PRODUCTIVITY AND COST ANALYSIS OF A WHEELED SKIDDER IN CHESTNUT COPPICE FORESTS IN THE NORTH OF SPAIN. PRELIMINARY EVALUATION OF SOIL COMPACTION OF FOREST ROAD.

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SUMMARY

This study evaluates the productivity and cost of the JD 540 D skidder in skidding from roadside to landing (mean skidding distance, 850 m), in two clearcuts of chestnut coppice stands on steep terrain. A time study was conducted over 58 work cycles using the time study software UMT. Productivity was found to be 7.6 m^3/SMH and 7.86 m^3/PMH.and operational costs 49,61 €/PMH and 48,14 €/SMH.

Various independent variables were measured in order to analyze their influence on time or productivity. Different models predicting productivity per effective and total hour, with load volume per cycle and distance as independent variables were evaluated, and two linear models finally selected explaining more than 83 % of total data variation.

Additionally, a preliminary evaluation of soil compaction was carried out taking into account the number of passes made along the forest road, measured using Geographical Information Systems (GIS). Soil compaction was evaluated by Cone Index (CI) using a cone penetrometer CP40II in 75 perpendicular transects along the forest road, measurements being made in ruts, and in a control area. In addition, several soil samples were taken to evaluate moisture. Skidder traffic was evaluated using a GPS Trimble Explorer XH, mapping the number of passes (both loaded and empty) onto a raster map (pixel 0.5 m). The compaction produced by the forest machinery in this study was 60% higher than that found in the control zone and compaction in areas with high traffic intensity was 25% higher than in low traffic intensity areas.

Keywords: wheeled skidder, time study, soil compaction

INTRODUCTION

The relative low profit margins in forest harvesting in mountainous areas makes the careful planning and evaluation of harvesting systems essential, and in reality this means seeking improvement in productivity and reduction of costs. Moreover, the forestry sector has an obvious interest in the sustainable management of resources, reducing the negative effects of logging on the environment while maintaining profitability.

These generally high harvesting costs are increased further in the case of chestnut coppice stands due to this species being principally found as coppice forest on steep terrain, in small forest properties.

At the same time, chestnut coppice stands have a high potential productivity in the north of Spain (rapid growth, high quality products, large area of distribution, etc.),

Taking this into account, time studies allow the evaluation of productivity and cost of a machine, as well as bottlenecks, causes of delays, etc. in order to assess and improve the productivity of the machines employed.

In Northern Spain, tracked and wheeled skidders are very often employed on steep slopes and both are considered suitable. Numerous studies have been made in order to evaluate these machines in Europe and North America (Spinelli and Baldini 1992, Kluender and Stokes 1996, Marenče and Košir 2008, Spinelli and Visser 2008).

The overall objective of this study was to determine and analyse the productivity and cost of a John Deere 540D cable skidder in chestnut coppice on steep sloped stands, in Asturias (Northern Spain). Various models were evaluated and the two best were fitted in order to predict productivity per effective and total hour, depending on different factors (travel distance and load volume per cycle). Finally, a preliminary evaluation of soil compaction was carried out taking into account the number of times the machinery passed along the forest road.

MATERIAL AND METHODS

This study was conducted in two homogenous clearcut chestnut coppice stands over 40 years old in Asturias (Northern Spain). The total felling area was 1.98 ha and the mean skidding distance was 850 m.

In order to obtain data, prior to felling a stand inventory was conducted. Two circular plots (*R* = 15 m*)* were established and diameter at breast height (1.30 above ground level) of each tree was measured twice using calipers, and height measured with a Vertex III hypsometer. After making the inventory, different dasometric parameters were calculated (Table 1).

Moreover, all trees in the whole stand with a diameter equal to or greater than 5 cm were marked with one of seven different paint bandings, corresponding to eight 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.

Manual felling using a Stihl MS 460 chainsaw was employed. The steepness of the terrain, coupled with long skidding distances, prompted the choice of a two-stage extraction process: initial skidding from stump to an intermediary landing with a tracked skidder (Caterpillar D3G XL), and a second skidding from the intermediary landing to the roadside landing by a wheeled skidder (John Deere 540 D).

This study evaluates this second skidding stage (from intermediary to roadside landing) using the John Deere 540D cable skidder. The machine has a power engine of 115 HP and a winch JD of 20 t and uses steel cable with a diameter of 1.5 cm. Both stands used for the study were skidded using the same machine, operated by the same driver, who had over 25 years' experience.

Table 1. Stand characteristics of the study areas.

Stand	1	2
Species	chestnut	chestnut
UTM coordinates	X:276,043.81 Y:4,790,806.19	X: 276,244.89 Y:4,790,669.96
Slope (%)	50	52
G(m^2/ha)	42.02	47.06
N (trees/ha)	933.7	933.7
H_{mean} *(m)*	20.77	20.42
D_{mean} (cm)	23.24	24.63
Area (m^2)	5,592	14,232

Productivity and cost analyses

For the productivity analysis, a continuous time study was performed. Each work cycle was divided into work elements (Table 2) and classified as productive time or service 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.

Table 2. Work elements for JD 540D skidder hauling chesnut wood.

Task	Description
Hooking	Release of the steel cable and hooking up of load. Usually requires more than one turn of the cable and one or two operators. Finishes with the initiation of roller movement, which in turn moves the cable.
Cable recoiling	The winch turns and drags the load until the cable is fully recoiled. Ends when the skidder wheels begin to move.
Travelling loaded/empty	Displacement to/from the landing zone. Finishes when the wheels of the skidder stop.
Unhooking	The time when the operator or driver releases the cable from around the load. In some cases this release is produced by a quick movement of the skidder. Begins when someone (usually the skidder driver) leaves the skidder to unhook the cable and ends when the empty skidder begins to move (to go the landing or to manoeuvre and carry out complementary tasks at landing).
Rearranging load	Handling of logs in order to prepare them for hooking.
Interference	Delay which is due to other elements of the job apart from the skidder activity, such as the tracked skidder or chainsaw operations.
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 up of the track, sawing branches and tasks carried out at landing.
Other activities	Delays, Maintenance, Breakdown, Refueling, Planning, rest and personal needs, etc.

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 27 hours and 57 minutes were timed in the two stands (58 skidding cycles). 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). The movement of the skidder is clearly one of the most influential variables thus a GPS Trimble Explorer XH was installed in the skidder to record its position.

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). Work time and total time productivity of the wheeled skidder were calculated by dividing harvested volume (in m^3) by productive or total time (PMH or SMH, in hours) respectively. The Pearson correlation coefficient was determined for each work element and influential variable and then, linear regression was used to develop equations to predict productivity per effective and total hour as a function of the most 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.

The GPS data relating to the accurate location (UTM coordinates) of the skidder were combined with the time study data (the variable of time, hour, minute and second, being the common factor) thereby obtaining the accurate location of the machine at the end of each work element. This enabled the movement of the skidder during each work element to be calculated, specifically loaded and empty distance, two crucial variables in skidding productivity.

For cost calculations, fixed and variables costs were evaluated (Miyata, 1980; FAO, 1992) using data provided by the forest company.

Evaluation of soil compaction

At the end of harvesting, soil damage caused by skidding machine traffic was evaluated using a cone penetrometer CP40II to measure Cone Index (CI). Data from 75 perpendicular transects (with four insertion points; in control area, one in each rut and one in the area between the two ruts) along the forest road were collected. All transects were georeferenced with a GPS in order to relate location and the physical-mechanical properties of the soil with the number of passes of the machines (besides the wheeled skidder studied here, the tracked skidder involved in the initial skidding was also taken into account in this part of the study as it worked, at least some of the time, in the same areas). Finally, several soil samples were taken from different forest roads, and the total sample was weighed in the laboratory and dried to estimate moisture content, a key factor in resistance to penetration. The penetrometer data was analysed with CP40II software.

To calculate the number of passes of the machines, the GPS data relating to their movements were analysed with ArcGIS 9.2, although GPS data was only recorded during the period of the time study and hence the traffic data available was not complete. A traffic map of skidder activity was created using the methodology developed by other authors (McDonald *et al.*, 2002). The paths of the movement of the machine were created, grouping them by cycle and type of displacement (loaded or empty). Then, a buffer was created with a width of 2.5 m (machinery width). These buffers were raster transformed (with a pixel of a 0.5 m) where a value of 1 was given to pixels through which a machine passed and a value of 0 to those without traffic. Finally, all layers were summed and a raster map created, including data related with number of passes by fixed intervals. These intervals were based on the study by Balbuena *et al*. (2003) which considered that the passes which provoke the greatest compaction are the first 10, after which the number of passes becomes less important.

Once this map of number of passes was created, the relation between number of passes and compaction was analyzed. As only the traffic data from those days when time study was conducted was included, only a preliminary evaluation could be made comparing the soil compaction produced in areas with high traffic (areas with traffic of both machines) with areas with low traffic (forest tracks where only the wheeled skidder worked).

RESULTS AND DISCUSSION

During the study, 58 cycles were recorded, but after removal of errors and outliers, only 53 cycles remained for analysis.

In Table 3 the descriptive statistics of time consumed in the different work elements of skidder 540D are shown. The average total time per cycle was 31 minutes and 38 seconds, and the skidder had a technical availability of 97%. The machine spent approximately 78% of its time in travelling (loaded and empty) and 9% in hooking.

Table 3. Descriptive statistics of the different work elements of cycle for skidder 540D (hh:mm:ss).

	N	Min	Max	Sum	Avg	Std.dev	%
Hooking	53	0:01:14	0:05:36	2:35:31	0:02:56	0:01:07	9.27%
Cable recoiling	51	0:00:08	0:00:56	0:23:59	0:00:28	0:00:10	1.43%
Travelling loaded	53	0:08:27	0:15:54	11:11:54	0:12:41	0:01:59	40.07%
Unhooking	53	0:00:04	0:03:46	0:40:03	0:00:45	0:00:40	2.39%
Travelling empty	53	0:05:11	0:16:30	10:34:05	0:11:58	0:02:11	37.81%
Rearranging load	7	0:00:24	0:11:50	0:22:32	0:03:13	0:04:05	1.34%
Landing tasks	49	0:00:03	0:06:37	1:09:26	0:01:25	0:01:10	4.14%
Track opening	3	0:00:58	0:02:04	0:04:31	0:01:30	0:00:33	0.27%
Other complementary tasks	1	0:00:54	0:00:54	0:00:54	0:00:54		0.05%
Interference from tracked skidder	20	0:00:02	0:00:38	0:04:26	0:00:13	0:00:11	0.26%
Other interferences	6	0:00:31	0:02:43	0:08:31	0:01:25	0:00:43	0.51%
Interference chainsaw	9	0:00:08	0:03:52	0:08:33	0:00:57	0:01:09	0.51%
Operational time	1	0:00:40	0:00:40	0:00:40	0:00:40		0.04%
Planning time	3	0:00:20	0:01:20	0:02:44	0:00:55	0:00:31	0.16%
Rest and personal time	5	0:00:53	0:23:45	0:29:06	0:05:49	0:10:02	1.74%
Cycle time	53	0:22:08	0:56:07	27:56:55	0:31:38	0:05:41	100.00%

Table 4 shows the descriptive statistics of the influential variables (volume and number of logs extracted per cycle and distance travelled). The average number of logs per cycle is high because it only involved skidding from an intermediary landing to the final landing, and logs had previously been grouped by the tracked skidder during the first stage of the skidding, from stump to the intermediary landing.

Table 4. Descriptive statistics of influential variables in work cycle.

,	Min	Max	Avg	Std. Dev.
logs/cycle	4	22	10,72	4,33
V_{cycle}	1,92	5,38	3,61	0,74
Distance travelled loaded	740,72	1.009,70	864,53	73,73
Distance travelled empty	320,45	9.992,16	830,04	152,32

Note: logs/cycle: number of logs skidded per cycle; V_{cycle} m^3 skidded per cycle; distances in m.

Total volume extracted during the study was 212.56 m^3. The productivity of the John Deere 540D skidder was 7.6 m^3/SMH (7.86 m^3/PMH).

Analysis of the correlation between productivity and the influential variables showed a good correlation with distances (loaded and average distance per cycle) and volume skidded per cycle. These variables were used to fit models using linear regression techniques and SAS statistical software (SAS Institute Inc., 2004). Finally, two models were selected to predict productivity per productive and total time (m^3/PMH and m^3/SMH). Table 5 shows the models selected, with their goodness-of-fit statistics.

Table 5. *Goodness-of-fit statistics of models selected to predict productivity (m^3/h).*

Model	R^2	REMC
$\eta_{productive\_time} = 5{,}6765 + 2{,}0110 \cdot v_{cycle} - 0{,}0065 \cdot dist_{avg}$	0.8347	0.8117
$\eta_{total\_time} = 5{,}4072 + 2{,}0923 \cdot v_{cycle} - 0{,}0068 \cdot dist_{avg}$	0.8433	0.8173

Note: v_{cycle} is the volume extracted per cycle (m^3) and $dist_{avg}$ is the average skidding distance per cycle (m).

Skidding costs were 49.61 €/PMH and 48.14 €/SMH.

Soil compaction

In the study of soil damage caused by the skidding phase, soil compaction was analyzed considering a moisture content of 50% following laboratory analysis of the soil samples. Figure 1 shows the penetration resistance in control areas and those with traffic. The compaction in areas of traffic were up to 60% higher than in control areas in depths up to 60 mm, whilst at depths of between 60 and 500 mm trafficked areas were consistently in the region of 35-45% more compacted. In areas with machine traffic, values above 2,000 kPa were reached, which could cause the regrowth of vegetation to be slowed due to the compaction hampering adequate root development of plants, something which is especially important in the case of temporary tracks.

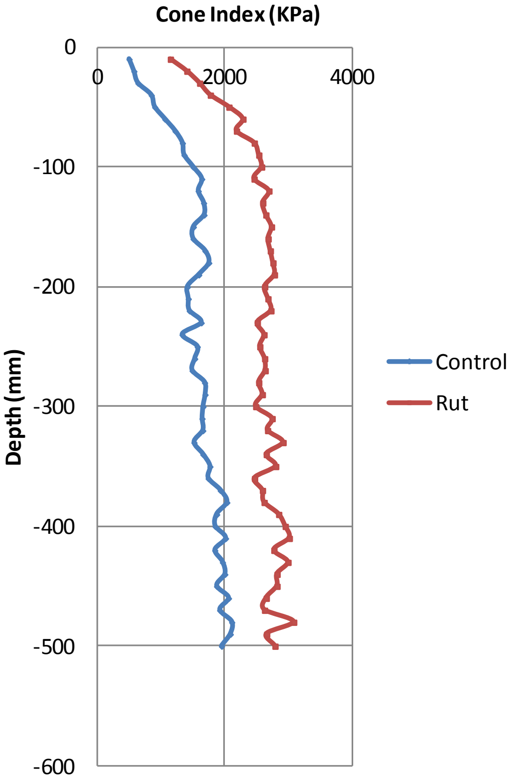

Fig. 1. Relation between penetration resistance (Cone Index, CI) and soil depth in areas with and without traffic.

In the next step, penetration resistance in areas with different traffic intensity was compared. From the analysis of the number of passes using GIS, a map of skidding machinery traffic was created taking into account the machine displacements (GPS data). This was a raster map (pixel size 0.5 m) indicating the number of passes made in each pixel. Figure 2 shows the comparison between the compaction produced by the passage of skidding machinery in maximum traffic areas (areas where both machines worked) and in lower traffic areas (those in which only the wheeled skidder was worked). Comparing high traffic intensity areas with low traffic intensity areas, an increase of 25% was observed.

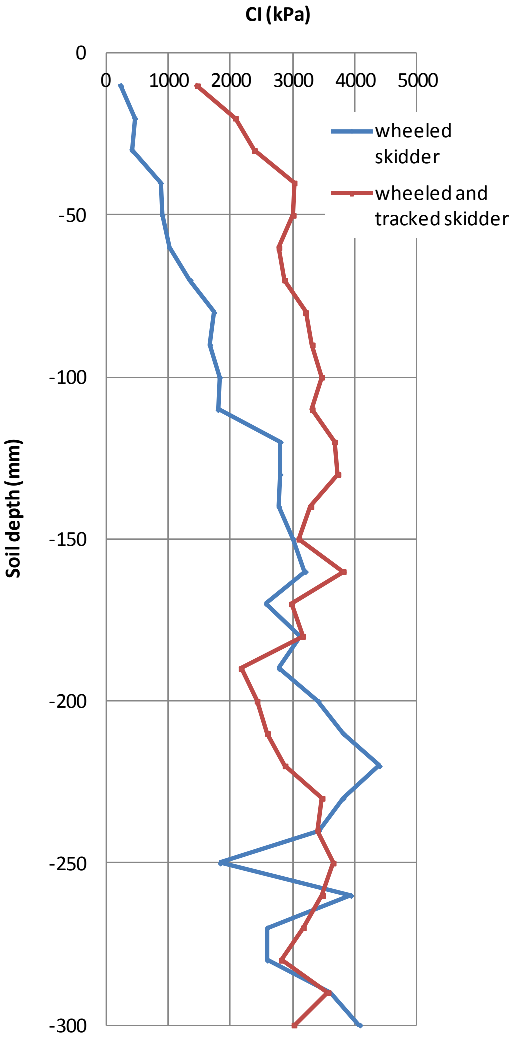

Fig. 14. Comparison between penetration resistance in areas with wheeled skidder traffic and areas with wheeled and tracked skidder traffic.

CONCLUSIONS

A time study of a John Deere 540 D skidder was performed during a secondary skidding (from intermediary landing to roadside landing) in a chestnut clear cut. The average cycle time was 31 minutes and 38 seconds, and the skidder had a technical availability of 97%. Productivities were calculated as 7.6 m^3/SMH and 7.86 m^3/PMH, and two models to predict these productivities were fitted using the volume extracted per cycle and average distance travelled as independent variables (R^2 greater than 83%).

The hourly costs were calculated as 49.61 €/PMH and 48.14 €/SMH.

In the study of soil compaction produced by the skidding machines employed in this study (tracked and wheeled skidder), penetrometer data showed an increase of up to 60 % in the compaction of areas with traffic in relation to control areas. Comparing high traffic intensity areas with low traffic intensity areas, an increase of 25% was observed. This compaction is likely to cause problems in the root development of future vegetation.

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