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A SHORT REVIEW OF EFFICIENT GROUND-BASED HARVESTING SYSTEMS FOR STEEP AND MOUNTAINOUS AREAS

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Abstract: *There is an increased interest to find cost-efficient and environmentally sound options for timber harvesting in steep terrain since such operational conditions are widespread around the world. Several low or fully mechanized options were tested in steep terrain in order to assess their performance. This study gives an overview on achieved results when testing ground-based forest equipment such as harvesters, forwarders, skidders and chutes on steep terrain. The results as well as the testing conditions presented herein may help forest practitioners in decision making on what kind of equipment to use in similar work conditions.*

Keywords: *ground-based logging, feller-buncher, harvester, skidder, tractor, chute, productivity, environmental impact.*

1. Introduction

Increased environmental concerns coupled with higher harvesting costs have renewed interest in the impacts of ground based harvesting systems on steep terrain. Harvesting impacts include such things as erosion risk, soil and site disturbance, residual stand damage, and unfavorable aesthetics. When ground-based systems are used, these adverse impacts become increasingly severe as slopes become steeper and logging difficulty increases [8]. This review includes an analysis of some of the studies performed so far on chutes, forest tractors, skidders, forwarders, harvesters and feller-bunchers, in order to emphasize figures concerning the performance in use of forest equipments. Key factors such as operational patterns, productivity, environmental impact and operational conditions are also discussed.

2. Feller-bunchers, harvesters and forwarders

There are two common types of fully mechanized felling methods: 1) Felling-bunching - where the tree is grabbed, felled and is placed on the ground and 2) Directional felling with harvester (dangle) heads – where the tree is grabbed, felled and the butt end of the tree while still secured is guided to the ground. The

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mechanized cut-to-length system using a harvester and a forwarder introduced from Scandinavia has been developed for even-aged, coniferous stands with small-sized up to volume of one cubic meter. Because of the silvicultural demands in Central Europe, harvesting technologies must be modified [12]. For instance, in Baden-Wuettenberg (Southern Germany) the Koenigstiger tracked harvester was used to fell, delimb and buck the stems to the assortments for forwarding operation in selective cutting on steep slopes. Then, the logs were extracted with a Valmet 860 forwarder to the landings at the forest road. In this particular case, the slope averaged 40%, while in these conditions, the harvester managed to cut and process on average 16-18 m^3/h or 25-40 trees/h. In a similar study performed in Switzerland [21] productivities of 21 m^3/h or 24 trees/h were reported. Based on hourly cost of 153.4 Euro/h, the costs of felling, processing and bucking were 8.7-9.7 Euro/m^3. Forwarding operation in this study yielded a productivity of 12 m^3/h and a cost of 7.15 Euro/m^3. Following the use of this system 14.8% of the residual stands was damaged [12]. In an Austrian case study a Valmet 911 Snake tracked harvester was used on slopes ranging from 22 to 56%. The productivity for an average tree volume of 0.6 m^3 was 22 m^3/h, which was very high in such conditions characterized by steep terrain. In thinning operations increasing slope has decreased the productivity. In addition, the production rate in thinning operations was lower than in clear-cut operations [18]. The Valmet 500T was studied in Stanislaus National Forest of California where average slope was 30%. This machine is a purpose-built harvester, especially designed for steep-terrain operations. It consists of a heavy-duty Caterpillar 325 undercarriage, connected to the main rotating platform through a self-leveling joint. The platform can tilt 27° to the front, 7° to the rear and 20° on both sides. The average production of this harvester for natural sands and plantations were 25.1 m^3/h and 11.3 m^3/h respectively. Tree volume and branches had significant effects on the productivity. This machine could negotiate rough terrains and is flexible enough to harvest different stand types due to its self-leveling carriers and efficient harvesting head [17]. The Ponsse Ergo Harvester was studied in Georgia when operating in steep terrain of *Pinus* (slope between 0 and 46%). The harvester has self-leveling cab feature which keeps the cab and operator level even on steep slope. In this case, study slope had a significant impact on moving time, swing time and total productive time [3]. In Japan, the small and large size harvesters were studied when operating on slopes of 40%. The working time was not significantly different in thinning operations between the two harvesters [9]. A recent development in western Norway is the use of harvesters and forwarders in very steep terrains. In such a steep terrain (up to 75%) the skid roads were constructed firstly by an excavator. Then a harvester with crane and chain saw were used to fell the trees. After this phase, a Valmet forwarder extracted the logs through the skid roads with average slope of 25-30%. The production rates of harvester, forwarder and chainsaw averaged 29 m^3/h, 10 m^3/h and 10 m^3/h [11]. The other option in steep terrain is using cable forwarders. In Germany, the PistenBully was connected by a deflection roller with the cable of the winch at the rear tow-bar of the forwarder Timberjack

1010 B. The forwarder was able to operate downhill extraction up to 85% without slippage with the average productivity of 6.1 m^3/h. The soil was not highly disturbed due to decreasing slippage. The researchers proposed that most flexible way would be putting the winch on an old skidder with a traction force of 80 kN [4].

In Southern Austria, a Gremo 950R forwarder was used to extract the logs that had been cut and piled by a harvester. In steep terrain, this forwarder uses a cable which is fixed to a standing tree in order to allow the machine to operate safely on steep trails [20]. For an average slope of 39% the production of downhill forwarding was about 20.36 m^3/h and the cost was about 5.89 Euro/m^3.

3. Skidders and tractors

Dozers are limited to a maximum of 75% downhill respectively a 55% uphill slope. Common forestry practices are that tracked skidders have an operational ground slope limit between 40-50%, depending on other site factors. Dozers are used to access ground too steep or rough for wheeled machines. The most critical terrain hazards for dozers are side slopes over 40%, rock, unstable soils, wet areas, and boulders. The wheeled tractors (skidders) can operate on the slope up to 35% [10]. Skidding can be performed overland or on a skid road. Disadvantages of overland skidding arise when slopes become moderately steep (30-40%) and begin to limit the mobility and efficiency of rubber-tire skidders, at which time the potential for adversely impacting the site increases [16]. Most of the potentially detrimental soil disturbance associated with ground-based systems takes place on steep slopes in mountainous terrain ranging in the slope from 30 to 50%. Soil disturbance is related to skid road construction, cross-contour skidding, and improper rehabilitation or drainage control measures. These disturbances can result in mass wasting and erosion. A Canadian study showed that seedling vigor and growth strongly related to the disturbance type on skid roads. The growth of species on the inner track was generally poorest [15]. An alternative method in steep terrain is that referring to the use of preplanned bladed skid roads to reduce stand damages. Ericson et al. (1991) reported a productivity of 11.7 m^3/h for John Deere cable skidder in West Virginia where slope ranged from 20 to 40%. Variables such as skid distance, turn volume, number of trees per turn and slope had a significant impact on skidding time. The productivity was reduced by 17.9% as compared to overland skidding [8]. In the mountains of western Virginia the site disturbance of ground-based logging was studied. Average slopes for tracts ranged from 21 to 43%. Logged slopes exceeded 50 percent. Six to 15 percent of the area was slightly disturbed; a condition which would increase the risk of soil movement on the tracts but not impact tree growth. Some soil compaction did occur but the amount (1 to 3 percent of the tract area) was too small to develop inferences concerning tree growth or water inflation [19]. Marence and Kosir (2007) tested two kinds of wheeled skidders (Woody 110 and AGT 835) on different slopes. They indicated that proper load formation (butt-end forward if possible) in uphill skidding is more effective on steeper slopes. Borz et al. (2013) tested two winch skidders (TAF 657 respectively TAF 690 OP) in wind-throw cuttings, located on a slope ranging from 6 to 61%. For skidding distances in range of 871-980 m, they found out that the gross and net production rates were, in average, of 3.46-6.53 m^3/h. In another study performed in group shelterwood cuts [5], a net production rate of 12.65 m^3/h was achieved for a TAF 690 OP machine in conditions of a mean slope of 30% and a skidding distance of 1037 m. Of course, in this the extraction intensity was greater while the average terrain slope was significantly smaller.

4. Chutes

Modern timber chutes are slides constructed from synthetic materials shaped into channels that carry timber using gravity force. Nowadays the chutes channels are used in Europe in steep terrains. The channels have an internal diameter of 350 mm with the thickness of 9 mm. The length of each channel is 5 m which weighs 25 kg. Because of ergonomic and economic reasons the best length of wood is from 2 to 4 m with the maximum diameter of 30 cm at larger end. Minimum and maximum required slope are 15-25% and 50% respectively. The speeds larger than 15 m/s should be avoided because of safety reasons. In a case study in Rendsina in Austria the chutes were used in the slopes of 35% where forwarding operation was not possible because of the ecological restriction due to wet soil and rainy weather. A skyline was also not an option since low harvested volume per ha. For these reasons, to operate thinning mechanically, the only option was using chutes. The average productivity was about 2.32 m^3/h for average chute length of 73 m [14]. According to a wooden chute study in Turkey, productivity was found as 5.9 m^3/h at the slope of 37% and the transport of softwood from 300 meters in Rize, İkizdere region [2]. In the other Turkish study, chute has been settled on to the slope ranging from 5% to 40% and 770 stere fuel wood has been carried along a line of which length was 364 m. The efficiency was 2.14 steres/h with the cost of 4.63 US$/h for this study [1]. This kind of equipment represents also a viable alternative to manual-gravitational bunching in steep terrains and low extractions, options which yield also smaller productivities [7] and disturb the soil and residual stand to a greater extent.

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