PRODUCTIVITY AND ENERGY EFFICIENCY OF WINCHING OPERATIONS IN PINE STANDS IN MOUNTAINOUS REGIONS

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Resumo

Produtividade e rendimento energético de operações de guinchamento em plantios de Pinus em regiões montanhosas. Objetivou-se com estudo foi avaliar a produtividade e o rendimento energético da extração de árvores em regiões montanhosas através de um trator agrícola com guincho em duas composições de equipe de trabalho: I: um operador de trator e um operador de cabo; e II: um operador de trator e dois operadores de cabo. O estudo foi realizado na região do Vale do Ribeira em um sistema de colheita de árvores inteiras, por meio de um estudo de tempos e movimentos em diferentes condições de distância de extração (6 até 135 metros) e ao pátio de toras (5 até 241 metros), e declividade do terreno (de 7º até 37º). Para avaliar os ciclos uma análise de regressão foi realizada em cada tratamento e posteriormente comparada pelo teste F de Graybill. Depois foi realizada uma regressão com variável *dummy*. A produtividade foi de 9,26 m³.he com um operador de cabo e 12,12 m³.he em uma distância de extração de 100 m; o consumo específico de combustível foi de 44,26 g kW^{-1}.he em ambos os tratamentos, e o rendimento energético foi de 4,92 g kW-1 m³ com um operador de cabo e 3.13 g kW^{-1} m³ com dois operadores de cabo. Apesar do consumo específico de combustível ter sido igual, o aumento da produtividade resultante da adição de um operador de cabo fez com que o rendimento energético melhorasse na extração com trator agrícola e guincho.
Palavras-chaves: equipe de trabalho, extração, trator agrícola, trabalhador florestal, consumo de combustível.

Abstract

The objective of this study was to evaluate the productivity and energy efficiency of tree extraction in mountainous regions by means of a tractor with winch in two work team compositions: I: one tractor operator and a cable operator; and II: one tractor operator and two cable operators. The study was carried out in Vale do Ribeira region using a full tree harvesting system through a time and motion study in different conditions of extraction distance (6 to 135 meters) and log yard (5 to 241 meters), and land slope (from 7 to 37º). To evaluate the cycles, a regression analysis was carried out for each treatment and subsequently compared using the Graybill F test. Then a regression with a dummy variable was performed. The productivity was 9.26 m^3 PMH$_0$$^{-1}$ with a cable operator and 12.12 m³ PMH$_0$$^{-1}$ at an extraction distance of 100 m; the specific fuel consumption was 44.26 g kW^{-1} PMH$_0$$^{-1}$ in both treatments, and the energy efficiency was 4.92 g kW^{-1} m³ with a forest worker and 3.13 g kW^{-1} m³ with two forest workers. Consequently, although the specific fuel consumption was equal in both treatments, the increase in productivity resulting from the addition of a cable operator, improved the energy efficiency in the extraction using a tractor with winch.
Key words: work team, extraction; farm tractor; forest worker, fuel consumption.

INTRODUCTION

Wood extraction in slope condition results in a high degree of danger to the extraction activity (TSIORAS *et al.* 2011). On land with smooth topography, vehicles such as forwarders and skidders can move through the forest plantations in order to perform the log extraction. However, in mountainous terrains, alternatives such as extraction by cables, helicopters and cable yarding must be used to overcome the obstacles imposed by the land. Even though options that fully mechanize forest harvesting are available on the market, its high initial investment ends up discouraging some forest producers (SPINELLI; MAGAGNOTTI, 2012). In this way, farm tractors become a low initial cost option, with easy operation and satisfactory productivity (MOUSAVI; NIKOOY, 2014). Another advantage is the farm tractor versatility, that can work on several terrains, presenting good productivity in stands where trees present medium and low individual volumes (GILANIPOOR *et al.*, 2012).

Farm tractors are also a good alternative to extraction tractors, especially when used on sloped terrain and by small scale forest owners. Although currently limited to special locations and small producers, farm tractors can be adapted with the required equipment to perform the extraction activity (SPINELLI; MAGAGNOTTI, 2012).

Winching with farm tractors presents higher productivity when performed by one tractor operator and two forest workers (STUDIER; BINKEY, 1976; SKOGSARBETEN, 1983 cited by MACHADO *et al.* 1990). Nevertheless, despite the advantages, Volpato (1991) guided that for distances of more than 100 meters winching is not a recommended alternative.

In addition to the challenges of harvest planning in difficult access areas, there is the need to rationalize both the activity and the consumption of fossil fuels for this specific forest operation (PICCHIO *et al.*, 2012).

Fossil fuels use is still a good indicator of the sustainability of human activities (MAGAGNOTTI; SPINELLI, 2011) and also one of the main current forest operations research areas in Europe (RINGDAHL *et al.*, 2012). Energy analysis is the name given to the study that aims to evaluate the use of energy while manufacturing a product or executing a service (VUSIĆ *et al.*, 2013). According to Machado *et al.* (1990) adding workers would increase productivity, therefore it might increase energy efficiency of timber extraction in mountainous areas when using a farm tractor with winch. Hence, it is important to understand which elements of the cycle are the most relevant and in which element of the cycle there will be a reduction in time when adding a worker.

This study aimed to evaluate the productivity, the fuel consumption and the energy efficiency of a farm tractor with a winch in two different working modes on a mountainous terrain.

MATERIAL AND METHODS

The study took place in wood harvesting operational areas, belonging to a forest company, located in the cities of Itaperuçu and Rio Branco do Sul, Paraná, Brazil (between the coordinates 25.09 S and 49.19 W). The land relief is classified as strong corrugated and mountainous presenting from 20 to 75% of slope. The climate in the region was classified as Temperate Oceanic (Cfb) according to the Köppen classification, being temperate humid. It is characterized by winter with average temperatures below 18° C and summers with average temperatures below 22 ° C. The indigenous vegetation is Mixed Ombrophilous Forest.

The evaluation was carried out in a *Pinus taeda* L. stand, under clearcutting at 16 years old. The density presented was 563 trees ha^{-1} and individual tree volume of 0.6 m³. The destination of the wood was mainly sawmills, for the assortments of larger diameters, and process, for assortments with smaller diameters and logs of lower quality.

The harvesting system adopted was the full tree. The trees were felled by a team of chainsaw operators who carried out motor-manual felling. After that, farm tractors with winches carried out timber extraction, where the extraction distances observed in the study did not exceed 150 meters. The farm tractor worked fixed at a point, and from that point the cable was pulled at various angles of extraction. Each operational cycle extracted 4 trees at a time, the same number of chains available to tie the trees.

A farm tractor with a power of 96.7 kW and 2,300 RPM, using diesel as fuel, and a winch with 33,000 Kgf of traction power, with cables ¾ of an inch in diameter were evaluated. The tractor had between 600 and 900 hours of work.

The treatments (work team) evaluated were: I - one winch-tractor operator and one forest worker (traditional); and II - one winch-tractor operator and two forest workers (proposed).

The winching distance was considered from the trees to be winched to the farm tractor at the edge of the stand, and the skid distance was considered from the stand to the log yard. A time and motion study using the individual timing method was performed in order to timing the time of the elements that formed the operational cycle of the tractor. The operational interruptions were computed but excluded from processing.

Operational cycle was divided into seven elements: (1) travel empty, started when the tractor left the yard, ending with its arrived at the winching site; (2) cable pulling, started when the forest worker took the cable hook and ended when he arrived where the trees were; (3) hook load, started with the passing of the chains around the trees that were been winched, ended with an expected signal from forest worker; (4) winching, started at the moment where the winch drew the load to the tractor awaiting by the road, ended when the drawing reached this road; (5) travel loaded, started once the trees were off the field, ending when the tractor arrived at the yard; (6) unhook load, started when the tractor arrived at the yard, the unhooking process ended when the forest worker placed all chains on top of the implement of the tractor; and (7) yard organization, started with the trees all misplaced at the yard, ended when they were properly positioned by the tractor's implements.

Figure 1 presents some aspects of the winching operations. It is possible to verify in Figure 1.a the general aspect of the region with mountainous topography, while the 1.b, 1.c and 1.d show winch details, timber skidding and unhooking logs.

Figure 1. Extraction operation performed by farm tractor with winch: (a) farm tractor at embankment border performing extraction; (b) winch details; (c) logs being skidding; and (d) forest worker unhooking logs.

Figura 1. Operação de extração realizada com trator agrícola com guincho: (a) trator agrícola na borda do talhão realizando a extração; (b) detalhe do guincho; (c) árvores sendo arrastadas; e (d) operador de cabo desconectando as árvores.

A pilot time and motion study was performed, using the individual timing method, in order to define the minimum number of observations necessary to reach a maximum error of 5%, according to the method proposed by Peinado and Graemi (2007) and described in eqn. (1).

$$n \geq \left(\frac{Z \times R}{E \times d_2 \times \underline{x}} \right)^2 \tag{1}$$

Where: n = minimum number of cycles required; Z = normal distribution coefficient for a given probability; R = amplitude of the actual cycle time samples observed; E = admissible error (5%); d_2 = coefficient according to the number of timings performed in the pilot study; and $\underline{x}$ = average of the observed effective cycle time values.

Sampling was performed through 124 timed operational cycles. Sufficiency was reached with 34 operating cycles to achieve an acceptable error of 5%.

Effective productivity was determined by cycle, in minutes, divided by 60, multiplying this result by the volume extracted and the number of trees by their individual mean volume, as expressed in eqn. (2).

$$Pr = n(IAV) \times \frac{t_{cycle\ i}}{60} \tag{2}$$

Where: Pr = effective productivity per machine hour (m³. PMH_0^{-1}); n = number of trees extracted per working cycle; IAV = individual average volume with bark (m³); and $t_{cycle\ i}$ = effective time to perform cycle i without delay time (minutes in decimals).

Specific consumption expresses the amount of fuel consumed per unit of the machine nominal power, where its value was determined according to the eqn. (3) (OLIVEIRA, 2013).

$$C_{spc} = \frac{D \times C_c}{Pt} \tag{3}$$

Where: C_{spc} = specific fuel consumption per productive machine hour (g.kW^{-1}.PMH$_0^{-1}$); D = density of the diesel (g L^{-1}) for this work it was used the value of 856 g L^{-1}; Cc = fuel consumption per effective working hour (L.PMH$_0^{-1}$); and Pt = nominal power of the tractor (kW).

Energy efficiency, the amount of energy per unit of nominal power of the machine to extract a cubic meter with bark, was calculated by eqn. (4) (OLIVEIRA, 2013).

$$EY = \frac{C_{spc}}{Pr} \tag{4}$$

Where: EY = energy efficiency (g.kW^{-1}.m^3); C_{spc} = specific fuel consumption (g.kW^{-1}.PMH$_0^{-1}$); and Pr = effective productivity (m^3.PMH$_0^{-1}$).

Kolmogorov-Smirnov test was performed in order to establish the data normality, before proceeding with the linear regression. Once the normality was verified, a Bartlett variance homogeneity test was performed. For data analysis, linear models were adjusted, in treatments I and II. Then, a model fitted was done with these grouped data. The adjusted model is shown in eqn (5).

$$Y = \beta_0 + \beta_1.X + \varepsilon \tag{5}$$

Where: Y = dependent variable; β_0 = intercept; β_1 = angular coefficient; X = independent variable (winching distance: distance to the yard and slope); and ε = standard error.

In order to verify statistical difference between regressions, a Graybill F test was performed, which answers if one model explains two treatments. It was verified that it was not possible for a pooled model to explain the behaviour of both productivity and energy efficiency in the two working modes.

A categorical variable (dummy) was added with the purpose of adjusting a model capable of explaining the differences in treatment, according to expressed in the eqn (6).

$$Y = \beta_0 + \beta_1.X + \beta_2.Z + \beta_3.XZ + \varepsilon \tag{6}$$

Where: Y = dependent variable; β0 = intercept; X = independent variable (winching distance, distance to the yard and slope); Z = dummy variable; and ε = standard error.

In order to assess the models, coefficient of determination (R²adj) and standard error of estimate (Sxy%) were used as parameters.

RESULTS

Below in Figure 2 is presented the contribution of each element of the operational cycle in the two treatments.
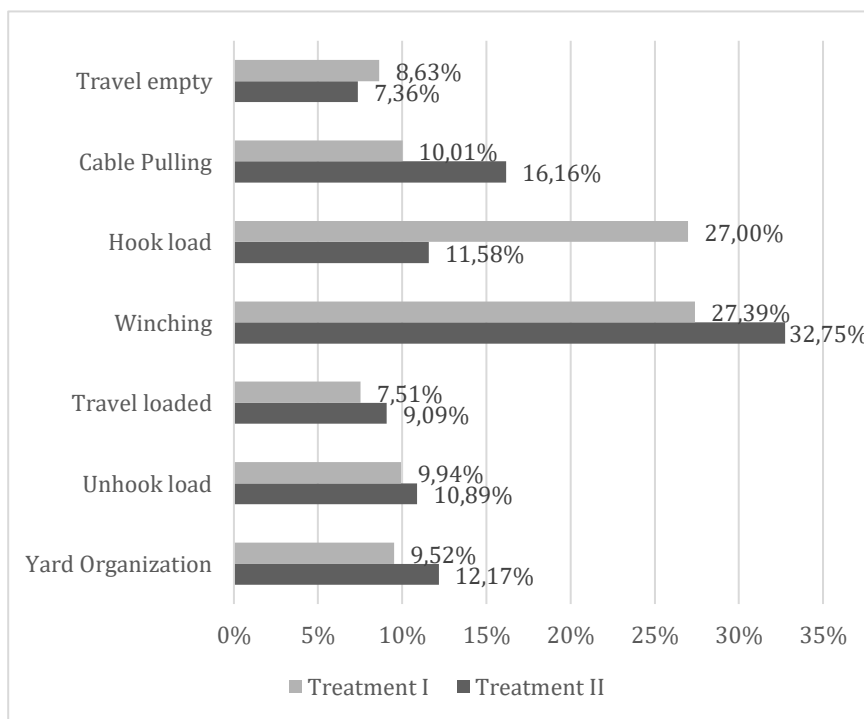
Figure 2: Distribution of time consumption by cycle elements
Figura 2: Distribuição do tempo consumido por elemento de ciclo

Table 1 shows the estimated values of productivity and energy efficiency according to the adjustment equation for both treatments.

Table 1. Estimated values of productivity and energy efficiency.
Tabela 1. Valores estimados de produtividade e rendimento energético.

Variables	Treatments	
	I	II
Productivity ($m^3\,PMH_0^{-1}$)	9.26	12.12
Specific fuel consumption ($g.kW^{-1}.PMH_0^{-1}$)	44.26	44.26
Energy efficiency ($g.kW^{-1}.m^3$)	4.92	3.13

*Values estimated for 100 meters winching distance.

The fuel consumption was 44.26 $g.kW^{-1}.PMH_0^{-1}$ in the two treatments studied, Table 2 summarizes the adjustments made.

The first column presents the R²Adj values. Both the adjustment of estimated productivity and energy efficiency presented a low R²Adj (0.3622 and 0.455). This accrues from the fact that the reduced model tries an adjustment with either 1 or 2 forest workers (Table 2).

Table 2. Parameters and coefficients resume.
Tabela 2. Índices do ajuste e resumo dos coeficientes.

Coefficients	Productivity		
	Reduced Mode	I	II
R²Adj	0.3622	0.6409	0.6501
Syx	1.8942	1.1541	1.3392
Syx%	17.50	10.66	12.37
β_0	16.5512	15.7872	19.8166
β_1	-0.0328	-0.0363	-0.0493
β_2	-0.0181	-0.0098	-0.0650
β_3	-0.0381	-0.0473	0.0119^{ns}
	Energy efficiency		
	Reduced Model	I	II
R²Adj	0.455	0.6888	0.6155
Syx	0.677	0.4824	0.4260
Syx%	15.81	10.41	11.49
β_0	1.8166	1.9784	1.9768
β_1	0.0133	0.0164	0.0096
β_2	0.0079	0.0053	0.0220
β_3	0.0177	0.0198	-0.0067^{ns}

R²Adj = adjusted coefficient of determination; Syx = residual standard error; Syx (%) = residual standard error; β_0 = intercept; β_1 = winching distance coefficient; β_2 = skidding distance coefficient; β_3 = slope coefficient; and [ns] = non-significant coefficients ($p>0,05$).

To highlight the differences between treatments, Table 3 presents the Graybill F test for both productivity and energy efficiency adjustment.

Table 3. Graybill F test results.
Tabela 3. Resultado do Teste F de Graybill

Model	F calc	F tab
Productivity	9.25044*	2.68147
Energy efficiency	4.10560*	2.68147

*Significative calculated F at the level of 95% of confidence.

Using ANOVA, productivity (m³ PMH$_0^{-1}$) and energy efficiency (g.kW^{-1}.m³) could not be estimated by a single adjustment with the pooled treatments data. This expressed the need to adjust the working modes separately, since they have different behaviours. Therefore, an adjustment model was performed with the dummy variable (Table 4).

Table 4. Indexes and adjustment coefficients with a dummy variable resume.
Tabela 4. Índices e coeficientes do ajuste com a variável *dummy*.

	Productivity	Energy efficiency
R²Adj	0.7242	0.7375
Syx	1.2260	0.4623
Syx%	11.33	10.80
β_0	19.8166	1.9768
β_1	-4.0295	0.0016
β_2	-0.0493	0.0096
β_3	-0.0363	0.0164
β_4	-0.0650	0.0220
β_5	-0.0098	0.0053
β_6	0.0119	-0.0067^{ns}
β_7	-0.0473	0.0198

Where: R²Adj = adjusted coefficient of determination; syx = residual standard error; syx (%) = residual standard error; β_0 = intercept; β_1 = alternative mode dummy coefficient; β_2 = multiplication of treatment I dummy variable by winching distance; β_3 = multiplication of treatment II dummy variable by winching distance; β_4 = multiplication of treatment I dummy variable by skidding distance; β_5 = multiplication of treatment II dummy variable by skidding distance; β_6 = multiplication of treatment I dummy variable by slope; β_7 = multiplication of treatment II dummy variable by slope; and [ns] = non-significant coefficients (p>0,05).

Figure 3 shows the productivity behaviour with the increase of winching distance. At the same winching distance, the treatment II is more productive, has a larger intercept and a different angular coefficient in relation to the adjustment with the traditional modal only. This is due to the difference of the intercept coefficient in the two working modes and because the regression lines tend to intersect at a point of greater winching distance. The fact that the two lines intersect at greater distance results from the loss of efficiency with the addition of a second forest worker since the cycles become longer at greater distances.

Although the productivity improvement with two forest workers is sensitive to the increase of the winching distance, the same does not occur with the energy efficiency. It presents different intercepts, but a certain parallelism between the tendency lines of the estimates with both working modes (Figure 3). This improvement of productivity was responsible for making the alternative mode present a better energy efficiency, being able to extract the same wood volume using less fuel.

It can be observed above that energy efficiency and productivity are negatively influenced by winching distance, becoming smaller as the winching distance increases.
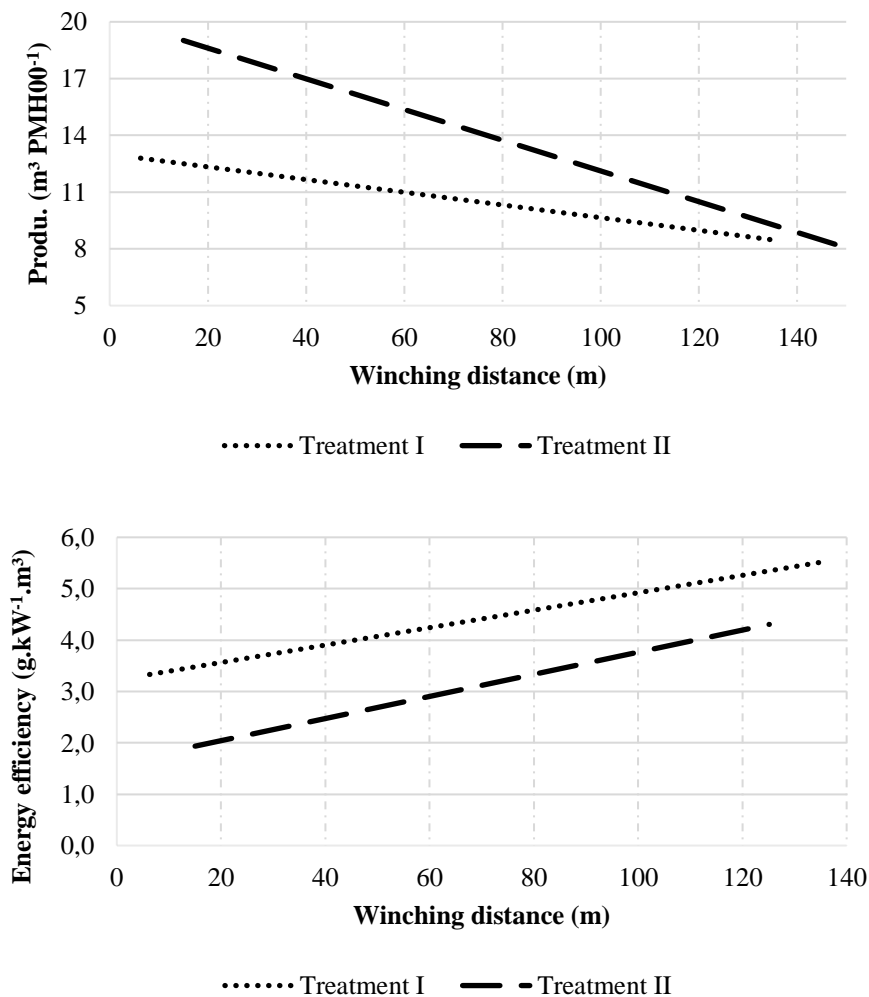
Figure 3. Productivity (m³.PMH0$_0^{-1}$) behaviour related to winching distance increase and energy efficiency behaviour related to winching distance increase

Figura 3. Comportamento da produtividade em relação com o aumento da distância de guinchamento e comportamento do rendimento energético em relação ao aumento da distância de guinchamento

DISCUSSION

It can be seen in Figure 2 the reduction in the participation of the hook load element in the treatment II. In a work with a choker skidder, Lopes and Diniz (2015) found values of 28% for the sum of the elements cable pulling and hook load values close to those found in this work of 27.74% in treatment II, while in treatment I this value rises to 37.01%. It is noteworthy here that the team configuration as well as the activities involved with the extraction with a choker skidder of the work of Lopes and Diniz (2015) are similar to that of a farm tractor with winch when with the treatment II.

The productivity in the best scenario found in this study did not exceed the value of 18.52 m³. PMH$_0^{-1}$, when we compared the work teams, we found that in an extraction distance of 100 meters the traditional team had a productivity of 9.69 m³. PMH$_0^{-1}$ and 12.11 m³. PMH$_0^{-1}$ in the proposed team.

In this study, a negative relationship between productivity and extraction distance was clear, as expected and also found by Simões *et al.* (2010), Lopes *et al.* (2011), Gilanipoor *et al.* (2012), Santos *et al.* (2013), Leite *et al.* (2014) and Lopes and Diniz (2015) who worked with various forms of extraction found this relationship of worsening in productivity with the extraction distance.

The results of specific fuel consumption found on this study were very close to the found by Lopes *et al.* (2011). Both machines worked on stationary driving power, which means they do not need to move inside the stand neither for the extraction with farm tractor with winch nor with cables.

For comparison purposes, Table 5 is displayed below with a compilation of various machines specific fuel consumption for forestry extraction, including a farm tractor working with irrigation studied by Simões and Silva (2012).

Table 5. Compilation of specific fuel consumption for different studied machinery.
Tabela 5. Compilação do consumo específico de combustível em diferentes estudos com maquinário.

Equipment	Sources	Power (kW)	Specific fuel consumption (g.kW^{-1}. PMH$_0^{-1}$)
Farm tractor:	The Authors (2020)	96.7	44.26
Cable:	Lopes *et al.* (2011)	102.9	45.19
Skidder:	Minette *et al.* (2004)	163	95.26
Forwarder:	Pereira *et al.* (2015)	128.3	97.88
Forwarder:	Oliveira (2013)	150	71.20
Skidder:	Oliveira (2013)	180	151.8
Skidder:	Lopes *et al.* (2009)	119	119.63
Farm tractor:	Simões and Silva (2012)	55	69.57

For higher values than those observed in this study, the most adequate method for extractions performed on forest stands, in the same conditions, is using forwarder and skidder. Cable yarding showed similar values to those observed on farm tractors, however, to perform the task with efficiency and effectiveness, more time and consequently higher investments are needed.

It can be noticed that, when using stationary driving power and working on mountainous terrains, the specific fuel consumption of both the farm tractor and the cable yarding were very close to one another. When comparing the data found in this case to those where machines had to move inside the stand to perform the extraction, the second ones present a higher specific consumption.

Simões and Silva (2012) and Simões *et al.* (2011), in studies that observed irrigation and subsoiling, found higher fuel consumption values since these activities required displacement across the whole work area. At a winching distance of 100 meters the energy efficiency of the alternative mode was 3.13 g.kW^{-1}.m³, while the traditional mode was 4.92 g.kW^{-1}.m, which represents an increase of 57% of energy efficiency with a single forest worker.

Extraction done by a cable mini-skidder in two different sites were 45 g.kW^{-1}.m³ and 20 g.kW^{-1}.m³, despite being high, these values represent operations in forests with distinct characteristics from this study ones, such as, not being a planted forest, greater species variability, winching distances superior to 200 meters, bigger diameters and selective cutting (VUSIĆ *et al.* 2013).

Both energy efficiency values found in this study are superior to those found with skidders in a forest with similar production, however the relief of the skidder study was not known (LOPES *et al.* 2009; FERNANDES *et al.* 2009).

In a similar environment, with mountainous conditions, energy efficiency was 1.79 g.kW^{-1}.m³ for a cable yarding. Despite the similarity of specific consumption to that of the farm tractor, higher productivity improved energy efficiency of the cable yarding system (LOPES *et al.*, 2011).

Analysing harvesting systems Oliveira (2013), both tractors observed, forwarder and skidder, presented energy efficiencies of 2.3 and 1.3 g.kW^{-1}.m³ respectively, both are better than the farm tractor despite working on smoother topography, on a slope of 6%.

CONCLUSION

- Second forest worker addition made the winching operation more productive;
- Specific fuel consumption of farm tractor, for wood winching operation, was the same in both treatments;
- The improvement of productivity was responsible for making the treatment II present better energy efficiency, being able to extract the same wood volume using less fuel; and
- Energy efficiency is negatively influenced by winching distance, becoming smaller as the winching distance increases.

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