furthermore, we aimed to test whether different winch materials (steel cable or synthetic rope) affected skidding performance.

Material and methods

This study was conducted in four clearcuts of *Castanea sativa* coppice stands over 40 years old in Asturias, Northern Spain. The study areas were selected to be as homogenous and comparable as possible. The total felling area was 10.32 ha and the average skidding distance was 50 m.

In order to obtain data, prior to felling a stand inventory was conducted in the maximum slope direction with three repetitions per stand. Twelve plots were established, following the methodology used by Eliasson *et al.* (1999), with a plot size between 800 to 1,400 m² depending on the stand. The main characteristics of the four stands are presented in Table 1. Trees with a diameter equal to or greater than 5 cm were inventoried and marked with one of seven different paint bandings, corresponding to seven diameter classes (width of 5 cm), in order to relate cycle times or productivity with the parameters most likely affect them, like load volume, mean diameter of load, etc. The diameter at breast height (1.30 above ground

Table 2. Values of the main dasometric variables in the areas under study: density (N), basal area (G), quadratic mean diameter (d_g) and harvested volume (V)

Stands	N (trees/ha)	G (m ² /ha)	d_g (cm)	V (m ³)
Stand 1	1,690.55	44.17	18.49	313.43
Stand 2	2,520.70	50.78	16.02	374.82
Stand 3	1,517.28	41.97	18.75	285.94
Stand 4	1,714.36	59.06	21.13	411.30

level) of each tree was measured twice using callipers and the height was measured with a Vertex III hypsometer. After making the inventory, different dasometric parameters were calculated (Table 2): density (N), basal area (G), quadratic mean diameter (d_g) and harvested volume (V). The volume of each individual tree was calculated using the chestnut volume equation for Asturias from the Third National Forest Inventory (DGCN, 2003).

Manual felling was made using a Stihl MS 460 chainsaw. In some areas, due to steep slopes, trees needed to be secured at the time of felling. Due to long skidding distance and steep terrain, twin-stage extraction was applied: an initial skidding with a tracked skidder (Caterpillar D3G XL) from stump to intermediary landing and a secondary skidding from the intermediary to the roadside landing by a wheeled skidder (John Deere 540 D) or, in one of the stands, a forwarder (Dingo F6L 913). The tracked skidder was also used for opening skid trails.

In this work, we compared skidding by the same tracked skidder operating with two types of winch material (steel cable or synthetic rope, both of 14 mm diameter). The synthetic rope used is made of high-density polyethylene (AmSteel® Blue 12: weighing 105 g.m⁻¹ with this diameter) and is similar in strength to steel cable of the same diameter but is over 9 times lighter.

The studied machines were operated by the same driver (who has more than 25 years experience) and the same extra operator (over 3 years experience) who did the following tasks: pulling out the cable, choking, winching, rehooking and sometimes preparing the tree (topping and delimbing) with a chainsaw prior to it being skidded to make hauling easier.

For the productivity analysis, a continuous time study was performed. Each work cycle was divided into work elements (Table 3) and classified as productive time or services time, following the terminology suggested by the IUFRO Working Group (Björheden *et al.*, 1995). To avoid later mistakes, the work elements

were clearly and concisely defined, setting the start and finish points.

Data acquisition was conducted using the time study software UMT. The time spent in each work element of the skidder work was recorded on a Trimble Nomad handheld computer. A total of 57 hours and 12 minutes were timed in the four different stands. In addition, some influential variables were measured in order to relate them with productivity (*e.g.* number of logs and volume skidded in each cycle).

After timing, data was reviewed to eliminate errors and outliers (Olsen *et al.*, 1998). Once the data base was established, statistical analyses were performed with SAS/STAT® (SAS Institute Inc., 2004). The differences between work elements using the two types of winch material were also analysed. Work time and total time productivity of the tracked skidder were calculated dividing harvested volume (in m³) by productive or total time (in hours) respectively. The Pearson correlation coefficient was determined for work elements and independent variables (parameters which can have an influence on the work elements or the productivity). Then, regression techniques of time study data were used to develop equations to predict cycle and productive times as a function of more correlated independent variables. Goodness of fit statistics (root mean square error, RMSE, and coefficient of regression, R^2) were employed to select the best models.

Results

We recorded a total of 534 cycles and after removal of errors and outliers, 525 cycles remained for analysis. As a first step the influence of number of workers was evaluated; in 56 cycles the operator worked alone whereas in all the other cycles an extra operator did various tasks, like hooking, complementary tasks etc. The analysis of variance (Table 4) showed that there was significant differences in cycle and productive time between those cycles with or without assistant,

Table 3. Work elements for Caterpillar D3G XL skidding chestnut wood

Work elements	Description
Hook (opening)	Release of the cable and hooking the load. Begins when the operator releases the cable from the winch and walks towards the log(s) which should be hooked and ends when the stems/log(s) are mounted on the back of the skidder. Composed of various elemental activities: cable release, hook up, partial haul/winching, re-hooking and complete haul.
Trunk	Non-timed activity that serves to indicate the number of trees hauled by the machine.
Travel (loaded and empty)	Displacement of logs to or from the landing zone. Begins when the skidder starts to move from or to the landing and finishes when the skidder stops.
Unhook	The time when the operator or driver releases the cable that from around the load. In some cases this release is produced by a quick movement of the skidder. Begins when the skidder driver (usually) leaves the skidder to unhook the cable and ends when the cable is fully recoiled.
Interferences	Delay due to other elements of the job, such as the forwarder, wheeled skidder or chainsaw. <i>E.g.</i> movement to one side of the skid trail to allow the wheeled skidder to continue travelling.
Complementary tasks	Activities that are necessary to complete the task and are an integral part of the cycle but are not directly part of the skidding activity and do not modify the work object. We conducted a detailed classification of the type of additional work, such as opening track, rearranging load, sawing branches and planning (time spent in developing an operational strategy, <i>e.g.</i> thinking about the best way to skid in a specific place).
Work-related delay	The portion of the non-work time that can be related back to the organization of the work (<i>e.g.</i> rest and personal time), or tasks that allow work to continue in a productive system, such as ancillary work (<i>e.g.</i> assisting in the cycle of other machines).
Non work-related delay	Portion of the non-work time that cannot be related back to the organization of the work.
Planning operations	The portion of the preparatory time used to develop operational strategy that involves all of the personnel and machines of the logging
Maintenance	The portion of the service time used to carry out upkeep tasks in order to keep machines in the best possible working order.
Breakdown	Time spent in repairing the machine; the time involved depending on the severity of the damage: <i>e.g.</i> jam, minor repairs, small fault (less than two hours), major crash (over two hours). Begins when the skidder has to stop because of the breakdown. Ends when either the operator or the mechanic repairs the machine.

Table 4. Analysis of variance of cycle and productive times between cycles with or without extra-operator

		Sum of Squares	df	Mean Square	F	Sig.
Cycle time	Between groups	1,451,936.364	1	1,451,936.364	4.781	0.029
	Within groups	1,588.10 ⁸	523	303,701.723		
	Total	1,603.10 ⁸	524			
Productive time	Between groups	979,629.359	1	979,629.359	4.592	0.033
	Within groups	116.10 ⁸	523	213,330.415		
	Total	1,126.10 ⁸	524			

Table 5. Descriptive statistics of work elements (hh:mm:ss)

Work elements	N cycles	Avg.	Min	Max	Std. Dev.	%
Hook	468	0:03:02	0:00:12	0:19:58	0:02:43	47.43
Travel loaded	251	0:01:35	0:00:09	0:10:44	0:01:14	13.25
Unhook	400	0:00:18	0:00:00	0:01:36	0:00:14	3.95
Travel empty	260	0:01:06	0:00:04	0:11:00	0:01:01	9.53
Complementary tasks	226	0:01:36	0:00:07	0:15:24	0:02:13	12.09
Interferences	156	0:01:34	0:00:03	0:09:15	0:01:38	8.13
Work-related delay	65	0:01:45	0:00:04	0:14:25	0:02:41	3.80
Non work-related delay	6	0:00:56	0:00:37	0:01:31	0:00:22	0.19
Planning	23	0:01:22	0:00:15	0:12:36	0:02:33	1.05
Maintenance	1	0:03:43	0:03:43	0:03:43		0.12
Breakdown	2	0:06:50	0:01:20	0:12:21	0:07:47	0.46
Productive time	469	0:05:31	0:00:30	0:25:45	0:04:40	86.25
Cycle time	469	0:06:24	0:00:30	0:27:13	0:05:32	100.00

Table 6. Average values of diameter, load volume and number of logs extracted per cycle for each stand

Stands	Winch material	d / cycle	V / Cycle	Logs /Cycle
Las Melandreras 1	Synthetic rope	20.21	0.32	1.55
Las Melandreras 2	Synthetic rope	20.10	0.50	2.52
Vegafriosa	Steel cable	20.29	0.96	3.26
Las Vegas	Steel cable	22.28	0.71	2.74

so the 56 cycles where the operator worked alone were removed in the subsequent analyses.

The average productive time per cycle was 5 minutes and 31 seconds. Table 5 shows the descriptive statistics of the work elements. The tracked skidder had a technical availability of 86% of the main time. The machine spent approximately 47.43% in hooking, 22.78% in travel (loaded and empty) and 8.13% in interferences caused by other elements of the system (79.53% of which was waiting for manual delimbing and topping of trees and 19.42% waiting for the wheeled skidder).

During the study a total of 324.04 m³ of wood was harvested. Table 6 shows the average values of diameter, volume and number of logs extracted per cycle. For the different stands, the average volume per cycle was between 0.32 and 0.96 m³. Differences between stands were attributable to the steep slopes and the rocky conditions of some of them, and in these situations the average number of logs removed per cycle was considerably reduced.

The results (Table 7) show significant correlation between work elements (hooking, loading, cycle time and productive work time) and influential variables (*e.g.*, volume and logs per cycle). Different models

Table 7. Significant Pearson correlation coefficients between different variables ($p < 0.01$)

	V/cycle	Logs/cycle	Slope
Hook time	0.69	0.73	0.39
Travel loaded time	0.47	0.35	0.28
Cycle time	0.59	0.58	0.46
Work time	0.64	0.62	0.51

were evaluated using linear regression, the following models (equations 1 and 2), which have coefficients of determination (R^2) of 0.4746 and 0.4458 respectively finally being selected:

$$t_{\text{productive}} = 462.2 \cdot v_{\text{cycle}} + 17.10 \cdot \text{slope} - 781.5 \quad [1]$$

$$t_{\text{cycle}} = 549.2 \cdot v_{\text{cycle}} + 18.58 \cdot \text{slope} - 836.1 \quad [2]$$

where $t_{\text{productive}}$ is productive time in cmin (1 cmin = 1/100 min), v_{cycle} load volume per cycle in m³ and t_{cycle} the cycle time in cmin. All parameters were significant at the 5% level.

Table 8 shows a comparison of the average of work elements between steel cable and synthetic rope. The cable type has a great influence on hooking time; synthetic rope enabling the task to be done in almost

Table 8. Comparison between steel cable and synthetic rope of time for each elemental operation

Work element	Steel cable			Synthetic rope		
	<i>N</i>	Avg.	%	<i>N</i>	Avg.	%
Hook	215	0:04:15	44.99	253	0:02:01	52.52
Travel loaded	196	0:01:43	16.64	55	0:01:05	6.16
Unhook	155	0:00:21	2.71	245	0:00:16	6.55
Travel empty	196	0:01:06	10.64	64	0:01:06	7.20
Complementary tasks	166	0:01:28	11.97	60	0:02:00	12.36
Interferences	100	0:01:29	7.30	56	0:01:43	9.87
Work-related delay	35	0:02:28	4.27	30	0:00:55	2.82
Non work-related delay	5	0:00:56	0.23	1	0:01:00	0.10
Planning	15	0:01:37	1.19	8	0:00:55	0.76
Maintenance	—	—	—	1	0:03:43	0.38
Breakdown	1	0:01:20	0.07	1	0:12:21	1.27
Productive time	216	0:08:10	86.94	253	0:03:15	84.80
Cycle time	216	0:09:23	100.00	253	0:03:50	100.00

Table 9. Productivity of the Caterpillar 3DG XL

Winch material	<i>N cycles</i>	<i>m</i> ³ /PMH	<i>m</i> ³ /SMH
Synthetic rope	299	8.65	7.95
Steel cable	226	7.58	6.83

half the time it took with steel cable (2 minutes 1 second compared to 4 minutes and 15 seconds respectively). The average cycle times show that a productive time per cycle using steel cable took 8 minutes and 10 seconds, while for the synthetic rope this time decreased by around 60%.

Table 9 shows the productivity in m³ per PMH (Productive Machine Hour) and in m³ per SMH (Scheduled Machine Hours). These results prove that the use of synthetic rope allows increased productivity in both m³/PMH and m³/SMH, with an average productivity using steel cable of 6.83 m³/SMH compared to 7.95 m³/SMH with synthetic rope.

Discussion

In spite of the importance of chestnut stands in the north of Spain, no previous time studies of skidding have been conducted. This study provides information on time consumption and productivity of skidding of chestnut trees in coppice stands.

It is important to highlight that the percentage of time spent travelling is lower than in other studies (Behjou *et al.*, 2008; Lotfalian *et al.*, 2011) as the skidding was in fact only a pre-skidding, comprising

extraction from stump to the roadside from where a second machine completed the extraction process to the final landing (a wheeled skidder or a forwarder depending on the slope). At the same time, consumption in hooking is longer than in other studies (Behjou *et al.*, 2008; Barari *et al.*, 2011) as we included winching in this work element because the steep terrain made it difficult to separate the two activities.

The average volume removed per cycle depends strongly on the power of the machine used, slope and terrain conditions. This explains the differences in this variable compared to other studies (Spinelli & Baldini, 1992; Sabo and Poršinsky, 2005; Bavaghar *et al.*, 2010). Pilkerton *et al.* (2003, 2004a) studied several tracked and wheeled skidders with synthetic rope and found, on slopes less than 20%, an average extraction rate of 3 to 4 logs per cycle, results very similar to those observed in this work (see Table 4), despite the slopes in the present study being greater. In this study, the number of stems loaded per cycle was greatly influenced by the large number of stems per stump and by the fact that the operators did not use chokers for multiple hooking, meaning that they had to unhook and re-hook when they wanted to include more than one tree in a cycle, and in many cases it was not in fact worthwhile to do this due to the delay it caused. Furthermore, to prevent accidents and maintain stability during winching or loading on the steep slopes, the tracked skidder did not work at maximum load capacity.

In relation to the time prediction models fitted in this study, it is important to emphasize that in these

equations the time consumed only refers to skidding from stump to roadside. In this study the winching distance was similar in all cases (50 m) so this variable was not included in the models. The results showed that skidder cycle was mainly affected by slope and load volume per cycle. According to other studies, the skidding distance, winching distance and slope are the main factors that affect the productivity of skidder (Ghafarian *et al.*, 2007; Lotfalian *et al.*, 2011).

Greater productivities have been observed in other studies (Bavaghar *et al.*, 2010) which is mainly due to gentler slopes compared to in the present study. Furthermore, it has to be taken into account that the tracked skidder was also working to open up the skidding trail during the study (5.23% of total time), which had the effect of decreasing productivity. Skidder productivity was also affected by the fact that directional felling to optimize skidding was made difficult by the steep terrain and the high number of stems per stool among other factors.

In relation to type of cable used, the decrease in cycle time for synthetic rope in this study was similar to the results of a comparative study of winch materials by Pilkerton *et al.* (2003). Recent studies have shown that high strength, light weight synthetic rope can remarkably increase productivity (Wright, 2007; Magaud & Vilette, 2008). In our study the use of synthetic rope improved average productivity in m^3/PMH by 12.33%, and average productivity in m^3/SMH by 14%. In similar studies (Pilkerton *et al.*, 2001, 2004a) the use of synthetic rope resulted in a 10% increase in productivity. The operators in the present study did not have previous experience in using the synthetic rope, most probably contributing to the load volume being lower than the actual capacity of the cable, thus decreasing productivity.

Synthetic rope is much easier to work with in difficult terrain and on steep slopes, as well as it reducing safety risks and physical demands on the operator. As a consequence of workload reduction, moreover, the number of operators needed is also reduced.

For the most efficient operation of the skidder, the use of specific chockers to allow multiple hooking is recommended with synthetic rope. Furthermore, although due to the small load volumes there were not any cable breakages in our study, the use of specific end connectors at the point where the cable and the tree are in contact can extend the working life of synthetic rope (Garland *et al.*, 2003).

Conclusions

The Caterpillar D3G XL tracked skidder for skidding in steep chestnut coppice stands was evaluated and two equations were developed to predict its productive time and cycle time. In the assessment of the effect on the productivity of the winch material (steel cable or synthetic rope), an improvement of 14% in productivity (in m^3/SMH) was found for synthetic rope. Furthermore, its use improves working conditions and has evident benefit on the ergonomics of forest harvesting, indicating that there is great potential for future research on skidding in mountain conditions using synthetic rope in order to develop more robust time consumption models, that incorporate new variables and which are suitable for other species.

Acknowledgments

The authors are grateful to the Ministry of Science and Innovation of Spain (MICIN) and the Plan for Science, Technology and Innovation of the Principality of Asturias (PCTI) for funding the research project "Forest and industrial evaluation of Spanish chestnut" (VALOCAS). Special thanks to the technical assistance of Ernesto Alvarez for their field assistance in this project. The authors especially wish to thank the Maderas Siero Company who worked together with us on this study.

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