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RESEARCH ARTICLE

# Reviewing productivity studies of skidders working in coniferous forests and plantations

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## Abstract

Skidding is an important element of harvesting operations, which contributes to the extraction of wood. A skidder can be used in different types of harvesting operations, such as thinning, clear fell, native forest thinning or salvage work. The main goal of this article was to review the available studies on productivity of skidding operations in coniferous forests/ plantations. Information on skidder productivity was collected from publications and then was classified in three regions, including North America, Europe and the Southern Hemisphere. The parameters affecting machine productivity included machine type/ size, tree volume/ log volume/ load volume, average skidding distance and slope of the ground for each reported productivity. The average productivity reported in the published reports ranged from 9.3 $m^3$/PMH to 78.0 $m^3$/PMH. Detailed information and conclusions collected from various studies can be of use to forest academic and industry users to gain knowledge about variations of skidder productivity in different regions and site/ operation conditions, which can be helpful for predicting, controlling and improving current levels of productivity.

## Keywords

Harvesting, Skidder, Productivity, Time study, Skidding distance, Load volume

## Introduction

Skidding is an important element of harvesting operations, which contributes to the extraction of wood (Conway, 1982; Uusitalo, 2010). A skidder is a large front-line forest machine. The main function of which is to skid or to snig logs or entire trees held by a large grapple attached behind the machine in a toeing action. For some ground conditions or difficulty in getting logs or trees, the skidder may be fitted with a powerful winch and a cable. A skidder can be fitted with different implements, depending on the harvesting (Commonwealth of Australia, 2011). The implements that can be fitted to a skidder are: different types of grapples; a winch and a cable (used to pull logs or whole trees); a dozer blade (used for levelling, repairing snig tracks, pushing up slash); a front- end slash grab (used for removing bulk slash and a single or a dual arch).

The skidder can be used in different types of harvesting operations, such as thinning, clear fell, native forest thinning or salvage work. All operations of the skidder should be conducted to meet manufacturer's specifications, contractors, forest owners and site- coupe planning policies and procedures. Operating the skidder in forest terrains and changing weather conditions is of the utmost importance when extracting trees (Commonwealth of Australia, 2011). Hartsough et al. (1994) indicated that the skidders tend to sweep duff and litter from trails, exposing bare mineral soil to possible compaction and disturbance, and thus might damage residual trees because of the relatively long lengths of the skidded whole trees. Higher damage to smaller trees can occur, which is important to consider when a diverse stand structure is desired.

## Materials and methods

Studies on work productivity of skidders have indicated that the skidding distance, piece size, load volume and the slope of the trail highly impact on the machine productivity (Sobhany, Stuart, 1991; Abeli, 1993; Egan, Baumgras, 2003; Sabo, Porsinsky, 2005; Zecic et al., 2005). Most of the above studies indicate that the skidding cycle time may include the following work elements: travelling empty, loading, moving during loading, travelling loaded to landing/ roadside, unloading/ stacking and clearing debris (Ghaffariyan, 2020).

The main goal of this paper was to review available studies on the productivity of skidding operations in coniferous forests/ plantations (Figure 1). In this review, the main parameters impacting the skidder productivity were collected from the literature and were then summarised. The parameters for each reported productivity included machine type/ size, tree volume/ log volume/ load volume, average skidding distance and slope of the ground. The average productivity reported in each study was collected from the literature. When studies reported a developed productivity predicting model, the variables included in the models were reported in this review. Work delays were excluded in this review due to variability in different operations and locations as the focus was on reporting net productivity of different skidders to enable any user to make reasonable comparisons. Review results were classified into three main regions, including North America, Europe and the Southern Hemisphere.

**Figure 1.** Grapple skidder working in pine plantations (Queensland, Australia)

The published data and information were obtained using the following sources: online research papers/ reports/ bulletins published in English language academic journals based on various searching electronic databases including Google Scholar, Scopus and Web of Science. The keywords used during the search included skidding, productivity, coniferous/ pine plantations, time study, tractor, grapple skidder and cable skidder.

## Skidder productivity studies in coniferous stands
## North America

One of the earliest studies was reported by Boe (1963) in Forest Service, United States Department of Agriculture, where tractor-logging costs were investigated in old-growth redwood forests (*Sequoia sempervirens)* located in California (USA). Diameter at breast height (DBH) ranged from 35 cm to 495 cm. Large trees were felled and bucked manually. Then logs were extracted using a D-8 tracked bulldozer. For the average skidding distance of 170 m, slope of 22% and log volume of 4.8 $m^3$, the productivity averaged at 15.8 $m^3$ per productive machine hours ($m^3$/PMH). The average log volume was the only significant factor that impacted the work productivity (Boe, 1963). In 1983, a mobility model for predicting skidder productivity was developed by Olsen and Gibbons in Oregon (USA) for wheeled skidders. According to this study, the travel time was a function of skidding distance, slope and turn weight. Machine horsepower and soil type (weak soil or a cone index of 50 and strong soil or a cone index of 250) were other parameters considered in the model (Olsen, Gibbons, 1983). A study on a John Deere 640 grapple skidder was conducted in thinning operations of 18-year-old loblolly pine plantations. The skidder was combined with a feller-buncher, which was equipped with a shear head. The bunches of trees were extracted to the roadside and were delimbed with agate delimber. The tree size varied between 0.1 $m^3$ and 0.8 $m^3$ (average load volume 2.0 $m^3$) and skidding distance averaged at 194.5 m. Mean skidder productivity was 48.4 $m^3$/PMH. The time elements of the working cycle included travelling empty, grappling, travelling loaded with full trees to the gate, gate delimbing, travelling loaded with tree lengths to the loader, various delays and gate maintenance, which consisted of cleaning limbs from around the gate. A similar study on thinning operation of loblolly pine stands was conducted by Visser, Stampfer (2003). The average DBH was 21 cm and the average skidding distance was 204 m. The terrains were flat. The reported productivity for a Tigercat 630 skidder was 42.9 $m^3$/PMH. Visser, Stampfer (2003) developed the productivity predicting model, using variables such as skidding distance, piece volume and load volume. Hartsough et al. (1994) studied skidding operations applied to extract whole trees for biomass production in naturally-regenerated stands in the Stanislaus National Forest, California. Timberjack 450B and Caterpillar 528 grapple skidders were tested in old ponderosa pine plantation and a mixed conifer stand that had been partially logged because of a railroad in the 1940ies and had naturally regenerated afterwards. The Timberjack skidder had a larger grapple than the Cat, which led to extracting larger loads of biomass per turn. The average slope was about 25% (downhill skidding). Variables such as skidding distance, slope and number of logs per turn were significant factors, impacting the productivity predicting model (note that the productivity amounts reported by Hartsough et al. (1994) were based on BDt and the number of logs and it was not possible to accurately transfer these into $m^3$/PMH to be included in this review).

Another study on skidding productivity was conducted in the shortleaf pine (*Pinus echinata*) and loblolly pine (*Pinus taeda*) stands in western Arkansas (USA). An average productivity of 24.9 $m^3$/PMH was reported for a grapple skidder hauling trees with DBH of 30 cm in a clear-cut operation (with a power of 88 kW and an average skidding distance of 411m). For shelterwood harvesting where DBH was slightly lower (25 cm), the productivity was estimated to be about 16.3 $m^3$/PMH. For cable skidders, the productivity ranged from 1.5 $m^3$/PMH to 12.7 $m^3$/PMH for a DBH range of 15 cm to 110 cm (with a machine power of 59 kW and an average skidding distance of 345 m). The independent variables found to be statistically significant in estimating skidding time were: the total distance travelled, number of stems in the load, harvest intensity and the skidder power (Kleunder et al., 1997). Kellogg, Davis (2004) mentioned that small crawler-tractors have proven to be efficient and manoeuvrable machines for timber extraction in thinning operations and likely cause minimum damage to stands and soil. All stands consisted almost entirely of *Pseudotsuga menziesii* with some scattered western hemlock (*Tsuga heterophylla*) and western red cedar (*Thuja plicata*). Felling and bucking was operated manually, then during the thinning operation timber was extracted to the side of the road using crawler-tractors (models including CASE 550, D-5 Caterpillar, CASE

850G, John Deere 550). The slope varied between 0 and 35%, while the load volume per turn ranged from 0.58 $m^3$ to 2.5 $m^3$. The skidding distance varied between 178 m and 255 m for the different machines tested in that study. The machine productivity varied between 7.1 $m^3$/PMH and 15.3 $m^3$/PMH (Kellogg, Davis, 2004).

Dodson et al. (2006) studied the productivity of grapple skidders in Central Oregon. The western juniper (*Juniperus occidentalis*) was harvested using two systems in flat terrains: a conventional system consisting of manual felling, delimbing and bucking using a chainsaw and skidding logs with a rubber-tired grapple skidder (Caterpillar 518), and a mechanical system that used a fellerbuncher, a rubber-tired grapple skidder (Caterpillar 525) to skid whole trees and a stroke-boom delimber. In the case of the Caterpillar 518, the average skidding distance was 107 m resulting in average productivity of 88.7 $m^3$/PMH. Only stems of sawlog quality were skidded to the landing. The number of trees per turn, skidding distance and stand type (mixed stand or single species stand) were impacting significantly the skidding cycle time. In the case of the Caterpillar 525 skidder (mechanical system), the average skidding distance was shorter (99 m) resulting in average productivity of 31.1 $m^3$/PMH. Unlike the conventional system where only merchantable logs were skidded to a central landing, the mechanical system skidded all stems as whole trees (Dodson et al., 2006). Skidding whole trees was obviously more productive than skidding merchantable logs (assuming same DBH of 30 cm and skidding distance of 107 m). Adebayo et al. 2007 studied the use of crawler tractors for harvesting mixed-conifer stands (Douglas fir (*Psuedotsuga menziesii*), grand fir (*Abies grandis*), lodgepole pine (*Pinus contorta*), ponderosa pine (*Pinus ponderosa*), western larch (*Larix occidentalis*) and white pine (*Pinus strobes*) in northern Idaho. In whole- tree harvesting operations a Cat D-518 grapple crawler extracted the trees felled by a mechanical feller-buncher. The direction of skidding operation was downhill (slope ranging from 3% to 34%) at an average skidding distance of 130 m. A productivity of 58.3 $m^3$/PMH was achieved for the first study site with average load volume of 0.5 $m^3$ (average DBH of 27.9 cm) and skidding distance of 130 m. Within the second site in this study, the skidding was done downhill, while the average skidding distance was 191 m, the average load volume was 0.5 $m^3$ (with an average DBH of 27.9 cm; tree volume was not mentioned in the report), where the slope varied between 2% and 32%. The crawler productivity for the second study site was on average 38.2 $m^3$/PMH (Table 1). Despite the downhill skidding because of the longer skidding distances, the work productivity was lower. This could be due to the longer time required to travel loaded and empty over longer distances. Another study was conducted in stands of the ponderosa pine (*Pinus ponderosa*) in Arizona (Pan et al., 2008). The ground slope ranged from 0 to 28%. Small trees less than 12.5 cm were removed based on the prescribed silviculture. Trees were felled and bunched by a feller-buncher then skidded to the side of the road using a rubber-tired grapple skidder (CAT 525B). For the average skidding distance of 312 m, the skidder yielded a productivity of 17.4 Bonne Dry Tonnes (BDT)/PMH (note that the value in $m^3$/PMH was not available in the mentioned report). The cycle time was associated significantly with travel distance, position distance, number of trees per cycle and distance of travelling loaded.

Removing fuel from forests to reduce fire risk is another task conducted by skidders. Vitorelo (2011) studied this functionality in a national forest as a part of the Mt. Ashland in California (USA). The area comprised of mixed conifer forests including white fir (*Abies concolor)*, Douglas fir *(Pseudotsuga menziesii)*, ponderosa pine *(Pinus ponderosa)*, incense-cedar *(Calocedrus decurrens)* and sugar pine *(Pinus lambertiana).* A whole- tree mechanised harvest method (including feller-buncher and grapple skidder) was applied for thinning a unit with a gentle slope (0-32%). An integrated harvesting system for fuel reduction thinning was implemented because of the extraction of both large trees (DBH ≥22.5 cm) containing sawlogs and small-diameter trees (DBH of 7.5-22.5 cm) for production of combustible wood products (biomass). After tree felling-bunching, a Cat 527 high track swing boom grapple skidder, along with John Deere 648 E and 748 GIII rubber-tired dual stage grapple skidders were employed to complete the task of skidding sawlogs to the landing to be processed by a processor. Skidding distance varied between 10 m and 260 m. The cycle time included elements such as travel empty, positioning, turn building, pre-bunching biomass, grappling, travel loaded and decking. The time of the skidding cycle was significantly correlated with travelling- empty distance, travelling- loaded distance, number of pieces per turn and skidder type (tracked skidder, small- wheeled skidder or large- wheeled skidder). The average productivity for the John Deere 748 GILL, John Deere 648 E and Cat 527 were 33.4 $m^3$/PMH, 17.3 $m^3$/PMH and 24.4 $m^3$/PMH, respectively. The subsequent biomass operation began after sawlog extraction had been completed. Two skidders (John Deere 648E and 848H) were used to extract trees left along skid trails after the felling operation. There was an average of 13.9 trees per bunch as they were small trees (DBH of 7.5-22.5 cm). Skidders often accumulated the loads that averaged 1.9 bunches (averaged 26.4 trees per turn). The observed skidding distances ranged from 15 m to 215 m and were limited to slopes less than 35%. The cycle time was significantly impacted by travelling- empty distance, travelling- loaded distance and skidder size (small- or larger- wheeled skidder). The average machine productivity was 0.38 $m^3$/PMH for the small skidder and 0.39 $m^3$/PMH for the large skidder. The load volume for the skidders was influenced primarily by the grapple size. The skidder cycle times for both skidders was not much different, which was likely due to the highly comparable load volumes. Because of the low density of the biomass bundles, the smaller skidder was not limited by the load weight and forced to skid less volume than the large skidder (Virtelo, 2011).

Seven whole-tree harvesting sites (various combinations of feller-bunchers and grapple skidders) were observed by Hiesel (2012) during the summer of 2012. All sites were partially harvested, with light to heavy removal intensities. The study sites were classified as mixed hardwood (e.g. *Fagus grandifolia* and others) and softwood (*Abies balsamea, Picea rubens* and others) located in Maine. The slope varied between 0 and 18%, while the average skidding distances had a range of 50 m to 800 m.

The load volume ranged from 2 $m^3$ to 3.5 $m^3$. The skidders' power ranged from 127 kW to 162 kW. Given the mentioned operational conditions, the observed productivity of grapple skidders ranged from 13 $m^3$/PMH to 24.3 $m^3$/PMH. The skidding distance and the load volume were significant factors influencing the cycle time (Hiesel, 2012).

Pine energy plantations in Alabama were harvested using different harvesting systems including high-capacity grapple skidders (Tigercat 630D) in combination with a feller-buncher and in-field chippers within a whole-tree harvesting method (Taylor, 2015). Kelpac, Mitchell (2016) carried out a study to evaluate and compare the performance and cost of four harvesting systems while operating in a young plantation of the loblolly pine (*Pinus taeda*) in Alabama. Felling was conducted using feller-bunchers. Skidders (a Tigercat 630D rubber-tired large-capacity grapple skidder or a Caterpillar 525B rubber-tired conventional grapple skidder) were used to extract whole trees to roadside. Trees with DBH larger than 9 cm were harvested (average DBH was not reported but average tree weight was 236 kg). The terrains were gently sloping to moderately steep (average slope was not reported). The evaluated work elements included landing empty, travelling empty, position, grapple, intermediate travel, travelling loaded, landing and ungrapple. The Cat 525B skidder yielded a productivity of 77.8 green tons/PMH when working with a TimberKing 340 rubber-tired feller-buncher (woods travel distance of 180 m) and 54.2 green tons/PMH (woods travel distance of 556 m) when working with a tracked feller-buncher (Tigercat 630D). The Tigercat 630D reached a productivity of 147 green tons/PMH (woods travel distance of 335 m) when combined with a rubber-tired feller-buncher (TimberKing 340) and a productivity of 134.6 green tons/PMH (woods travel distance of 349 m) when combined with a tracked feller buncher (Tigercat 630D) (Kelpac, Mitchell, 2016).

Kim et al. (2017) reported that the mountain pine beetle had affected large forestry areas in the region of the Rocky Mountains in the United States. Their study quantified the difficulty of harvesting beetle-killed stands caused by downed trees. Whole- tree clear-cut harvesting, using a ground-based system, was studied in western Montana in August 2015. Stand conditions with various levels of downed trees affected the unit production cost and productivity of the entire harvesting system by increasing operational delays in the combined felling, skidding and delimbing operation. Harvesting machines included one tracked feller-buncher, two rubber-tired grapple skidders (John Deere 848H and Caterpillar 535C), a dangle-head processor, a stroke boom delimber and a log loader. The dominant tree species was lodgepole pine (*Pinus contorta*). The average ground slope was 9%, while the quadratic mean tree diameter was 19 cm. The skidding distance and load volume averaged at 138 m and 3.6 tons, respectively. Two of the skidders that operated simultaneously had the highest productivity (77.36 tons per PMH- note $m^3$/PMH was not available in the article) among the harvesting machines. The skidding cycle consisted of elements such as travelling empty, positioning and grappling, travelling loaded and unloading. Travel distance (distance empty and loaded) and number of trees per turn were the variables impacting significantly the time of the skidding cycle. Kim et al. (2017) noted that according to their observations, broken stems from standing dead and down trees could result in increasing cycle time and reducing productivity (due to need to spend more time clearing breakage from the site) although they had not quantify this effect in their study.

Han et al. (2018) reported that according to Duda et al. (2015), since 1996 approximately 1.37 million hectares of coniferous forests in Colorado (USA) have been affected by the eruptive populations of bark beetles. Another study on beetle-kill salvage harvesting methods was conducted in a clear-cut unit of the lodgepole pine (*Pinus contorta*) in northern Colorado (Han et al., 2018). The harvesting unit was located on a relatively flat terrain. The first method used was whole- tree harvesting, where Tigercat 615C grapple skidder extracted trees felled by a feller-buncher. The second method used was the lob and scatter method, where trees were delimbed and bucked at the stump, with an intention to leave all non-merchantable material on the forest floor. A processor was applied at the roadside to process the trees. The mean DBH for both harvest methods was 22.4 cm. With the lop and scatter method, the skidder yielded a productivity of 24.5 oven dry ton per SMH (load size of 1.5 oven dry ton), where skidding distance averaged at 140 m and average number of logs per turn was 20.2. With the whole- tree method, the skidder productivity averaged at 23.7 oven dry ton per SMH (load size of 2.5 oven dry ton) for the average skidding distance of 152 m and average number of trees of 21.9. Work elements included travelling empty, position and grappling, travelling loaded and unload. Variables affecting the work time were skidding distance and number of logs per turn.

Harvesting of forest biomass (restoration harvest practices) in the US southern Rocky Mountains was studied by Townsend et al. (2019). On the study sites, ponderosa pine (*Pinus ponderosa*) was the dominant species, with Douglas fir (*Pseudotsuga menziensii*), white fir (*Abies concolor*) and two hardwood species as secondary cohabitants. Five ground-based harvesting systems were studied. Felling and processing in different study treatments were carried out using a chain saw, tacked/wheeled feller-buncher and a harvester. The skidding was operated using a rubber-tired grapple skidder in two operation systems where trees were felled by feller-bunchers and processed at the roadside with dangle-head processors. The time of the work cycle included travelling empty, assemble turn, travelling loaded and decking/pilling. The skidding distance and number of bunches per turn were the variables affecting significantly the cycle time. The slope of both sites was 7% and 8%. DBH for the first site was 22.9 cm. The average skidding distance was 300 m with two bunches assembled containing 10.3 trees per bunch. The observed productivity averaged at 16 tonnes per Scheduled Machine Hours (SMH) (note that $m^3$/PMH was not reported in this case study) (Table 1). Townsend et al. (2019) found that skidding following hand-felling was significantly slower than other operations combined with mechanical felling at the same skidding distance. Some of the felling operators had previous experience operating a skidder, thus they could assemble optimal- sized bunch so that the skidder could achieve a full payload in a single bunch and seldom needed to assemble a second bunch or break apart a bunch that was too large for a single cycle (Townsend et al., 2019).

In Canada, skidders are utilised within whole- tree harvesting systems. A study was conducted by Andersson, Dyson (2012) in mixed stands of pine, spruce and balsam north of Veron, British Columbia. Four sites were studied. Slopes varied from 10% to 40%. Sawlogs and long logs were produced by a roadside processor following mechanical felling-bunching and wood extraction. The study showed that the grapple skidder productivity was impacted significantly by the tree size, skidding distance and slope. The tree size affected the load volume, which ranged from 5.5 $m^3$ per turn in smaller woods (tree size of 0.3 $m^3$) to 6.7 $m^3$ per turn in larger woods (tree size of 0.6 $m^3$). Steep slopes reduced travel speed and increased loading and unloading times per turn. The skidder mostly travelled empty uphill in this case study. The skidding distance varied between 50 m and 200 m (averaged at 125 m). The projected productivity for grapple skidders in the small wood stands (considering tree size 0.25 $m^3$) with a gentle slope (0 to 20%) varied between 28 $m^3$/PMH and 78 $m^3$/PMH depending on the skid distance (a range of 50 m to 200 m). On steep slopes (25% to 40%), the productivity was lower and was ranging from 20 $m^3$/PMH to 48 $m^3$/PMH for the same range of skidding distance. For larger wood (seven logs sort and tree size of 0.6 $m^3$), the skidder productivity on gentle slopes varied between 40 $m^3$/PMH and 110 $m^3$/PMH (skid distance ranging from 50 m to 200 m), while on steep slopes productivity range dropped to a range of 20 $m^3$/PMH to 65 $m^3$/PMH (Andersson, Dyson, 2012).

## Europe

The Europeans apply skidders in flat and mountainous terrains for wood extraction. Gluschkov, Markoff (2007) indicated that in the 1970ies the application of wheeled skidders started in Europe, which led to a decline in the usage of cable yarding and animal logging. In Bulgaria, tractor logging was dominant in the 1990ies, while and caterpillar tractors have been the dominant type of skidders in the country ever since (Gluschkov, Markoff, 2007). A TDT-55 caterpillar tractor (equipped with a cable winch) was used in Bulgarian forests and yielded a productivity of 5.3 $m^3$/PMH (note this was calculated based on the reported productivity of 32.1 $m^3$/day while considering a machine productive of 6 hours) when extracting large logs on distances ranging from 500 m to 700 m (Table 1). Akay et al. (2004) reported an average productivity of 19.2 $m^3$/PMH for a Cat 525 grapple skidder in Turkish forests. They explored a study area that was covered by cedars, pines and firs (species were not reported). The average load volume was 0.68 $m^3$ and the mean slope was 31%. The skidder was working in combination with a feller-buncher (in the stand), manual sawyers and loader (at the landing). A Cat D5HCS Crawler tractor yielded an average productivity of 9.3 $m^3$/PMH within similar stands (Table 1). According Akay et al. (2004), the skidder capacity was highly dependent on its drawbar horsepower, weight and traction obtainable under the ground conditions during operation. The skidding distance is generally the most important variable since it affects cycle time more than any other variables (Akay et al., 2004).

Forest operations in Croatian fir-beech mountainous forests were impacted by terrain slope, micro-relief with surface obstacles, bearing strength of deep soil, snow and ice conditions in winter and stand conditions of selective silvicultural regimes (Karpan et al., 1999 cited in Sabo, Porsinsky, 2005). Cable rubber-tired skidders are one of the conventional machines for timber extraction in Croatia. Sabo and Porsinsky (2005) studied the productivity of a Timberjack 240C cable skidder for extracting roundwood from Croatian mountainous forests. Fir-beech mixed stands were felled and processed into assortments (4-12 m), then extracted to roadside by the skidder. The average load volume was 4.4 $m^3$ and the skidding distance varied between 50 m and 400 m, while the slope ranged from 8% to 34%. The machine productivity ranged from 9.9 $m^3$/PMH to 16.9 $m^3$/PMH. A study by Spinelli et al. (2014) was carried out during the second thinning of a pine plantation located near Pisa, Italy, inside the Regional Park of San Rossore. The stand composed of an old plantation of the umbrella pine (*Pinus pinea L.*). The study included a productivity assessment of a mechanised whole-tree harvesting treatment. Pine trees were felled and bunched with a tracked feller-buncher and skidded to the roadside with a JD460 G rubber-tired grapple skidder. The average slope was 2%. DBH averaged at 23.1 cm, while the mean skidding distance and load size were 189 m and 0.9 oven dry tonnes (odt) (volume in $m^3$ was not reported), respectively. The average productivity reported for the skidder was 13.5 odt/SMH (note $m^3$/PMH was not reported) (Spinelli et al., 2014).

A John Deere 548G-III grapple skidder was studied by Kulak et al. (2017) in southern Poland in stands of *Pinus sylvestris* under treatment of late thinning, removal cutting in beech undergrowth and clear-cutting in openings. The skidding distance varied between 124 m and 246 m. The load volume per turn ranged from 1.86 $m^3$ to 2.95 $m^3$. The terrain was flat. The skidder achieved a productivity ranging from 8 $m^3$/PMH to 14 $m^3$/PMH in different study treatments. The working elements included travelling loaded, forming a load, skidding (travelling loaded), log stacking and aligning ground beams. Variables such as skidding distance, number of logs per turn, load volume and study treatments (late thinning, removal cutting and clear-cutting) were among the factors influencing significantly the time of the work cycle (Kulak et al., 2017).

## Southern Hemisphere (Australia, New Zealand and South Africa)

Oberholz (2002) mentioned that articulated wheeled skidder was an important component in the primary transportation of timber in South Africa. Among the main factors influencing the skidder productivity were the skidding distance, bunch size, terrain, grapple and engine capacity and operators' decisions. Oberholz (2002), while referring to the Guidelines of Forest Engineering in South Africa (1999), provided application limits of the skidders in South Africa (Table 2). A case study was carried out in Raiply (Malawi), South Africa, where the plantation composition included *Pinus patula*, *P. kesiya*, *P. elliottii* in addition to a small share of *Eucalyptus sp* (Ngulube, 2012). The harvesting system included a chain saw (for manual felling) and a Cat 525C grapple skidder. The harvesting method was whole- tree to roadside. The slope varied between 5% and 25% (with an average of 11.5%). The average log volume was 1.45 $m^3$ and the distance averaged at 134 m. The ground condition was reported as very good, while the terrain was slightly uneven. The results of Ngulube (2012) indicated that the skidding time per cycle was affected significantly by skidding distance, load volume per cycle, slope and ground condition (good or moderate). The work elements included driving empty, clearing, changing position, bunching, driving loaded, unloading, turning and aligning. Given the mentioned study conditions, the average productivity was 21.5 $m^3$/PMH (Ngulube, 2012). In South Africa, the cable skidder's productivity (machine power ranging from 90 kW to 130 kW) may range from 12.0 $m^3$/PMH to 49.6 $m^3$/PMH, depending on the work and site variables in the studied pine stands. The grapple skidder productivity (machine power ranging from 90 to 130 kW) might be higher than the one of a cable skidder varying from 16 $m^3$/PMH to 80 $m^3$/PMH. A Clambunk skidder with the capacity of 18 t (machine power was not reported) could yield a productivity of 5.7 $m^3$/PMH to 50 $m^3$/PMH when operating in pine stands (Oberholz, 2002).

In Brazil, skidders are applied within a whole- tree harvesting method. A study by Lopes et al. (2014) was conducted in stands of *Pinus taeda* in the Mandirituba, Parana Stare. The average slope was 8% and the average tree volume was 1.58 $m^3$ at the age of 35 years in a clear-cut regime. After felling-bunching, the bunched trees were skidded by a Cat 545 grapple skidder. Three types of skidders were used, including: skidders with four wheels equipped with tracks (SD4), skidders with front wheels equipped with tracks (SD2) and skidders with rubber wheels (SDP). The cycle time included travelling empty, manoeuvring/loading, travelling loaded, manoeuvring/unloading. For an average skidding distance of 100 m, the productivity of SD4, SD2 and SDP averaged at 59.4 $m^3$/PMH, 59.1 $m^3$/PMH and 62.8 $m^3$/PMH, respectively. Using tracks reduced the machine productivity. Another study was conducted by Diniz et al. (2018) in a 15- year old plantation of *Pinus taeda* located in the Central-West region of the state of Paraná, Brazil, in three slope classes: flat to moderate, steep and very steep. The average tree size was 0.30 $m^3$, which produced pulpwood and sawlogs. Trees were felled using a feller-buncher and whole trees were skidded with a grapple Caterpillar 525C skidder to a processor at roadside. The skidding distance averaged at 150 m and the average load size was 1.7 $m^3$. The average productivity in downhill extraction for flat to moderate (0-27%), steep (28% to 48%) and very steep terrains (>49%) were 52.8 $m^3$/PMH, 62.2 $m^3$/PMH and 34.2 $m^3$/PMH, respectively. The work cycle was divided into elements including travelling empty, loading, travelling loaded, unloading and wood yard organising.

Skidders have been applied in shortwood logging operations in Australian coniferous plantations. Whiteley (1973) reported that in the 1950ies and in the 1960ies,

**Table 1.** Summary of selected productivity studies on skidders working in coniferous stands

| Machine model | Species | Slope (%) | Load volume ($m^3$) | Average extraction distance (m) | Productivity ($m^3$/ PMH) | Reference |
|---|---|---|---|---|---|---|
| **North America**<br>D-8 bulldozer | *Sequoia sempervirens* | 22 (downhill) | 4.8 | 170 | 15.8 | Boe (1963) |
| John Deer 640 (grapple) | *Pinus Taeda* | flat | 2.0 | 194.5 | 48.4 | Lanford, Stokes (1996) |
| Tigercat 630 (grapple) | *Pinus Taeda* | flat | 3.8 | 204 | 42.9 | Visser, Stampfer (2003) |
| Grapple skidder (model not reported) | *Pinus Taeda* | flat | 2.5 | 411 | 24.9 | Kleunder et al. (1997) |
| Cable crawler (CASE 550, D-5 Caterpillar, CASE 850G, John Deere 550) | *Tsuga heterophylla*<br>*Thuja plicata* | 0-35 | 0.58-2.5 | 178-255 | 7.1-15.3 | Kellogg, Davis (2004) |
| Cat D-518 crawler | *Psuedotsuga menziesii* mixed with others | 3-34<br>2-32 | 0.5<br>0.5 | 130<br>191 | 58.3<br>38.2 | Adebayo et al. (2007) |
| Grapple skidder (model not reported) | Mixed stands of pine, spruce and balsam (sp. Not reported) | 0-20<br>25-40 | N/A (small tree 0.25 $m^3$) | 50<br>200<br>50<br>200 | 78<br>28<br>48<br>20 | Andersson, Dyson (2012) |
| Grapple skidder (model not reported) | *Pinus ponderosa, Pseudotsuga menziensii* | 7.5 | N/A | 300 | 16 | Townsend et al. (2019) |
| **Europe**<br>TDT-55 | N/A (article only reported mixed species of beech, fir, spruce and pine) | 58 | 6.0 | 500-700 | 32.1 | Gluschkov, Markoff (2007) |
| Cat 525 (grapple)<br>Cat D5HCS (crawler) | Mixed cedar, pine and fir<br>Mixed cedar, pine and fir | 35<br>35 | 0.68<br>N/A | N/A<br>N/A | 19.2<br>9.3 | Akay et al. (2004) |
| Timberjack 240C (cable skidder) | Mixed *Abies alba* and *Fagus sylvatica* | 8-34<br>8-34 | 4.4<br>4.4 | 50<br>400 | 16.9<br>9.9 | Sabo, Porsinsky (2005) |
| Southern Hemisphere-Brazil<br>Cat 545 (grapple)<br>Cat 525 C (grapple) | *Pinus taeda*<br>*Pinus taeda* | 8<br>0-27<br>28-48<br>>49 | N/A<br>1.7<br>1.7 | 100<br>150<br>150 | (SD4) 59.4<br>(SD2) 59.1<br>SDP 62.8<br>52.8<br>62.2<br>34.2 | Lopez et al. (2014) |
| **South Africa**<br>Cat 525C (grapple) | *Pinus patula, P. kesiya, P. elliottii* | 11.5 | 1.45 | 134 | 21.5 | Ngulube (2012) |

**Table 2.** Application limit of skidders in South Africa (Oberholz, 2002)

| Criteria | Wheeled skidders (normal tyres) | Wheeled skidders (high- floating) | Clambunk skidders |
|---|---|---|---|
| Uphill slope (%)<br>Downhill slope (%) | 0-10<br>0-30 | 0-20<br>0-40 | 0-25<br>0-40 |
| Ground roughness | 1-2 | 1-3 | 1-3 |
| Ground conditions | 1-2 | 1-4 | 1-3 |
| Skidding distance | 50-300 m | 50-500 m | 50-1000 m |

trees were felled and processed into shortwood billets which then were extracted by a skidder equipped with a loading boom and a winch. The average machine productivity for large skidders (72 kW, equipped with a loading boom and winch) was 37.9 $m^3$/PMH, while the application of a smaller skidder (31 kW, industrial tractor equipped with a winch) yielded a productivity of 13.9 $m^3$/PMH (Table 2). A small proportion of pine plantations in Australia are harvested using the whole- tree method (including feller-buncher, grapple skidders and processor at the roadside) due to concerns regarding high nutrient removal owing to whole- tree extraction. Berry (2019) studied a Tigercat 632E grapple skidder productivity in a site located in South East Queensland, Australia and consisting of 30-year-old Caribbean pines (*Pinus caribaea var. hondurensis* (PCH)) with tree volume of 1.5 $m^3$. The site was flat and the skidding distance averaged about 45 m. A projected productivity of 76.2 $m^3$/ $PMH_0$ was reported likely due to the short skidding distance and relatively large tree size in the study plot. More case studies and larger plot size in South East Queensland (Australia) harvested by the grapple skidder could probably help determining a more realistic average productivity for this machine.

## Conclusions

Adebayo et al. (2007) suggested that further research is necessary in order to explore the effect of other variables not considered in their study, such as the effect of other machine combinations (e.g., grapple skidder) and silvicultural prescriptions (e.g., single- tree selection) on cost and productivity of harvesting. The load volume and skidding distance are the most frequent variables, which can impact significantly the skidding productivity. However, for the individual machines, with changing piece volume, there should be a system balancing in the form of spare productivity capacity (Visser, Stampfer, 2003). As skidders work in combination with felling machines in the stands and interact with loading/processing machines at the landing, future studies can investigate the machinery interaction and the consequent impact on productivity for understanding the working delays and establishing potential operational improvements (Visser, Stampfer, 2003). As increasing skidding distance decreases the skidder productivity, Kellogg, Davis (2006) suggested that the unit layout needs to minimise skid, trail distances especially when removing smaller trees and relatively low volumes per ha. Andersson, Dyson (2012) suggested planners should consider the whole- tree harvesting system for shorter distances (<150 m) and Ngubule (2012) emphasised the harvest plan should ensure that optimum extraction distances are determined in order to increase productivity. Steeper terrains can reduce the skidding productivity. In a Brazilian case study, Diniz et al. (2018) reported that skidding productivity (of a rubber-tired grapple skidder) on very steep slopes was 35% to 45.0% lower as compared to the productivity on the flat to moderate and steep terrains. Diniz et al. (2018) suggested skidding with a skidder on slopes over 48% should be avoided, because the productivity was negatively influenced in this condition during their trial.

Silvicultural regimes can impact the skidder productivity. Kulak et al. (2017) indicated that skidders that are forced to manoeuvre among trees remaining in the stand during thinning operations are expected to be less efficient. Thus, properly designed and suitably utilised network of skid trails are essential in stands with younger age classes. Grapple skidders seem to be effective machines to apply in long- wood harvesting in clear-cuts of pine stands (Kulak et al., 2017).

The productivity of a grapple skidder is constrained by the absence of pre-bunching trees in semi- mechanised systems (e.g. when trees are felled manually). Pre-bunching of trees in mechanical felling would enable the machines to work on wetter ground with minimum production losses. This would help building heavier loads per turn and reducing manoeuvring time of skidders when loading, thus could ultimately help to optimise timber harvesting productivity (Ngulube, 2012; Townsend et al., 2019). Klepac, Mitchell (2016) indicated that machine selection could affect the costs of wood sourced from young pine plantations. Their study showed that large capacity grapple skidder could enhance production rates and reduce costs when harvesting small-diameter stems. This benefit was not dependent on the felling machine selection. In addition, the experience of skidder operators is a key factor in achieving higher productivity. Townsend et al. (2019) indicated that experienced operators alternated short and long-distance cycles when working directly with the processor to maintain balance and minimise operational delays.

The productivity of a skidder with rubber tires in a Brazilian case study was higher than that of tracked skidders in the longest distances of extraction due to the higher mobility of rubber-tired machines. On the other hand, the productivity and operational cost of the skidder equipped with tracks only on the front wheels were similar to the one of the rubber-tired skidder, which indicated the suitability of front tracks for the shorter skidding distances on steep terrains and humid soils with low support capability (Lopes et al., 2014). Skidders can also play an important role in integrated- biomass harvesting for fuel- hazard reduction thinning. This type of operations is suitable for removing small-diameter fuels in the western United States, while allowing costs to be somewhat offset by sawlog revenues (Vitorelo, 2011).

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