Original scientific paper

Productivity and Cost Analysis of Three Timber Extraction Methods on Steep Terrain in Thailand

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Abstract

Steep terrain harvesting in Thailand has low productivity because of the shortage of suitable logging extraction methods. Common methods involve extraction using manpower on steep slopes where machines cannot operate. This study compared the utilization of log chutes against manpower and mule methods with regard to productivity and cost-efficiency in the same logging compartment in Northern Thailand. The extraction methods were divided into work elements and data were collected based on described work cycles. The log chutes clearly had the highest productivity (2.29 m^3/h) compared to the other methods. The hourly cost was lowest using manpower and the highest cost was using the log chute. However, the unit cost indicated the most economic method was the log chute (THB 72.40/m^3) and the least was using mule extraction. From a logging contractor point of view, the log chute method helps reduce the number of working days during the harvesting season and provides a higher profit for business.

Keywords: manpower, mule, log chute, cost-efficiency

1. Introduction

Substantial amounts of Thai forests are located in mountainous areas due to the growing population causing flat and moderate grade land to be taken up for agricultural purposes. In the mountainous areas, forestry or nature conservation are primary types of land use. As a consequence of mechanization, the development of timber harvesting has been successful in recent decades when productivity has raised and costs have decreased. However, despite the general development of forest machinery technology, there is no harvesting method for steep terrain that could be applied in Thailand. Manual harvesting and extraction are still common when operations are executed on challenging steep terrain, where mechanized methods such as a skidder or a farm tractor cannot operate. In light of the above, it is important to investigate other solutions to improve the productivity and cost-efficiency of harvesting. Suitable harvesting methods for use in the Tropics and developing countries are characterized by many similar features (Sessions 2007, Heinrich 1987). There are four factors that influence the determination of suitable harvesting methods in Thai forestry: low labour costs, limited investment willingness, lack of professional workers and seasonal harvesting.

Log harvesting in Thai forestry uses both tree length (TL) and cut-to-length (CTL) methods. TL is used with valuable teak and CTL with other low value tree species, which provide raw material sources for sawmills, pulp mills and power plants. Bucking is based on short dimensions for CTL, with only 1–2 m log lengths (Manavakun 2014). The short dimensions of logs and pulpwood in Thai harvesting methods is due to the fact that felling, delimbing, cross cutting, extraction and truck loading are mainly carried out manually, which restricts the maximum weight of logs. With steep terrain harvesting, the slope gradient helps in moving the logs downhill with the assistance of gravity, making extraction using manpower easier. The term »ball hooting« has been used to describe rolling and sliding logs and pulpwood using manpower down the hillside to the landing area (Wackerman 1949). This work method is arduous and time consuming, especially when applied to a large amount of timber or where there is a long distance to the roadside.

Manpower extraction has been studied on flat land in Thailand, where productivity was 3.28 m^3/h (log size = 0.011 m^3) for a working group of eight persons. In the study, ready cut eucalypt logs were extracted to small piles along the stump line, to then be loaded onto a truck; therefore, the carrying distance was shorter than the length of tree (Manavakun 2014). A similar working method was used in rubberwood plantations, where the productivity was 4.09 m^3/h for a working group of four persons, the average log size was 0.038 m^3 and the length of trees was 20.4 m (Chuayyok 2014).

Another non-mechanical method uses animals for extraction. Animal extraction is still a reality in mountainous areas in Asia, Latin America and Africa, where it may even be a future solution for a sustainable management of mountainous areas and contribute to the development of the livelihoods of local communities (Rodrigues et al. 2017). In Thailand, the only suitable animal is the elephant (Korwanich 1974). The feasibility of animal power should only be considered after obtaining detailed knowledge about local operation circumstances. It can have higher productivity (3.8 m^3/h) than a farm tractor (2.8 m^3/h) when the working conditions of extraction are advantageous and the working methods properly implemented (Melemmez et al. 2014). Elephants are used in teak plantations for TL harvesting on terrain where a skidder is not able to operate. The use of mules is not common in forestry in Thailand; instead, they are mainly used for the transportation of agricultural products or for tourism and as such they are only temporarily used in the forest to provide complementary income for owners. Mule extraction is clearly a minor method compared to manpower extraction in Thailand. The use of mules spread widely before harvesting mechanization and they are well suited to hot weather, unlike horses (Brown 1950). In Thailand, mule extraction is only used for short logs, not for skidding long length logs to the landing area. A similar method was used with mules in a couple of studies in Iran. Ghaffariyan et al. (2009) studied the circumstances on 30% and 35% slope gradients and reported productivity of 3.3 m^3/h for a V-shaped saddle rack, 2.1 m^3/h for a conventional rope tightened technique for extracting firewood, and 1.2 m^3/h for a both-side-tightened technique for extracting pulpwood. Jourgholami (2012) studied the working cycle using mules and defined regression equations for lumber, pulpwood and fuelwood extractions, which predicted productivities of 0.84, 0.54 and 0.42 m^3/h, respectively, when the extraction distance was 500 m. The determining factor in productivity was mainly the extraction distance and the loading time, which were higher with pulpwood and fuelwood than with lumber. Productivity did not depend on the volume per hectare or stems size as much as on the distance and slope gradient (Sessions 2007).

A key factor in achieving cost-efficient and high productivity harvesting on steep terrain is the reduction of manual and labour-intensive work and the use of tools to achieve greater output. Not all harvesting methods are adaptable to Thailand. For example, cable logging would need a high level of professional skills to install and operate the system correctly, its high cost also being a hindrance (Studier and Binkley 1974, Sessions 2007). A considerable option for improvement in Thai logging is the log chute. Log chutes, originally made from wood for fixed installations and metal for portable chutes, use gravity to transfer logs from the logging area down to the landing area (Brown 1950). Log chutes made from polyethylene plastic were introduced in the 1970s, and since then, the length and weight of one log chute unit has remained the same. In FAO's study (1979), productivity was 5–6 m^3/h for a three person work group, when the slope gradient varied between 25% and 35% and the transfer distance was 100 m. Another FAO publication (1985) reported 1.06 m^3/h productivity for thinning harvesting in Austria, when the installed log chute was up to 60 m long, the slope gradient was 20% and diameter at breast height of trees 19 cm. Raab et al. (2002) reported productivity rates of 1.8, 2.2, 3.2 and 3.7 m^3/h for a three person work group when the average log size was 0.06, 0.12, 0.25 and 0.45 m^3 (measured under bark), respectively. The Research Agency of the Forestry Commission from UK recommended minimum 22% and maximum 56% slope gradients. The productivity of two person groups was 2.59 and 0.90 m^3/h, in two different studies, where the log size was 0.057 and 0.019 m^3, respectively. (UK Forestry Commission 1994 and 2002). The reason for different productivity rates in transferring timber in 10 m log chutes was mentioned above. The log chutes were observed to be working well with firewood log lengths of 1–2 m in Turkey, where the recommended minimum and maximum slope gradient was 20% and 60%, respectively. The productivity study revealed that the length or diameter of the log did not correlate with the transfer time. However, the length or diameter of log influenced the productivity as did the length of the log chute and slope gradient (Eroglu et al. 2007).

The aim of the current research was to investigate three extraction methods – dominant manual method, minor use of mule method and the new log chute method – by comparing their productivity rates, costs and economic profitability in thinning harvesting on steep terrain. There are no other known comparison studies of these three extraction methods. The main task was to define productivity and to investigate whether the mule or the log chute methods were more efficient than manpower extraction.

2. Material and methods

2.1 Study area

The study was carried out in Chiang Mai province, Northern Thailand, where the logging compartment was located in the forests of the Royal Agricultural Station Angkhang (19°914′N, 99°048′E). The study was carried out in August 2015. The average temperature was 28 °C during field work, and exceeded 30 °C during the daytime. The slope grade varied between 26.0 and 40.6%. The mean annual precipitation was about 2000 mm. The original vegetation type was determined as hill evergreen forest. The silvicultural treatment was a selection thinning to improve stand quality. The study area was part of larger forestry area, where annual timber removal was defined to be 250 m^3. The amount of annual removal was used also for calculations of the annual work load of timber extraction in the case study, although the collected data did not cover 250 m^3 of annual cutting.

2.2 Extraction methods

In manpower extraction, the logs were moved using three different techniques. The simplest technique involved carrying the logs on a padded shoulder (Fig. 1). With the two other techniques, gravity was exploited to move the logs. Ball hooting involved rolling a log downhill by kicking using a foot or by dragging them with a rope tied around the log. The work elements are described more precisely in Table 1. The average extraction distance was 25 m to the landing area.

Mules (Fig. 1) can work five days per week for a few hours per working day in the Tropics. During hot weather, full working days are not possible; the work rate needs to be calm to avoid overstress. In this study, three forest workers and a mule made up the team. Three workers were required for the loading and unloading methods using a mule. In this method, the logs were loaded to a rack saddle, which was lifted onto the mule's back by manpower. The workers also manually lifted down the rack saddle when unloading. Because of these work elements, the workers walked between the logging area and landing area along with the mule. The average extraction distance was 25 m for the mule. The work elements of this method are described more precisely in Table 1.

Table 1 Description of work elements for three extraction methods

Method	Work element	Description
Manual	Walking	Begins when the worker starts walking towards the log to be moved and ends when the worker reaches the log
	Hooking	Begins when the worker bends down to lift the log from the ground to the shoulder or attaches a rope around the log and ends when the worker is in standing position
	Moving	Begins when the worker starts to walk with the log or drags the log or kicks the log in order to roll it down slope and ends when the worker stops at the landing area
	Piling	Begins when the worker drops the log down or bends down to remove the rope from the log or move the log by hand and ends when the worker gets the log into the stack
Mule	Walking	Begins when the workers and mule walk towards the log and ends when they reach the log
	Loading	Begins when the workers take down the rack and ends when the rack is loaded and tightened on the mule's back
	Carrying	Begins when the workers and mule start to move and ends when they stop at the landing area
	Unloading	Begins when the workers start to take the rack down and ends when the empty rack is placed on the mule's back
Chute	Walking	Begins when the worker starts walking towards the log and ends when the worker reaches the log
	Lifting	Begins when the worker bends down to lift the log to the shoulder and ends when the worker is in a standing position
	Carrying	Begins when the worker starts to walk with the log and ends when the worker stops next to the log chute
	Sending	Begins when the worker starts to send the log to chute and ends when the log is in the chute
	Stacking	Begins when the worker starts to take log from the end of the chute and ends when the log gets into the stack

Fig. 1 Three different timber extraction methods: a) Manual method, b) Timber extraction by mule, and c) Log chutes

With the log chute method, the study included the installation and take off time of the chutes. The additional time was only roughly estimated for this study based on field experiment, because this was the first time that log chutes were used in Thailand and hence experienced staffs were not available. The log chutes were made from split polyethylene pipes by sawing and drilling adequate amount of holes on both sides for attachment ropes. The total length of the installed log chute was 48 m, where the average distance was 24 m. Two workers dispatched the logs and one worker stacked the received logs (Table 1).

2.3 Productivity

The productivity of extraction work was studied based on a work cycle method. Every extracted log was measured on the landing area and the log volume was calculated. The time for one work cycle was measured using a stop watch (cmin) during the field experiment. Hourly productivity was determined using Eq. (1) for each extraction method. The productivity of manpower extraction was calculated from the time study data of the four different forest workers. Productivity rates for mule and log chute extraction were calculated for a three person working team. Additional time for log chutes was installation and de-installation times, which were divided to every log and allocated to work cycles.

$$P = \sum \frac{60x}{\frac{t_{\text{add}}}{N_{\text{logs}}} + t_{\text{tot}}} \quad (1)$$

Where:

- P productivity, m^3/h
- x log volume, m^3
- t_{add} additional time for log chutes installation and take off, min
- N_{log} number of logs in each installation
- t_{tot} total time for one work cycle, minutes/work cycle.

2.4 Cost calculation formulas

The basic components of the cost calculation are presented in Table 2. The cost structure for manpower did not require detailed labour cost calculations. The direct salary cost is the only actualized cost factor without any indirect social security contribution or daily allowances. The forest workers were local, and their work contract ended after the logging operations were finished. The labour cost was also only a variable cost and was uniformly defined for all extraction methods. Relevant fixed costs were allocated to the mule and the log chute methods. Purchase price included necessary ropes for the mule and log chutes and a rack saddle for the mule. Salvage price was for recycling the plastic used in the log chutes. Overhead cost was calculated only for the mule extraction and covered normal pasture, feed pellets and shelter only when the mule was used for forest work, not for the whole year. Utilization time was based on the annual work load and productivity rate of this study. Duration of working day was restricted to be shorter for the mule than for humans.

The common machine cost model was used for cost calculations, which was adapted to the mule and log chute extraction methods with certain changes. The fixed cost calculation was determined using the following formulas. Eq. 2 included the average value of annual investment formula, which is generally established for forestry (Miyata 1980, FAO 1992). It was used to determine cost of annual interest (Eq. 3). Annual straight-line depreciation was calculated as described in Eq. 4 (Kaakkurivaara and Korpunen 2017), whereas medicine costs of mule were estimated based on Eq. 5 (Rodriquez and Fellow 1986).

Table 2 Cost factors for three extraction methods

	Cost factor	Manpower	Mule	Log chute	Unit
Fixed costs	Purchase price	–	18,500	37,070	THB
	Service life	–	10	10	a
	Salvage value	–	15	1	%
	Salvage value, *SV*	–	2755	371	THB
	Interest for capital Int	–	6	6	%
	Overheads (Fixed+Variable)	–	*	–	%
Variable costs	Hourly wage	37.5	37.5	37.5	THB/hour
	Amount of workers	1	3	3	person/method
	Duration of working day	7	5	7	hour/day
	Annual workload	250	250	250	m^3/a

* see equation 7.

$$AVI = \frac{(PP - SV)(SL + 1)}{2SL} + SV \quad (2)$$

Where:

- AVI average value of annual investment
- PP purchase price
- SV salvage value
- SL service life.

$$C_{\text{Int}} = AVI \times \frac{Int}{100} \quad (3)$$

Where:

- C_{Int} cost of annual interest
- Int Interest percentage for capital average value of annual investment.

$$C_{\text{Dep}} = \frac{PP - SV}{SL} \quad (4)$$

Where:

- C_{Dep} cost of annual depreciation.

$$C_{Med} = \frac{PP}{AW} \times 0.05 \quad (5)$$

Where:

C_{Med} medicine and veterinary service costs of mule per year

AW annual workload.

For calculation of variable costs, labour costs were determined based on the working hours and the hourly wage (Eq. 6). The log chutes did not include overhead costs. Instead, mule extraction included an overhead cost, which took into account the annual quantity of working days in the forest (Eq. 7). It was essential to use the above-mentioned annual workload (m^3) for calculating the cost per hour (Eq. 8) in order to make the calculation consistent with the case study situation. Furthermore, this cost calculation expressed expenses in Thai baht per cubic meter (Eq. 9).

$$C_{Labor} = C_{Per} \times N_{Per} \times DH \times QD \quad (6)$$

Where:

C_{Labor} labor costs of working team per hour

C_{per} hourly salary

N_{per} number of workers

DH duration of working hours per day

QD quantity of working days per year.

$$C_{Total} = (C_{Int} + C_{Dep} + C_{Med} + C_{Labor}) \times \left(1 + \frac{OHC}{100} \times \frac{QD}{365}\right) \quad (7)$$

Where:

C_{Total} total costs per year

OHC overhead cost percentage (%).

$$C_{Hour} = C_{Total} / AW \quad (8)$$

Where:

C_{Hour} cost per hour.

$$C_{Cubic} = \frac{C_{Hour}}{P} \quad (9)$$

Where:

C_{Cubic} cost per cubic meter.

3. Results

3.1 Productivity

The productivity results of extraction are presented in Table 3. The log chute method included half hour for installation and ten minutes for taking it off. Despite of this, the working cycle of the log chute was the fastest. The maximum and average working times were shorter than the corresponding values measured for mule or manpower. The slowest method was clearly mule extraction. Slowness affected even the observed number of work cycles in the field survey. The collected data included only 21 work cycles for mule extraction, but several hundred from the manpower and log chutes. The number of observations on manpower extraction was determined for simultaneous work of the four forest workers in the logging area. Productivity of the log chute was significantly the highest (2.29 m^3/h), being five-fold compared to mule extraction and eight times higher than manpower extraction.

Table 3 Productivity of each extraction method, excluding delays (the manpower included one person, while the mule and log chute methods operated by three persons)

	Manpower	Mule	Log chute
Minimum working time min/work cycle	0.14	9.53	0.25
Maximum working time min/work cycle	2.96	17.6	1.78
Average working time min/work cycle	0.86	12.83	0.31
S.E.	0.03	0.46	0.01
S.D.	0.48	2.09	0.15
Variance	0.23	4.37	0.02
N	357	21	790
Productivity, m^3/h	0.30	0.45	2.29

The operation times for the different extraction methods were calculated based on working hours and days, which was based on the annual work load in the

Table 4 Annual operation time for three extraction methods based on annual workload of logging area (250 m^3) and productivity rates in case study (the manpower included one person, while the mule and log chute methods operated by three persons)

	Manpower	Mule	Log chute
Quantity of working hours hours/a	847.5	555.6	109.2
Quantity of working days days/a	121.1	111.1	15.6

forestry area (Table 4). The log chute method would need about 109 working hours, which means about 16 working days. In contrast, the mule and manpower methods would need roughly seven times more working days to carry out extraction. The difference in the required working days between these two methods compensated for the two hour shorter working day of the mule even though mule productivity was higher than that of manpower.

3.2 Cost calculation

The results of the hourly cost and unit cost for the manual, mule and log chute methods are presented in Table 5. As expected, the cheapest hourly cost was for manpower (THB 37.5/h), because it did not include any costs other than the direct salary cost. Mule extraction was over three times more expensive, as it involved the hourly wage of three workers and the costs for the mule, which together were THB 12.92/h. The hourly cost of the log chute was 4.5 times higher than for the manpower method. Nevertheless, the cheapest unit cost was recorded for the log chute (THB 72.40/m^3). The manpower method was almost double and the mule method was almost four times more expensive compared to the unit cost of the log chute.

Table 5 Extraction costs of three methods based on productivity study and cost calculation

	Manpower	Mule	Log chute
Hourly cost, THB/h	37.50	125.42	165.80
Unit cost, THB/m^3	127.12	278.70	72.40

The results of the case study are presented in Table 6, which was used as an example to study the economic viability of the extraction methods. The felling cost and income were the same for all methods. These values were actualized values based on practice. The high cost of mule extraction resulted in an operating loss (THB –20,568), which means that even the income from timber selling cannot cover the costs. In contrast, manpower extraction produced almost the same amount as profit (THB 17,328). The log chute provided cost savings and the log chute method had the highest benefit-loss value (THB 31,007), which underpinned the excellent 1.70 benefit cost ratio.

Table 6 Case study results (THB) of annual logging operation (250 m^3)

	Manpower	Mule	Log chute
Felling cost	25,893	25,893	25,893
Extraction cost	31,780	69,675	18,000
Total cost	57,672	95,568	43,993
Income	75,000	75,000	75,000
Benefit-loss	17,328	–20,568	31,007
Benefit cost ratio	1.30	0.78	1.70

4. Discussion

This study collected for the first time accurate productivity data on manpower extraction in steep terrain in a Thai forest. The low productivity of manpower was a surprise. The extraction productivity of short logs using manpower was 0.30 m^3/h in this study, which is about ten times lower than the manual method used with eucalypt logs on flat terrain (Manavakun 2014). Ball hooting did not seem to increase productivity, even though the physical stress was reduced by kicking and dragging logs downhill. On the other hand, walking back uphill certainly did not help workers to recover before moving the next log down to the landing area. It seems that ball hooting was not an efficient method to extract short logs in tropical conditions.

In our study, mule extraction productivity was 0.45 m^3/h, which was similar to that reported by Jourgholami (2012), whose results were between 0.42 and 0.84 m^3/h. However, our results were less than reported in the studies by Melemez et al. (2014) and Ghaffariyan et al. (2008), who reported the productivity of mule extraction as 3.80 and 2.14 m^3/h, respectively. These higher rates may have been dependent on the distance, log size and extraction equipment. In our study, the loading and unloading of the saddle racks required plenty of time in every work cycle, even when three forest workers were involved in extraction. Two other factors influencing low productivity were the maximum carrying capacity and the lack of experience in forest work. An average mule can carry approximately 100 kg per work cycle. The mule used had been trained to transport agricultural products; therefore, it was not familiar with the work elements in log extraction.

The study revealed high productivity rates for the log chute method, even though the log chutes were used for the first time in Thailand during this study. The productivity of the log chute method was 2.29 m^3/h, which was about the same as reported in the studies by Ghaffariyan (2014) and UK Forestry Commission (1994). The forest workers were mostly seasonal workers coming from rural villages, but this new method did not cause any trouble for them. On the contrary, the log chute method was the most favored by forest workers, because it helped to reduce work stress. The workers did not need to carry the logs at long distances.

The cost analysis showed clear differences between the extraction methods. Generally, the manual method was not the most cost-efficient when compared with the log chute method. The extraction operation could be carried out at half the cost by using log chutes. The literature review showed that Ghaffariyan (2014) reported USD 1.99/m^3 (approx. THB 66/m^3) unit cost for the log chutes, which was very close to our calculation of THB 72.40/m^3. The very high cost for mule extraction (THB 278.70/m^3) corresponded to the finding by Jourgholami (2012), where the extraction cost was USD 15/m^3 (THB 495/m^3).

This case study highlighted well the economic feasibility of extraction methods for Thai forestry using logging contract work. The normal use of manpower was not the poorest choice. It did not need any investment, and it provided quite a good profit. Mule extraction was not an option because the income did not cover the minimum salary for the workers. The working method should be developed to be more efficient either by reducing the necessary number of workers or by speeding up the work cycle. The mule itself was not costly; hence it may be reasonable to keep it when not working and when it is not needed for agricultural or tourism activities. The log chute was the fastest and most cost-efficient option. The low investment in log chutes allows a contractor to extract more cubic meters during the harvesting season and, with this method, the highest profit is achieved per cubic meter.

5. Conclusions

The log chute method was the best choice for harvesting short logs in steep Thai terrain. Productivity and cost-effectiveness were significantly better than with manpower or mule extraction. The field study showed other aspects of log chutes. There are several advantages in using log chutes: easy installation, reduced work stress, reasonable price investment, expandable total length and minimal environmental disturbance. However, there are also some limitations in using log chutes, which should be borne in mind: danger zone around end point for workers, need of a rubber mat to protect the log when it stops at the end point, suitable only for short logs, cannot be used in flat terrain and is limited to downhill extraction if a winch is not supplied. Future studies should determine the maximum length of logs and implement log chutes in teak plantation logging.

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6. References

Brown, N., 1950: Logging, The principles and methods of harvesting timber in the United States and Canada. New York, USA. 417 p.

Chuayyok, S., 2014: Productivity and cost of para rubber logging operations in Surat Thani province. Masters thesis. Department of Forest Engineering, Faculty of Forestry, Kasetsart University, Thailand, 137 p.

Eroglu, H., Acar, H., Ozkaya, S., Tilki, F., 2007: Using plastic chutes for extracting small logs and short pieces of wood, from forests in Artvin, Turkey. Building and Environment 42(10): 3461–3465.

FAO, 1979: Mountain forest roads and harvesting. Technical report of the second FAO/Austria training course on forest roads and harvesting in mountainous forest, Ort and Ossiach, Austria, 3 June – 2 July 1978. FAO Forestry paper No.14, Rome, Italy, 174 p.

FAO, 1985: Logging and transport in steep terrain. Report of the Fourth FAO/AUSTRIA Training Course on Mountain Forest Roads and Harvesting, Ossiach and Ort, Austria, 30 May to 26 June 1983. FAO Forestry paper No.14, Rev 1. Rome, Italy.

FAO, 1992: Cost control in forest harvesting and road construction. FAO Forestry Paper No. 99. FAO, Rome, Italy, 106 p.

Ghaffariyan, M.R., Durston, T., Sobhani, H., Mohadjer, M.R.M., 2009: Mule logging in Northern Forests of Iran: A study of productivity, cost and danger to soil and seedlings. Croatian Journal of Forest Engineering 30(1): 67–75.

Ghaffariyan, M.R., 2014: A short review of efficient ground-based harvesting systems for steep mountainous areas. Bulletin of the Transilvanija University of Brasow, Series II 7(2): 11.

Heinrich, R., 1988: Introduction to appropriate forest operations in supporting rural development. Appropriate Forest Operations, Proceedings of FAO/Finland training course Philippines 23.11.–11.12.1987. FTP Publications: Forest Harvesting 24. FINNIDA, Helsinki, Finland, 88–103 p.

Jourgholami, M., 2012: Small-scale timber harvesting: Mule logging in Hyrcanian forest. Small-scale Forestry 11(2): 255–262.

Kaakkurivaara, T., Korpunen, H., 2017: Increased fly ash utilization – value addition through forest road reconstruction. Canadian Journal of Civil Engineering 44(3): 223–231.

Korwanich, A., 1974: Logging. Kasetsart University.

Manavakun, N., 2014: Harvesting operations in eucalyptus plantations in Thailand. Dissertationes Forestales 177. Dissertation, University of Helsinki, Finland, 111 p.

Melemez, K., Tunay, M., Emir, T., 2014: A comparison of productivity in five small-scale harvesting systems. Small-scale Forestry 13(1): 35–45.

Miyata, E., 1980: Determining fixed and operating costs of logging equipment. Forest Service, North Central Forest Experiment Station, St. Paul, MN, General Technical Report NC-55, 14 p.

von Raab, S., Feller, S., Uhl, E., Schäfer, A., Ohrner, G., 2002: Aktuelle Holzernteverfahren am Hang. LWF aktuell, Magazin für Wald, Wissenschaft und Praxis. Nr 36, Bayerische Staatsforstverwaltung, Munich, Germany.

Rodrigues, J.B., Schlechter, P., Spychiger, H., Spinelli, R., Oliveira, N., Figueiredo, T., 2017: The XXI century mountains: sustainable management of mountainous areas based on animal traction. Open Agriculture 2(1): 300–307.

Rodriguez, O., Fellow, A., 1986: Wood extraction with oxen and agricultural tractors. Forestry paper 49. FAO. Rome, Italy, 92 p.

Sessions, J., 2007: Harvesting Operation in the Tropics. Springer, Germany, 170 p.

Studier, D.D., Binkley, V.W., 1974: Cable logging systems. Division of timber management forest service, U.S. Department of Agriculture, Portland, Oregon, USA, 204 p.

UK Forestry Commission, 1994: Glenfinnan log chute. Forest Research Technical Note 6/94. The Research Agency of the Forestry Commission, 12 p.

UK Forestry Commission, 2002: Log chute extraction of a broadleaved crop. Information Note ODW 9.10, The Research Agency of the Forestry Commission, 4 p.

Wackerman, A., 1949: Harvesting timber crops. The American Forestry Series, McGraw-Hill Book Company, inc. New York, USA, 437 p.

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