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Rubber-Tracked Forwarders—Productivity and Cost Efficiency Potentials

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Abstract: The extraction of timber is expensive, energy intensive, and potentially damaging to the forest soil. Machine development aims to mitigate risks for environmental impact and decrease energy consumption while maintaining or increasing cost efficiency. The development of rubber-tracked forwarders has gained renewed interest, not least due to climate change leading to unreliable weather in combination with low tolerance for soil damage. The increased cost of rubber tracks compared to wheels is believed to be compensated by higher driving speed enabled by semi-active suspension. Thus, the aim of this study was to theoretically investigate how the productivity and cost efficiency of rubber-tracked forwarders are affected by variations in driving speed and machine costs. The calculations were made with fixed stand parameters, to evaluate performance in well-defined working conditions, and with parameters from 2500 final felling stands in central Sweden, to evaluate performance in varied working conditions. Scenarios were compared to a baseline corresponding to mid-sized wheeled forwarders. The results show higher productivity with the increased driving speed enabled by rubber tracks and suspension at all extraction distances, with larger differences at long extraction distances. Assuming a 15% higher machine price for the rubber-tracked forwarder and a variable cost increase proportional to speed increase, extraction costs break even with the baseline at 400 m and 700 m extraction distance for moderate and fast driving speed, respectively. Furthermore, a rubber-tracked forwarder is likely to enable access to a larger part of the harvest area during longer seasons. For the studied set of stands, the year-round accessible volumes are estimated to increase from 9% to 92% with a rubber-tracked forwarder. With rubber tracks instead of wheels, good accessibility has the potential to be combined with low soil impact and cost efficiency in a favourable way for both industry and ecosystem.

Keywords: timber extraction; soil impact; accessibility; machine prototype; CTL logging

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1. Introduction

Forests cover about 30% of the global land surface [1] and play a crucial role in the total carbon balance between land and the atmosphere [2]. Whether harvest volumes in different regions should go up or down to align with and contribute to sustainability goals is debated, but regardless, the harvest operations themselves must strive for high efficiency with low ecological and social footprints [3]. Machine design and re-design have been ways to improve efficiency all through the mechanization of forest harvesting. During the 20th century, focus was mainly on cost efficiency, supply chain performance [4–6], and ergonomics [6,7]. During the last 20–30 years, the ecological sustainability pillar has also gained large attention [8–11]. Today, economic, ecologic, social, and political pressure on forestry is increasing, and forest operations need to evolve in a holistic way to be accepted and successful [3].

In a warming climate, the traditional boreal practice to harvest areas with sensitive soils in wintertime is a practice that becomes less and less feasible due to less reliable and shorter periods with frozen ground [12]. Different approaches to tackle this new reality are taken, such as increased flexibility and agility in harvest crew organization [13], increased flow of information throughout the supply chain [14], extraction route planning and optimization [15,16], and the use of purpose-built steel tracks [17,18] or auxiliary axles [19].

Forestry countries with smooth ground, either soft or sandy, use tracked harvesting equipment extensively, not least because tracked machines are state-of-the-art in the construction industry. Excavators form a cheap and robust base for harvester and processor head applications [20]. Furthermore, tracked machines can negotiate substantially steeper terrain compared to wheeled machines [21], which is important since forestry is referred to hilly areas in many countries [22]. Even though excavator-like steel tracks are convenient to adopt in many cases, there are countries and regions where the terrain is usually too rough and stony to allow that kind of equipment while maintaining cost efficiency. The solution in, for example, the Nordic countries, is to equip purpose-built wheeled harvesters and forwarders with steel tracks on their bogie axles (Figure 1). Different variants of tracks offer different levels of flotation and grip [23]. In Finland, an idea involving customized steel tracks for wet areas has been studied; the tracks are mounted on regular wheel bogies during part of the year and left unused when wheels are sufficient [18]. The idea was sprung from the fact that large forested areas in Finland consist of peatlands that normally need to be frozen to allow heavy traffic and that climate change makes this harder and harder. In essence, this is the same phenomenon that is also now visible in Sweden, with the difference that Sweden has a smaller portion of forests being peatland and thus ideally would need a more versatile machine—a machine that handles subtle and unforeseen changes in weather and ground conditions without the need for downtime for technical reconfiguration.

Figure 1. A Komatsu 855 wheeled forwarder with steel boogie tracks. Photo: Komatsu Forest.

In, for example, construction, agriculture, and military applications, rubber tracks have evolved to be the industry standard for many machines of different sizes, such as excavators, skid-steers, agricultural tractors and combine harvesters, and military transport and combat vehicles. The strength and durability of rubber tracks are no longer obstacles for practical forestry application. Trials have been made with standard forwarders of different brands equipped with undercarriages usually seen in other applications: for example, the 'Gentle' project, where a Komatsu forwarder was put on rubber-track carriages from the military equipment manufacturer 'BAE Systems Hägglunds' (Figure 2), or the similar solution 'On-Tracks' with a Ponsse forwarder on rubber tracks called 'Prinoth panter' (Figure 3) [24]. Both systems were attempts to achieve better bearing capacity from tracks while also avoiding the shearing forces on the ground and the harsh vibrations for the operator that come with steel tracks. Rubber-tracked forwarders potentially provide increased accessibility to wet areas throughout the year through low ground pressure [25] and better operator ergonomics through reduced vibrations. In addition, the lower ground pressure from rubber-tracked forwarders can reduce damage to the forest floor and minimize the risk of soil erosion and rutting, which is especially important in sensitive ecological areas [26].

Figure 2. The concept machine 'Gentle', a Komatsu forwarder equipped with undercarriage from BAE Systems Hägglunds. Photo: Rolf Björheden.

Komatsu Forest has presented the latest rendition of rubber-tracked forwarders with their 'Centipede' prototype (Figure 4). The machine is based on a regular Komatsu 855 (Figure 1) but is equipped with purpose-built tracks and a semi-active suspension, enabling higher driving speeds in the terrain due to less side-to-side oscillation and vibrations. A rubber-tracked forwarder with high driving speed would, aside from increased productivity in general, potentially enable the medium-distance hauling of wood over peatlands or forest roads covered in snow, opening for reduced preparation costs in terms of snow removal and the establishment of winter roads.

Figure 3. The concept machine 'Ponsse OnTrack', a Ponsse forwarder equipped with an undercarriage from Prinoth. Photo: Rolf Björheden.

Figure 4. Komatsu Centipede concept forwarder with rubber tracks and semi active suspension. Photo: Komatsu Forest.

Previous studies and testing have mainly been focused on soil impact, improved trafficability, and operator comfort, but there is currently no study on the effects on productivity and cost that is believed to come with rubber-tracked forwarders.

It is generally believed that a rubber-tracked forwarder has the potential for substantial increases in driving speed [24,27]. Other positive features might be increased load capacity, especially in situations where wheeled forwarders are forced to reduce load weight due to soft ground conditions. Both these features would, if realized, push productivity upwards and thereby potentially increase cost efficiency. However, new technology usually comes with investment and development costs that cut away some of the potential cost reduction [28]. Additionally, even without considering development costs, new technology might be more expensive due to more costly components and manufacturing processes. Those costs need to be off-set by an increase in productivity to be cost-efficient in relation to the traditional technology. Thus, the cost components of new technical solutions, such as rubber tracks on forwarders, are relevant for analysis. When a prototype is manufactured and ready for practical testing, it is also possible to conduct physical time studies in the field to measure productivity and calculate cost. There are, however, some drawbacks to studying the unfinished machine, since the results may be underestimated. On the other hand, theoretical calculations or simulations might overestimate potential if they neglect technical issues or differences that are associated with the new machine. In the end, though, a stepwise evaluation of a new concept, starting with theoretical analyses, is hard to argue against, since theoretical analyses are usually much cheaper than field tests [29] and, if properly set up, form an outer bound beyond which the potential of the new machine is unlikely to reach. That can guide as a protection against large investments in solutions that will turn out to be dead ends (see [30]). For rubber-tracked forwarders, there are, so far, to the best of our knowledge, no theoretical evaluations of increased driving speed.

Thus, the aim of this study was to investigate how the productivity and extraction cost of rubber-tracked forwarders are affected by variations in driving speed and machine costs. The study also addressed the potential of increased access to a larger part of the harvest area during longer seasons.

2. Materials and Methods

Analyses were made in two main ways in this study. First, calculations of productivity and cost with stepwise changed stand parameters was conducted, to assess performance for tracked forwarders in specific work conditions. Second, to evaluate the performance in real work conditions, the same algorithm was applied on a large number of harvested plots in central Sweden, with plot-specific volume data recorded at the receiving mills and extraction distances for each plot estimated before harvest by the planning personnel.

2.1. Stand Data

The stand data for the harvested areas used in this study were provided by a large Swedish forest company and consisted of 2959 final felled harvest plots located in the middle parts of Sweden. After cleaning out harvest plots with missing or erroneous values of harvested volume, harvested area, extraction distance, and ground conditions, 2465 harvest plots remained for the analysis. The total harvested volume was over 3 million m^3 solid under bark (sub), and the average volume per hectare and one-way extraction distance were 232 m^3/ha and 356 m, respectively (Table 1).

Table 1. Summary statistics of the harvest plots included in the analysis (N = 2465).

Variable	Average	Std Dev	Min	Max
Total volume (m^3)	1232	1151	100	12,059
Harvested volume (m^3/ha)	232	95	10	681
Extraction distance (m)	356	225	30	1900

The stand data were distributed into different classes of extraction distances and ground bearing capacity (Figures 5 and 6). Ground bearing capacity class one is accessible with wheeled machines all year round. Class 2 is also accessible all year round but extra care is needed during thaw break and copious autumn rains. Class three is average ground conditions where extra care is needed in low terrain and if passing the same spot many times. Class four might not allow heavy wheeled machines unless the ground is frozen, slash reinforcement will have large influence on trafficability. Extra care is needed near local marshes. Class five is very poor ground conditions and wheeled machines can only be used on frozen ground [31].

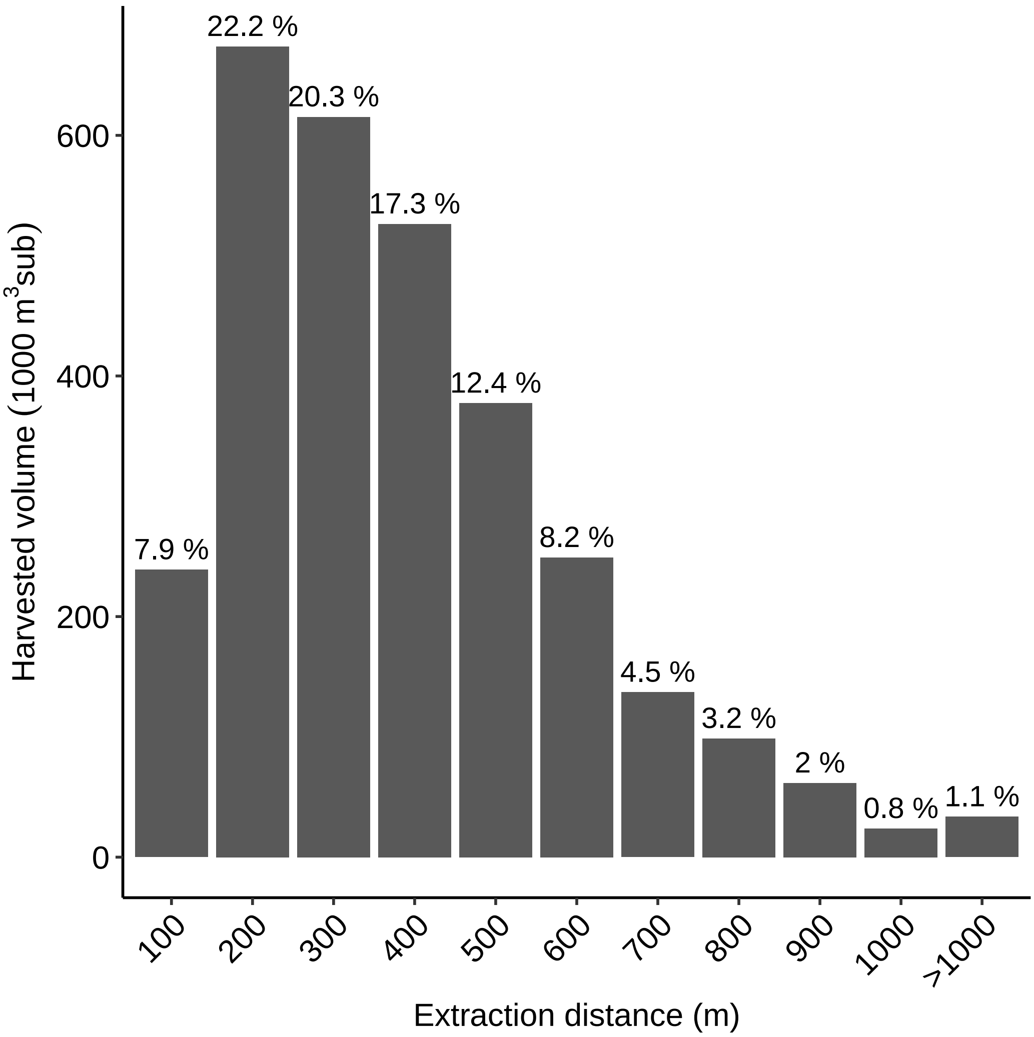

Figure 5. Distribution of the total harvested volume on classes of extraction distance. Absolute volume on y-axis and percentages above each class.

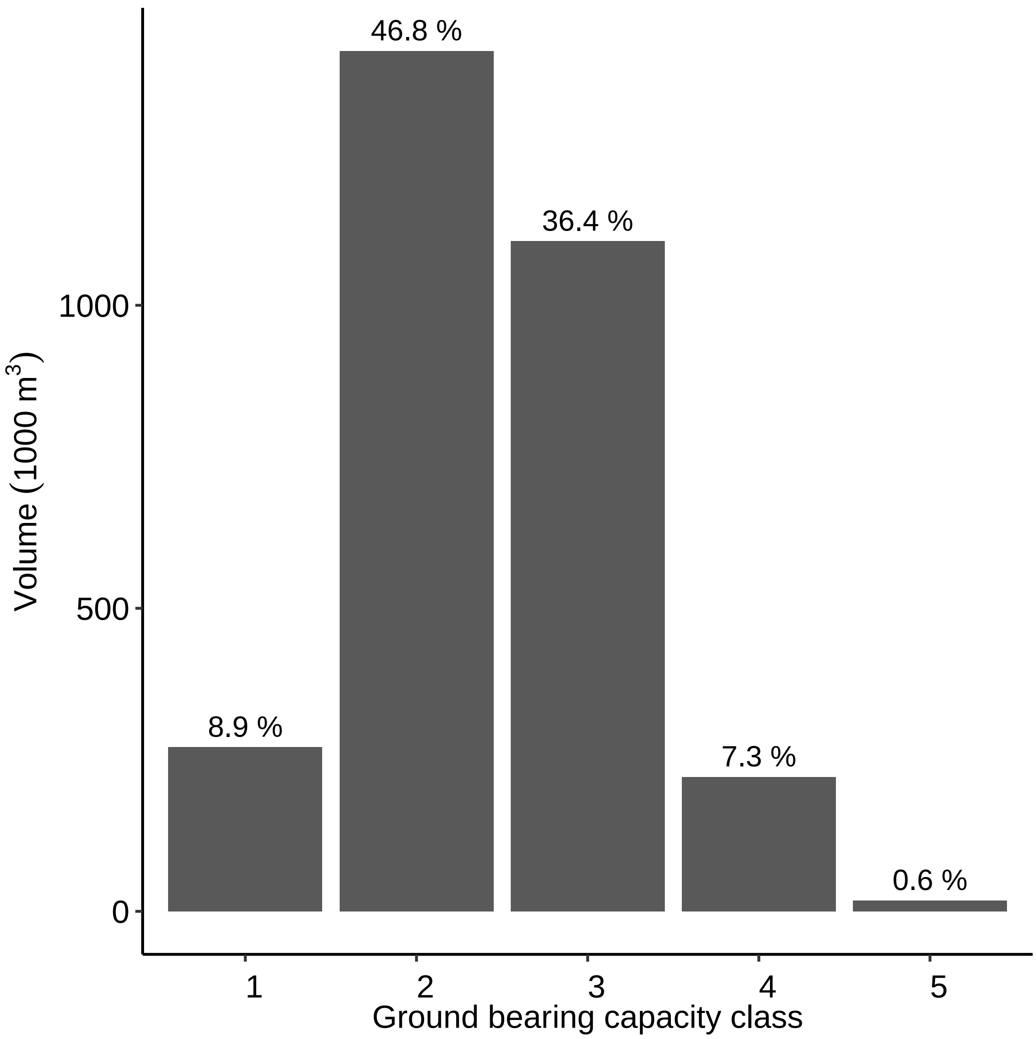

Figure 6. The harvested volume distributed on ground bearing capacity class. Absolute volume on y-axis and percentages above each class.

2.2. Time Consumption

Total time consumption in Scheduled Machine Hours (SMH) for a full forwarder load cycle was calculated by adding together the time consumptions for the separate work elements included:

$$T_{total} = T_{DE} + T_L + T_{DL} + T_{DF} + T_U + T_O \quad (1)$$

where:

T_{DE} is the time for driving with empty loadspace from landing to where the loading begins;

T_L is the time for loading (including simultaneous crane work and driving);

T_{DL} is the time for driving while loading (when the crane is resting);

T_{DF} is the time for driving with full load from where loading was finished to landing;

T_U is the time for unloading;

T_O is other time, also referred to as delays or non-productive machine time.

Specific time consumption for each work element was calculated with equations from [32] under the assumptions of one single forwarded assortment and equal distances for driving empty and loaded (see also [30,33,34]). Other input parameters in the calculations were assigned relevant values for the standard scenario (Table 2). Load size was estimated based on an average wood density of 900 kg/m^3 and the assumption that the forwarder can use the whole load weight at all times. The hourly costs were estimated by applying input parameters provided by a large forest company in the COST-model presented by [35]. In calculations based on stand data, total plot volume, harvested volume per ha, and extraction distance were stand-specific.

Table 2. Input parameter values in the analyses.

Parameter	Value	Source *
Baseline driving empty speed (V_{DE}) (wheeled machine)	56.67 m/min (3.4 km/h)	1
Speed driving loaded (V_{DF})	85% of V_{DE} (2.8 km/h)	1, 2
Speed driving while loading (V_{DL})	35 m/min (2.1 km/h)	1
Unloading time (T_U)	8.8 min/load	1
Delays (T_O)	6.5 min/load	1
Exchange rate	0.089 SEK/USD	3
Fixed machine cost (wheeled)	21.72 USD/PMH	4, 6
Fixed machine cost (rubber-tracked)	24.12 USD/PMH	2
Variable machine cost (wheeled)	32.57 USD/PMH	4, 6
Variable machine cost (rubber-tracked, moderate)	48.15 USD/PMH	2
Variable machine cost (rubber-tracked, fast)	79.30 USD/PMH	2
Operator cost (wheeled and tracked)	33.91 USD/PMH	4, 6
Extraction trail spacing (D_{TS})	13 m	5
Baseline load size (LS) (based on 900 kg/m^3 wood and 14 tons load weight)	15.6 m^3	2
Total plot volume (where not stand-specific)	814 m^3	7
Harvested volume per ha (where not stand-specific)	239 m^3/ha	7

* 1: [36]; 2: authors' assumptions; 3: themoneyconverter.com/SEK/USD; 4: estimates from a large Swedish forest company as of fall 2022; 5: [32]; 6: [35]; 7: average from stand data.

T_{DE} and T_{DF} were calculated by dividing the driving distances for driving empty and driving loaded (D_{DE} and D_{DF}) with their respective driving speeds V_{DE} and V_{DF} according to:

$$T_{DE} = \frac{D_{DE}}{V_{DE}} \tag{2}$$

and:

$$T_{DF} = \frac{D_{DF}}{V_{DF}} \tag{3}$$

Driving distances D_{DE} and D_{DF} were set equal and calculated according to:

$$D_{DE} = D_{DF} = D_{Est} - \frac{D_{DL}}{2} \tag{4}$$

where:

D_{Est} is the one-way extraction distance estimated by planning personnel before harvesting, coming from input data;

D_{DL} is the distance driven during loading.

The driving during loading distance was calculated according to Equation (5), where LS is the load size in m^3 and z is dependent on Vol_{ha} and D_{TS} according to Equation (6).

$$D_{DL} = \frac{100 \times LS}{z} \tag{5}$$

$$z = Vol_{ha}\frac{D_{TS}}{100} \tag{6}$$

Trail spacing (D_{TS}) of 13 m (Table 2) results in 770 m of extraction trails per hectare, and as only one assortment was used, the volume per hectare (Vol_{ha}) can be used directly in Equation (6). The time for driving while loading was calculated by again dividing distance by speed:

$$T_{DL} = \frac{D_{DL}}{V_{DL}} \tag{7}$$

Time for loading (T_L) is dependent on wood concentration and was calculated according to:

$$T_L = 0.59 + \frac{0.155}{Vol_s} \quad (8)$$

where Vol_s is the volume at each loading stop, calculated as:

$$\ln(Vol_s) = -0.447 + 0.3\ \ln(z) \quad (9)$$

To calculate productivity (m^3/SMH), the total volume on the harvest plot, 814 m^3 in the static calculations and plot specific values when using stand data, was divided by the total time consumption (T_{tot}) after multiplying it with the number of loads according to:

$$Prod = \frac{Vol_{plot}}{T_{tot} \times Nr\ of\ loads} \quad (10)$$

2.3. Costs

Cost calculations were made by adding together the hourly cost components (Table 2) expressed in USD, multiplying with time consumption, and finally dividing by volume. Delay time was not associated with variable machine cost, only with fixed machine cost and operator cost. Some of the input parameters used in the COST-model are corporate-specific sensitive information and therefore cannot be reproduced in detail. The fixed hourly cost for the rubber-tracked machine was estimated as the hourly cost effect of the price difference of a rubber track system compared to wheeled bogie axles equipped with steel tracks. Without specific knowledge of prices for any existing prototypes or other machines, assumptions were based on estimates that give an indirect indication. First, the difference in price between wheeled and rubber-tracked farm tractors, estimated to roughly USD 60–80,000, gives a roof for the difference in cost. Second, since a forwarder is usually equipped with boogie axles and steel tracks, the difference in price between a forest machine with 6 wheels and 8 wheels (about USD 30,000) plus the cost for a pair of steel tracks (roughly USD 10,000 depending on configuration) should be subtracted from the initial rubber track cost. In the end, a rubber-tracked forwarder would cost about 15% more than its wheeled equivalent, leading to an increased fixed hourly cost of about 11% according to [35]. To reflect the uncertainty in these estimates, the calculations were made with a ± 10 percent unit variation in the fixed hourly cost.

Variable cost was also assumed to be higher for rubber-tracked than for wheeled machines. Partly, the higher cost can be expected from increased maintenance of the track systems. However, the main effect was assumed to stem from increased fuel consumption due to higher driving speeds. Therefore, the hourly variable cost was increased with speed increase. To reflect that the whole variable cost component does not consist of fuel cost, 65% of the variable cost was affected by the increases in speed, again according to [35]. In a sensitivity analysis, the 65% figure was changed to 55% and 75%.

2.4. Parameter Variation

Apart from the increased cost for the rubber-tracked machine described above, driving speeds and extraction distance parameters were altered when calculating alternative scenarios. Two levels of increased average speed, 5.9 and 10.9 km/h, compared to the baseline of 3.4 km/h were modelled for the rubber-tracked forwarder, based on scenarios of maximum speed for other rubber-tracked vehicles [37]. A conservative approach was taken by expecting speed increases in the lower end of the ranges observed in the previous studies. Average speeds refer to driving forwarders without load. The relations between speeds for driving empty, driving loaded, and driving between log piles during loading, as well as the relationship between maximum and average speed, was adopted from [36].

Ground bearing capacity class was related to the estimated nominal ground pressure of the two machine configurations (Table 3). The relations are informal estimates created to quantify harvested volumes that would be accessible for extraction all year round with the rubber-tracked machine.

Table 3. Relations between nominal ground pressure and accessible terrain for the different technical configurations.

Driving Speed (km/h)	Machine Configuration	Estimated Nominal Ground Pressure (kPa)	Ground Bearing Capacity Classes Accessible All Year
3.4	Wheeled (baseline)	75	1
5.9	Rubber-tracked moderate	50	1–3
10.9	Rubber-tracked fast	50	1–3

2.5. Model Implementation

The abovementioned equations and assumptions were implemented in a script setting using the statistical programming language R [38], with ggplot2 for visualizations [39]. The base model for calculation of time consumption and cost was efficiently handling the different input parameter scenarios in an iterative way, enabling storage of results and visualization. In the first steps, the model was fed with fixed parameter values to show the effects of driving speed, extraction distance, and machine cost on extraction productivity and cost. In the next steps, the model was adapted to connect to the input stand data described above to make similar calculations on the real-world case, as well as to investigate the occurrence of certain favourable conditions in actual harvest operations.

3. Results

First are presented visualizations of the calculations made with parameters that were altered manually in fixed predetermined steps under controlled conditions (Figures 7–9). Second, visualizations of how the rubber-tracked machine performed in real case conditions are shown, i.e., parameters from each of the many input forest stands (Figure 10).

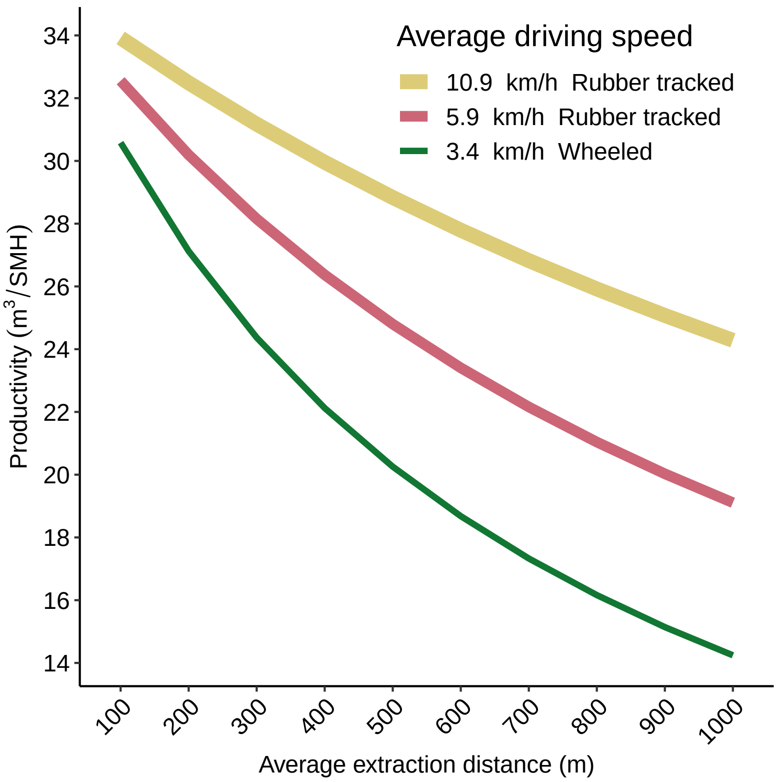

Figure 7. Productivity at different extraction distances and driving speeds.

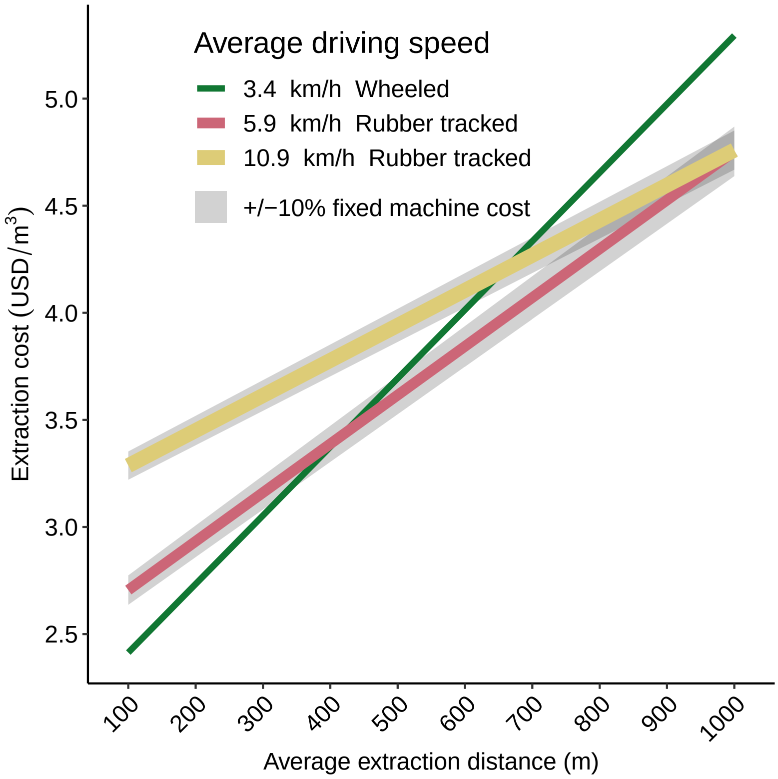

Figure 8. Extraction cost at different extraction distances and driving speeds. Sensitivity analysis on fixed machine cost, ±10%.

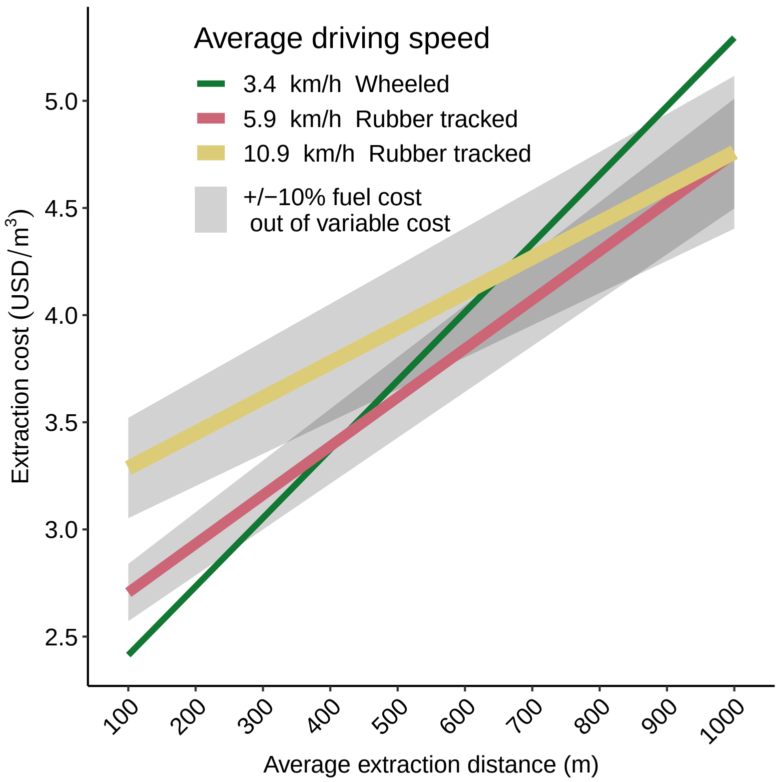

Figure 9. Extraction cost at different extraction distances and driving speeds. Sensitivity analysis on fuel cost as percentage of total variable cost, with 65% as baseline.

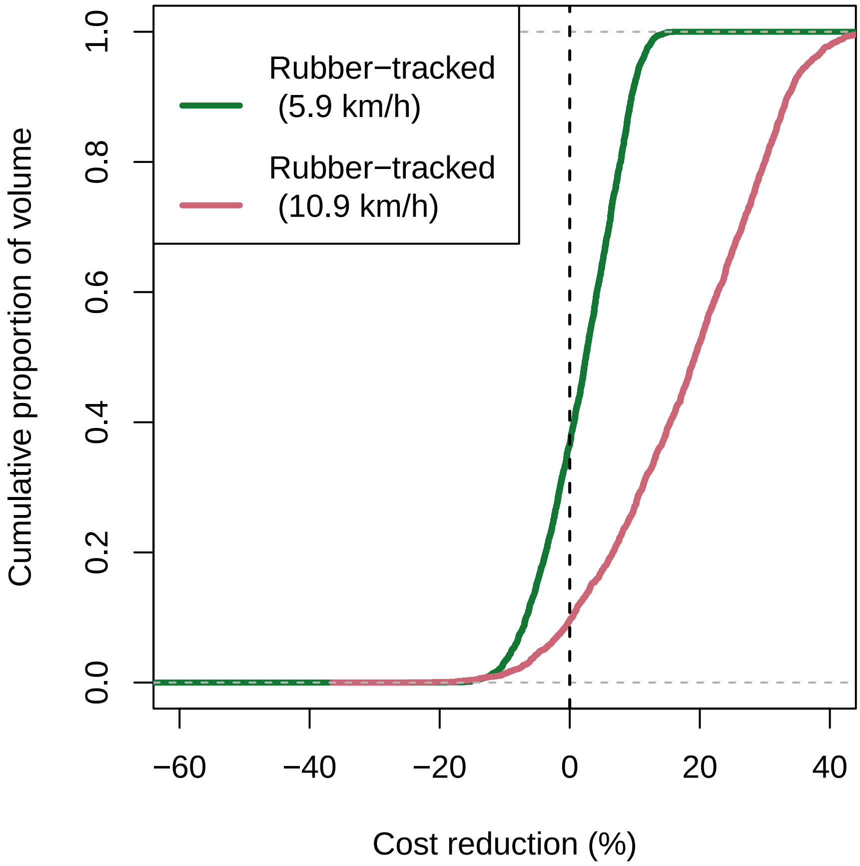

Figure 10. The cumulative proportion of harvested volume distributed in classes of extraction cost reduction, for the two machine configurations compared to the wheeled forwarder baseline.

3.1. Controlled Conditions

As expected, the forwarder productivity falls quite quickly with increasing extraction distance. The productivity drop was, however, mitigated by the increased speed of the rubber-tracked machine (Figure 7). With the moderate speed increase, the productivity would theoretically go up from 25 to 36 m^3/SMH at a 300 m extraction distance, a 44% increase.

The increased hourly fixed and variable costs for the rubber-tracked machine result in a higher extraction cost per m^3 at short and moderate extraction distances (Figure 8). Since the extra fixed cost for rubber tracks is independent of distance while the productivity increase from higher driving speed is not, the potential for better cost efficiency will be higher for long extraction distances. For the moderate (5.9 km/h) speed increase, the extraction cost came below the baseline at between 400 and 500 m extraction distance. For the fast scenario, the breakeven comes at almost 700 m. The effect of varied fixed cost was visible (grey areas in Figure 8).

The difference in variable cost between wheeled and rubber-tracked forwarders was based on assumptions. In a sensitivity analysis, the ratio of fuel cost out of total variable cost was altered ±10% around the 65% baseline (Figure 9).

3.2. Case Study with Stand Data

When applied to the stand data, the ‘moderate’ and ‘fast’ scenarios of driving speed resulted in saved extraction costs in some stands but higher costs in others. The average costs were very similar for the moderate scenario and the baseline while the fast scenario showed a 15% increase in average costs (Table 4).

Table 4. Average and relative extraction cost and estimated accessible volume all year around for the different machine configurations.

Machine Configuration	Average Cost (USD/m^3)	Relative Cost (%)	Proportion Accessible Year Around (%)
Wheeled (baseline)	3.45	0	9
Rubber-tracked moderate	3.48	+0.8	92
Rubber-tracked fast	3.99	+15.7	92

3.3. Potential Forwarding on Soft Terrain

Under an assumption that the decreased ground pressure of a rubber-tracked machine enables year-round access to stands with ground bearing capacity classes 1, 2, or 3 (compared to only class 1 for wheeled machines), the accessible volume increases dramatically but at a higher average extraction cost (Table 4).

4. Discussion

Both when analyzing the effects of individual stand conditions and when analyzing the effect on a case with stand condition combinations, as expected, productivity of forwarding increases with higher driving speed. This has also been shown indirectly for rubber-wheeled forwarders (c.f. [40,41]). Extraction distance has been more common to include in productivity models than driving speed since machine designs are traditionally, to a large extent, fixed. The cost efficiency of rubber-tracked forwarders compared that of wheeled forwarders in this study was dependent on cost assumptions but also on average speed and extraction distance (Figure 8). In most conditions, the rubber-tracked machine showed equal or higher extraction costs than the wheeled baseline. On long extraction distances, however, the higher driving speed resulted in a lower overall extraction cost (Figures 8–10).

The technological development of machinery always comes at a cost that must be compensated for by increased cost efficiency (c.f. [28]). When, as in the case of this study, cost parameters are unknown, conclusions need instead to be made from sensitivity analyses, and as seen in Figure 8, the ±10% variation in fixed costs does not change the overall conclusions very much. The two rubber-tracked scenarios cross the baseline approximately at the same extraction distance also with higher or lower fixed cost (Figure 8). Variable costs, on the other hand, seem to have a substantial impact on the extraction cost and the comparison of wheeled and tracked machines. When the impact from fuel cost, which was increased proportionally to driving speed, on total variable hourly cost was altered, the resulting breakpoints in extraction distance changed substantially (Figure 9). For example, the moderate speed scenario crosses the baseline at roughly 600 m instead of 400 m extraction distance if the variable cost was increased (Figure 9).

When the increases in driving speed were applied to the whole set of harvested areas (Figure 10), it becomes visible that the relative costs differ quite a lot between harvest areas. This is depending on the specific extraction distance and volume per ha on respective harvest area. It is also visible that the moderate scenario, i.e., the blue line in Figure 10, results in almost half of the volume extracted to a cost below baseline. The exact number is 43%. For the fast scenario, the corresponding figure was only 11%, leading to the conclusion that if a very high speed cannot be obtained without a linear increase in fuel cost, the extraction distance needs to be very long to offset the cost.

Under the assumptions made about the increased year-around trafficability of rubber-tracked forwarders, the potential volume increase was large (Table 4). Changing from a wheeled forwarder to a rubber-tracked forwarder with a moderate speed increase, i.e., 5.9 km/h driving speed, increased the accessible volume from 9% to 92% of the total harvested volume in the case study with a 0.8% higher cost. There is likely a will to pay more than that for such an increase in accessibility. Assuming that the rubber-tracked machine would only access ground bearing capacity classes one and two all year, instead of one, two, and three, reduces this increased proportion from 92% to 56%, which is still a large improvement from the original 9%. In areas without wet soils (e.g., only soils with class 1) the introduction of rubber-tracked forwarders instead of wheeled forwarders would not mean any difference in accessibility. In contrast, in areas with substantial amounts of class 3–5 areas, the difference in accessibility would probably be substantial.

In this analysis, all driving speeds were increased to the same extent, that is both the driving to and from the landing as well as driving between different log piles during the loading cycle. Especially for speeds that are much higher than current wheeled forwarders, the question of acceleration and deceleration for short driving distances becomes relevant [42]. The machine is not likely to be able to reach the maximum speed instantly if it is very high, and such dynamics were not modelled in this study. Making relevant assumptions about the speed increase for rubber-tracked forwarders was not trivial, and it would have been even more difficult to differentiate those assumptions in a relevant way to reflect accelerations, without more input information from manufacturers or other external parties. It is something that can be added in the model easily in the future, though.

Since this study was inspired by the presentation of the concept machine Centipede from Komatsu Forest, it would be more relevant with input parameters from that specific machine. The good side of keeping input parameters more general is of course that other similar projects can benefit more from the results regardless of their expected specific costs and increases in driving speed. It is likely that other regions than Sweden and Scandinavia see a similar need for increased accessibility in a changing climate, not least the Baltic countries. All cut-to-length operations around the world use forwarders of some kind, most with rubber wheels, and a potential transition to rubber tracks would be of interest for assessment also in other contexts than the Scandinavian one.

The calculations of productivity and cost were completely deterministic, without random variation for any of the input parameters. To check if the main results would be different, the scenarios were analysed in a more elaborate simulation model, including random elements for driving speeds, load-specific driving distances, and downtime for the machine. The simulation model in [33] was used for that, and due to lack of queuing effects or other major dynamic elements, the results were similar for both methods; thus, the simpler, deterministic approach was selected.

Future Research

Future research can be made on a variety of aspects of the rubber-tracked forwarder. The first and easiest step would be to review the input parameters of this analysis to get a better agreement with the real Centipede concept machine, or any other machine that might be planned for prototyping. The next level of extended theoretical analysis is to quantify the improvements in overall performance of the wood supply chain that might be unlocked with rubber-tracked forwarders. It is likely that the largest benefits and increases in cost efficiency are not due to the machine itself and its hourly productivity but to the effects of planning wood supply over the year and increased access to wet areas. To underpin the assumptions about terrain accessibility during the year for different machine configurations, some empiric data would be of future interest. The possibility and economic feasibility of performing extra-long extraction, so called 'two-staging' but with one machine, over frozen wetlands in roadless areas, or on snow-covered forest roads without the need for ploughing and maintenance, would also be interesting for future studies.

5. Conclusions

The conclusions of this study were as follows:

- Rubber-tracked forwarders have the potential to increase productivity by between 10 and 60% depending on the level of increased driving speed and extraction distance.
- Rubber-tracked forwarders have the potential to reduce extraction costs by about 40% and 10% of the volume for moderate and fast speed scenarios, respectively.
- The results of this study indicate that there is a price to pay in extraction costs for increased accessibility, despite increased driving speed. The size of the change in

price is case-dependent and also depends on particular cost parameters and levels of speed increase.

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