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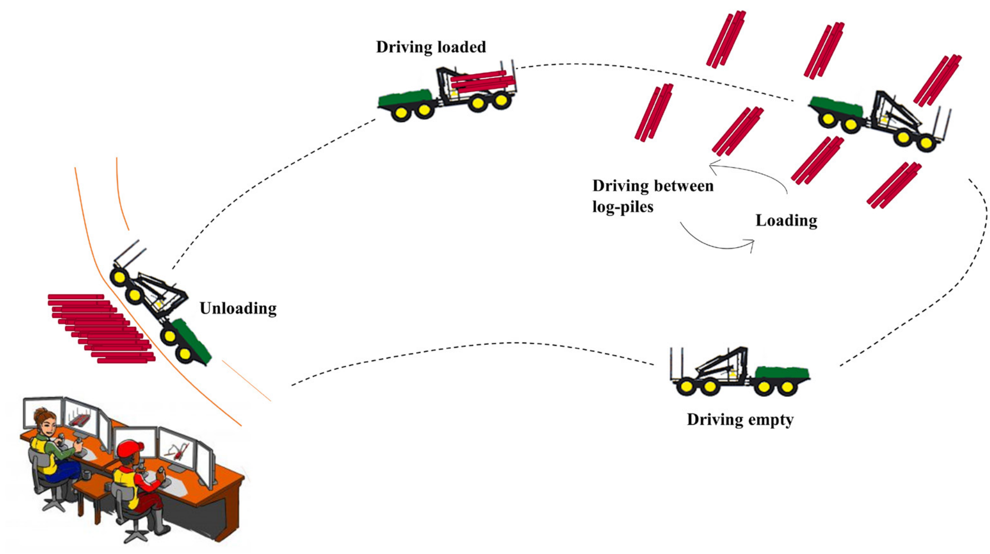
Roadmap for teleoperation and automation of forwarding

Mikael Lundbäck



Roadmap for teleoperation and automation of forwarding

Mikael Lundbäck
Faculty of Forest Science
Department of Forest Biomaterials and Technology
Umeå

SWEDISH UNIVERSITY OF AGRICULTURAL SCIENCES

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Cover: A potpourri of images, together showing the work elements of forwarding in a teleoperation context
(drawings by Mikael Lundbäck, Ola Lindroos, and Skogforsk)

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Swedish University of Agricultural Sciences, Department of Forest Biomaterials and Technology, Umeå, Sweden

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Abstract

Annually, about two billion m^3 of industrial roundwood is harvested worldwide. For a mature forest industry like the Swedish, the next technological development leaps regarding harvest operations are likely to involve increased level of tele-operation and automation. The overall aim of this thesis was to simulate and evaluate combinations of teleoperation and automation of forwarding within the cut-to-length (CTL) harvesting method, and to discuss their potential application internationally. The economic potential of different configurations of a novel concept called semi-automated tele-extraction or just tele-extraction was investigated. To evaluate the potential application of such a concept in other countries, a worldwide mapping of harvesting methods and reasons behind differences, as well as a global analysis of the slope of forest land was done. The overall result showed that there is potential for between 6% and 19% cost reduction in Swedish CTL forwarding if tele-extraction is applied. Automation of more time consuming work elements, such as loading, gave larger potential than automation of driving since more operator time was deliberated. The worldwide share of fully mechanized CTL harvesting was estimated to 37% and some of its drivers include high diesel price, gross domestic product and low share of steep terrain. About 80% of global forest land had slope less than 15°, with Africa, Russia, and the Amazon rainforest especially flat. Furthermore, there is potential for implementation of tele-extraction in at least ten countries with a high share of mechanized CTL harvesting, the potential annual volume is roughly between 100 and 150 million m^3.

Keywords: (harvesting systems, global slope, future development, remote control, CTL)

Framtidsscenarier för telestyrning och automation av skotning

Sammanfattning

Årligen avverkas cirka 2 miljarder m^3 industriellt rundvirke i världen. För en mogen skogsindustri som den svenska kommer nästa tekniska utvecklingssprång när det gäller avverkning sannolikt innebära ökad fjärrstyrning och automatisering. Det övergripande syftet med denna avhandling var att simulera och utvärdera kombinationer av fjärrstyrning och automatisering av skotning inom kortvirkesmetoden, och att diskutera deras potentiella tillämpning internationellt. Den ekonomiska potentialen för olika konfigurationer av ett nytt koncept kallat semi-autonom tele-skotning, eller bara tele-skotning utvärderades. För att undersöka potentialen för tillämpning av ett sådant koncept i andra länder gjordes en internationell kartläggning av avverkningsmetoders omfattning och orsaker bakom detta, samt en global analys av skogsmarkens lutning. Det övergripande resultatet visade att det finns potential för minskade skotningskostnader i Sverige på mellan 6% och 19% om tele-skotning tillämpas. Automatisering av mer tidskrävande arbetsmoment, såsom lastning, gav större potential än automatisering av körning eftersom mer operatörstid frigjordes. Andelen helmekaniserad kortvirkesmetod av världens totala avverkning skattades till 37% och underliggande drivkrafter var högt dieselpris, hög bruttonationalprodukt och liten terränglutning i skogsmark. Ca 80% av världens skogsmark hade en lutning om högst 15°, Afrika, Ryssland och Amazonas regnskog var särskilt platta områden. Det finns potential för implementering av tele-skotning i minst tio länder med hög andel avverkning med helmekaniserad kortvirkesmetod, den potentiella årliga volymen är ungefär mellan 100 och 150 miljoner m^3.

Nyckelord: (avverkningssystem, global terränglutning, framtida teknikutveckling, fjärrstyrning, kortvirkesmetoden)

Dedication

To Anna, Erik, Ingrid, Kerstin, Sonja, and Jonas. I would not be much without you!

”Har åldrats tjugo år på fem, år jag aldrig ser igen.”

David Ritschard, 2021

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List of publications

This thesis is based on studies described in the following papers, which are referred to by the corresponding Roman numerals in the text:

I. Mikael Lundbäck, Carola Häggström, Dag Fjeld, Ola Lindroos, Tomas Nordfjell (20xx). The economic potential of semi-automated tele-extraction of roundwood in Sweden. (submitted manuscript)

II. Mikael Lundbäck, Carola Häggström, Dag Fjeld, Tomas Nordfjell (20xx). Teleload or teledrive? New configurations of the tele-extraction concept. (manuscript)

III. Mikael Lundbäck, Carola Häggström, Tomas Nordfjell (2021). Worldwide trends in methods for harvesting and extracting industrial roundwood, International Journal of Forest Engineering, 32 (3), 202-215.

IV. Mikael Lundbäck, Henrik Persson, Carola Häggström, Tomas Nordfjell (2021). Global analysis of the slope of forest land. Forestry: An International Journal of Forest Research, 94 (1), 54-69.

Papers III-IV are published open access without restrictions of reproduction.

The contribution of Mikael Lundbäck to the papers included in this thesis was as follows:

I. Substantial part in development of original idea, study planning, and choice of method, leading part in model development, simulations, analysis of results and article writing, with input from the co-authors.

II. Participation in study planning, leading part in modelling and simulations, results analysis, and article writing, with input from the co-authors.

III. Participation in study planning and discussions of possible data sources, leading part in data gathering, analysis and article writing, with input from the co-authors.

IV. Substantial participation in study planning and choice of methods, leading part in analysis and article writing, with input from the co-authors.

Abbreviations

CTL	Cut-to-length
DES	Discrete Event Simulation
FT/TL	Full Tree/Tree Length
m^3sub	Cubic metres, solid under bark
PDF	Probability Density Function
PMH	Productive Machine Hour (excluding delays and downtime)
SMH	Sheduled Machine Hour (including delays and downtime)

Calculations of costs used an exchange rate of 1 USD = 9.05 SEK (Swedish crowns)

1. Introduction

Forests cover 31% of the world's land area (FAO, 2020) and serve as homes, sources of food, energy, building materials, and water for myriads of species. Forests, and their growth, also have enormous potential to mitigate or accelerate climate change (Canadell & Raupach, 2008). Annually, about 4 billion m^3 of roundwood is harvested in the world, of which half is industrially used and half used as firewood for cooking and heating etc. (FAO, 2019). Wood may be harvested for various reasons, e.g., preservation of certain species or habitats (by removing unwanted trees) (Grönlund *et al.*, 2020), removing forests for conversion of land to other uses (Chakravarty *et al.*, 2012), and of course extraction of raw materials for human needs. Industrial roundwood is harvested in various ways around the world (Heinimann, 2004; Heinrich & Arzberger, 2004; Arets *et al.*, 2011; Hiesl & Benjamin, 2013; Moskalik *et al.*, 2017), and sustainable use of forest products as substitutes for fossil-based alternatives has been on the agenda for a long time. Intensified international debate on ways to mitigate and adapt to climate change while meeting social welfare, biodiversity, and sustainable energy production goals has focused substantial attention on forestry and forest harvesting in many countries, not least in the Nordic countries. Effects of harvesting on C balances in the tree biomass and soil of forestland are of particular interest in a climate context, and intensively addressed by the international research community (Högberg *et al.*, 2021). Their importance is also recognized in the forest operations research field, as manifested by introduction of the term 'Sustainable Forest Operations' (Marchi *et al.*, 2018). Regardless of policy-makers' current priorities and debates, there are constant needs to improve and increase the efficiency of operations, the sustainability of the industry and its cost-effectiveness to optimize the balance between maximizing production and minimizing use of resources.

1.1 Mechanization of harvest operations in Sweden

Up until the mid-20th century wood was harvested in Sweden by farmers and their horses in the winter (Lindh *et al.*, 1961, 241). The main reason for this may have been that agricultural work was at a low level in the winter, so large workforces were available, but another was that pulling out timber was easier on snow, enabling bigger payloads per horse. Due to the scarcity of roads in the forests at this time the distances that timber was transported with horses could be very long, but big loads could be moved by preparing main trails with ice-rails that provided very low friction for the sleighs (Nordansjö, 1988). Timber was extracted in this manner to streams and rivers, stored until the spring flood then transported by waterways to sawmills situated by lakes or the coast (Lindh *et al.*, 1961, 247-248 & 252-259). In this context short logs were favored over full stems or trees for at least three reasons. First, horses have limited pulling power and they could pull loads on sleighs more easily than skidding full tree-lengths. Second, manual loading (the only option) limited the weight and size of the logs. Third, river-driving full-length trees would have been difficult, exhausting and dangerous manual work, if at all technically possible.

Apart from the introduction and diffusion of the chainsaw in felling and bucking, the mechanization of forest operations initially focused on the timber extraction and terrain transport (Lindh *et al.*, 1961, 242-243; Malmberg, 1988). There were significant changes when tractors and subsequently specialized forest tractors and forwarders could do what horses had done in the past (Nordfjell *et al.*, 2019). This development was largely driven by increases in wages and fears of shortages of workforces in the future. In the 1950:s and 60:s there were gains in productivity and costs declined for these reasons (Malmberg, 1968b).

The development of mechanized systems for felling accelerated in the late 1960s, and the most widely used machines at the time were various kinds of clipping tools. These could have one or two moving legs, were quite slow, and caused significant damage to the valuable timber. In parallel, assessments of sawing chains as felling tools started with promising cutting speeds (about three times faster than clipping,) but they had not yet been incorporated with a felling head (Malmberg, 1968a).

In the late 1960s and early 1970s the first variants of what are known as processors were developed. In this period numerous machines and tools were rapidly developed, tested, and diffused in Sweden. The machines handled various numbers of operations; some had varying capacities for felling, delimbing, and bunching. Specialized cross-cutting machines that could cut pulpwood in batches to standard lengths were also developed, but not widely adopted (Malmberg, 1968a). We would prefer:Machines that initiated major developmental efforts delimbed, bucked and sorted felled trees at the extraction trail. For example, productivity and production costs of two types of imaginable delimber-buckers were analyzed during this time. Their bases consisted of a forwarder chassis and their processing parts were equipped with a separate cabin, telescopic crane and the bucking-mill. The milling part of the first variant both delimbed and bucked trees, while the telescopic crane was used for delimbing with the second variant. Developments in this period included testing of a wide range of concepts regarding where and how to perform different work operations, and these conceptual explorations continued during the 1970s (Myhrman, 1968). In 1976, an illuminating summary was published of responses to questionnaires that had been sent out to the large forest companies during the 1960s and 1970s, asking them about percentages of volumes harvested by available methods (Boström, 1976) (Figure 1). Although the resulting time series covered just 8 years (x-axis) it revealed a clear increase in use of cut-to-length methods. Use of whole-stem methodology peaked at the end of the 1960s and beginning of the 1970s.

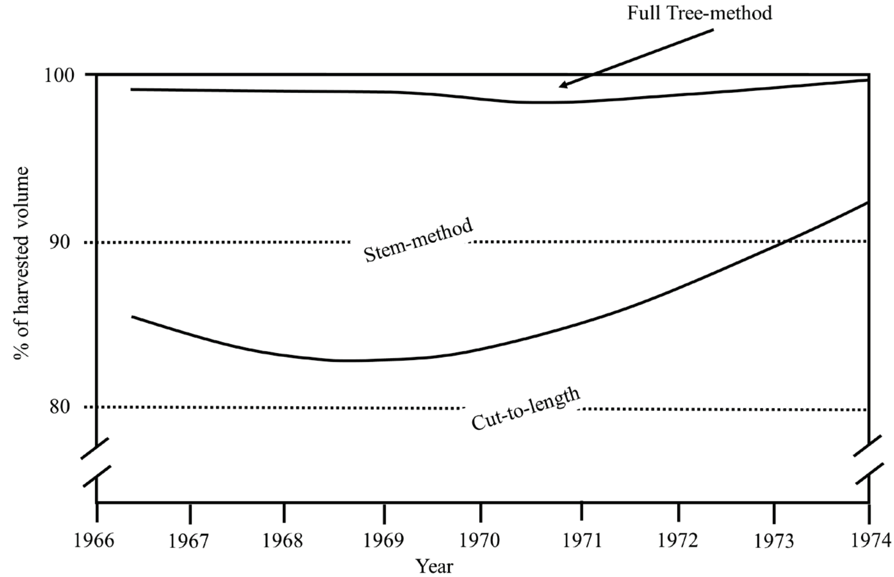

Figure 1. Percentages of volumes harvested using the full tree, stem and cut-to-length methods by the large forest companies in Sweden (after Boström, 1976).

In the early 1980s the widespread application of harvesters (single machines that could fell, delimb, buck and sort timber) began. The equipment became increasingly light and a few years later the single-grip harvester entered the market, a machine with the processor head mounted at the tip of the crane, which also enabled mechanization of thinning operations that proceeded throughout the 1990s (Jansson, 2011).

In the late 1970s, with fresh memories of the oil crises, strategic discussions of utilization of whole trees as wood fuels sparked new efforts to develop novel machine systems, for example, systems capable of chipping activities in the forest as well as at industrial sites. Advantages of chipping in the forest included reduction of costs of transporting material to mills, but the chipping itself is more efficient and cheaper at industrial sites (Wernius, 1974). Systemization and scrutiny of imaginable ways of extracting roundwood and bioenergy from the forests in the future were very high priorities for researchers and developers in several rounds during the mechanization of harvesting and extraction (cf. Hedbring, 1966).

In spite of the fast development towards cut-to-length (CTL) harvesting methods, in the early 1980s there was still some uncertainty in Sweden about the systems and methods that would be most widely used in the future by the large forest companies. Nilsson *et al.* (1984) discussed this at the end of an information paper from the 'forest-energy' project. It stated that surveys showed that CTL accounted for 95% of all harvest operations and predicted that 6% of final fellings and 23% of thinnings would be carried out with some kind of tree-part method by 1990. Nilsson *et al.* (1984) did not regard the system that would be used in the future as critical (in the context of the project's focus on energy production), because variants of either approach would probably provide biofuel at similar cost. However, CTL did become totally dominate, accounting for almost 100% of the harvested volumes today. Occasionally some volumes are harvested as tree-parts or whole-trees in early thinnings, but the incidence of this is strongly related to current energy prices. With high energy prices this system can be more profitable than ordinary pulpwood harvesting (Di Fulvio *et al.*, 2011). Furthermore, in the last 10-15 years there have been efforts to develop new technical solutions, but none so far have managed to compete with the common harvester-forwarder system on large scale.

During the last 20 years, the single-grip harvesters and forwarders used for harvesting have been conceptually similar, although they have been continuously improved in details. The Nordic two-machine harvesting system have proven to be good enough in terms of productivity, flexibility, cost, and product (log) quality to be the mainstay in Swedish harvesting for decades. A Swedish tradition of buffering market and production fluctuations by maintaining stores of harvested roundwood instead of adjusting the harvest capacity (Laestadius, 1990) has enabled high utilization of the advanced and expensive Nordic harvesters and forwarders. Alternative solutions have been tested, such as various iterations of the harwarder concept (a machine that can both harvest and extract timber) (Wester & Eliasson, 2003), but as long as the CTL harvesting method is dominant and preferred in the industry, the two-machine system seems difficult to beat.

1.2 Technological change and innovation

There is a vast amount of literature on the subject of technological development or technology diffusion (Schumpeter, 1942; Samset, 1966; Geroski, 2000; Heinimann, 2007; Christensen, 2013; Lindroos *et al.*, 2017).

A general concept often referred to is that the diffusion of new generations of technology follow an S-shaped curve, with a few early adopters initially, followed by mass-adoption and then a more extensive time (depending on the technologies' life cycles) with fewer and fewer adopters (Figure 2). This is described, for example, by Geroski (2000) as the epidemic model, and the rate of adoption in different stages of the S-curve depends on a number of variables, such as the complexity of the technology involved, the total number of potential adopters, the way in which information about the new technology flows and so on. Technological change has also been described in terms of disruptions (Christensen, 2013) caused by new solutions to certain problems, which major incumbent companies may initially regard as having little relevance to their operations. However, at a certain stage, the new technology itself or its environment changes in a way that favors it and old technology is then swept away. An illustrative example is the manufacture of excavators (Christensen, 2013, ch 3). For a long time cable excavators were the only feasible solution for large-scale excavation, while excavations in small-scale projects, e.g. domestic electric conduit and sewer installations, were manual. The small-scale digging was eventually improved with the introduction of hydraulic attachments to farm tractors, and later more purpose-built 'backhoes'. No one could imagine the hydraulic excavators as competitors to full-scale cable diggers; they simply did not have the power and capacity. However, as better hydraulic cylinders and pumps were developed, they suddenly became sufficient for use on full-scale 360-degree turning excavators, and thus disruptively swept away the traditional cable excavators. A somewhat similar sequence of events occurred in the Swedish mechanization of roundwood harvesting. In the 1980s and 1990s, single-grip harvesters were developed and used in thinning operations (Ager, 2017), but few people initially thought they would ever compete with the large, high-capacity two-grip harvesters generally used at the time in final fellings. Later, comparisons of the two types of machines showed that the single-grip harvesters still had difficulties in handling large trees, but forecasts about their future development were more open (Brunberg, 1987). However, the single-grip harvesters subsequently became substantially larger and stronger, and hence even more productive than the state-of-the-art two-grip harvesters of the 1980s and 1990s.

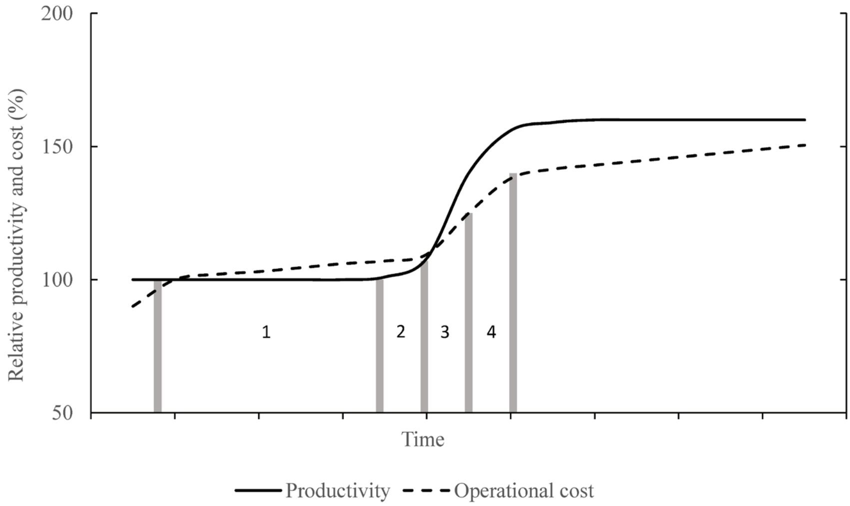

Figure 2. Schematic illustration of the stages of discontinuous evolution of harvesting equipment (after Samset, 1966). First (1) in a 'steady state' a current machine or system performs at a certain level of productivity (continuous line) and the operational cost slowly increases. At some point, the economic margin is stretched to the extent that harvesting is no longer profitable, triggering a search for new machines/systems. In the following stages a new machine or system is developed (2), introduced to the market (3) and finally diffused in practical forestry (4). After the diffusion, the productivity reaches a new 'steady state' with a new level of operational cost.

According to the law of discontinuous evolution, there are four productivity- and cost-related stages in the cycle of an evolutionary leap in technology (Figure 2). Initially costs are high because there is no operational productivity or revenue to offset development costs, but eventually revenues accrued from increases in productivity exceed the development costs. Costs increase slowly after the fourth stage because workers eventually want to share the benefit of rationalization and need to be better qualified (and thus better paid) to use the equipment in the new system (Samset, 1966). In conclusion, Samset (1966) describes technological development as occurring in leaps, so a new technology takes over when an old technology becomes obsolete. A practical example of this from the Swedish era of mechanization is the terrain transport productivity improvements gained by the introduction and development of forest tractors that replaced horses (Figure 3).

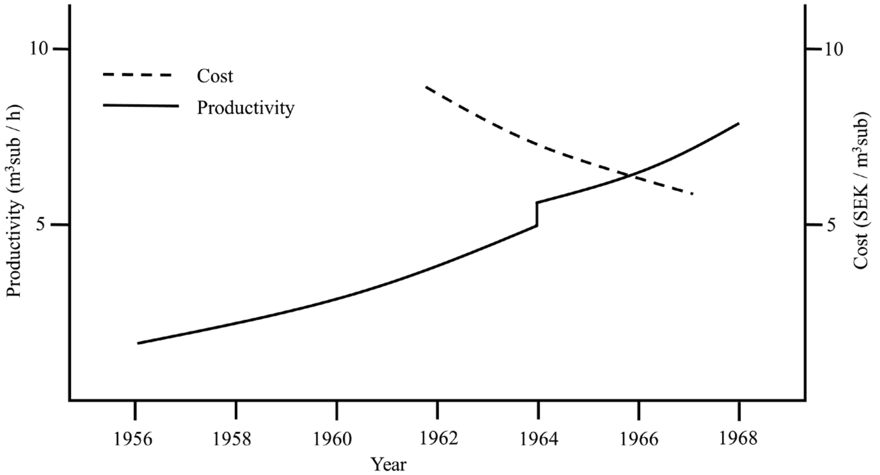

Figure 3. Changes in productivity (continuous line) and cost (dashed line) of terrain transport in Sweden (after Malmberg, 1968b). The cited author did not comment on the sudden jump in productivity around 1964, but is probably due to the major shift from horse- to tractor-mediated extraction during the 1960s in Sweden (cf. Nordfjell *et al.*, 2019).

1.3 Choice of harvesting methods and systems

Operations such as harvesting and extraction of roundwood are strongly affected by the physical environment. Terrain slope and roughness impose limitations for all machinery, but to highly varying degrees (Sundberg, 1988), and productivity levels of harvesting systems that could be used are differentially affected by biome-dependent variations in sizes and weights of trees and logs (Hiesl & Benjamin, 2013). Before harvesting, some sort of classification of the terrain is done in most countries. In Sweden and Norway, for example, a terrain classification scheme was jointly developed during the 1960s and 1970s (Anon, 1969; Von Segebaden, 1975; Berg, 1982). Although schemes for operative harvest planning have been formulated and are used in most places, there have not been strenuous efforts to quantify terrain characteristics from a forest operations point of view more broadly. International or global classifications of terrain would enable large-scale analyses of prerequisites for forestry work and started to be imaginable with the development of high-resolution remote sensing systems and methods for analyzing data they provided (Talbot *et al.*, 2017). Information on all terrain variables usually collected is important for a harvest operation, but slope may be the most important in terms of limiting possibilities for machines to traverse terrain in different directions. Ground softness can be very limiting, but also depends on the time of year and the weather, so it tends to fluctuate strongly. In extreme cases, terrain roughness can limit the choice of machinery, but it is usually more an indicator of the time needed to travel certain distances in the terrain, as increases in obstacles' size and number reduce speeds and increase both the frequencies and magnitude of detours. Thus, slope information is particularly valuable as it is consistently important, and relatively easy to acquire using general sources such as national or global remote sensing datasets.

In addition to the visible and actual terrain conditions, other factors such as socio-economic conditions, foresters' traditions, and culture in different parts of the world are believed to influence trajectories of operational developments. For such reasons, mechanization is very low in some countries (or parts of countries), while in others these factors influence choices of mechanized harvesting methods and systems. When labor is expensive, safety and/or productivity highly prioritized, and investment resources are available, operations tend to become increasingly mechanized (Axelsson, 1995; Silversides, 1997; Bonauto *et al.*, 2019). The mechanization of harvest operations has advanced more in some countries than others, but it always comes with choices and needs for decisions about the kind of equipment to employ and how to deploy it (choices of harvesting methods and systems). The choices may also be strongly affected by the current industrial infrastructure, and previous investments in factories, road networks, and other facilities that must be utilized throughout their lifetime. Thus, a certain application of methods and systems may stem from either present needs or traditions that arose during mechanization and associated legacy infrastructure.

The forest operations literature has not provided broad global maps of harvest operations in terms of applied methods. However, the harvesting method has long-term impact on the type of machinery used, which is highly important for manufacturers' market expectations when considering investments in development of autonomy and teleoperation. Since Sweden, and most other individual countries, constitute a small market for harvesting equipment, there is a need to consider international potential markets to offset research and development costs. For this, there is a clear need for broad mapping that does not rely on gathering and harmonization of diverse, country-specific datasets that were not originally intended for international comparisons.

1.4 Teleoperation and automation

Teleoperation is a combination of the Greek word *tele*, meaning *at a distance*, and *operation* as in getting work done. What is referred to here as teleoperation is also sometimes called telerobotics (Niemeyer *et al.*, 2016), in this thesis teleoperation is used both to describe the research field as well as specific control of machines. One of the earliest forms of robotics, teleoperation has found applications in, for example, handling of radioactive material (Clement *et al.*, 1985; Wei & Kui, 2004), underwater operations (Madni *et al.*, 1983; Yoerger & Slotine, 1987; Funda & Paul, 1991; Hirabayashi *et al.*, 2006), space missions (Bejczy & Szakaly, 1987; Bejczy *et al.*, 1990; Hirzinger *et al.*, 1993; Imaida *et al.*, 2004; Yoon *et al.*, 2004), telesurgery (Funda *et al.*, 1996; Madhani *et al.*, 1998), military missions (Kot & Novák, 2018; Rossiter, 2020), and mining (Hainsworth, 2001; Dadhich *et al.*, 2016). Starting with early applications in the nuclear industry, teleoperation systems have been frequently developed and implemented for uses in environments that humans cannot readily enter for safety, health, geographical, or other reasons. However, purely robotic systems (in the form of fully autonomous machines) have lacked (and still largely lack) sufficient capacities to perform all tasks (Clement *et al.*, 1985; Lindroos *et al.*, 2019). Therefore, teleoperation provides a very important and useful bridge between regular, manual, work and full automation, with scope to combine machinery capable of operating in harsh or otherwise inaccessible environments, with the cognitive abilities of the human brain that are still required for high-level decision-making (Niemeyer *et al.*, 2016). In addition to its value for work in hazardous or distant environments, teleoperation provides abilities to change the scaling of movements or actions between an operator and robot. In tele-surgery (which has received intense research attention), for example, highly specialized surgeons can perform their work all over the world, thereby increasing the quality of operations. Moreover, perhaps most importantly, tele-surgery can overcome the physical limitations of the human hand in controlling long-handled instruments with high precision inside a human body (Madhani *et al.*, 1998). For example, it greatly extends the degrees of freedom for suturing in tight spaces, and the movements in telesurgery can be scaled so that small, unintended movements by the human hand do not cause great damage to patients.

Over the years, a wide flora of interfaces for teleoperation, adapted to specific applications, has been developed. Regardless of the application, the interface must be able to give relevant and high quality feedback to the operator, then allow the operator to use a well-suited set of controls to adjust the behavior of the controlled machine (Schilling & Roth, 1999). To work properly, a teleoperation setup must also function reliably with a limited communication bandwidth, signal delays, noise, and interruptions in data transfer. The optimal media for signal transfer depend on the teleoperation applications (Table 1), and factors like range, bandwidth, cost, and signal stability must be considered when making choices.

Table 1. Examples of signal transfer media and some of their main characteristics.

Transfer medium	Range	Signal stability	Bandwidth	Cost	Reference
Cable	Short	High	High	Low	(Iastrebov *et al.*, 2008)
Bluetooth	Very short	Low	Low	Low	(Opiyo *et al.*, 2021)
Wlan/wifi	Short	Medium	Medium	Medium	(Opiyo *et al.*, 2021)
Low frequency radio	Medium	Medium	Low	Low	(Visser & Obi, 2021)
Internet 3G/4G	Unlimited	High	Medium	High	(Opiyo *et al.*, 2021)
High frequency radio (e.g. X-band)	Very long	Medium	Medium	High	(Satorius *et al.*, 2003)

Historically, automation in manufacturing industries has provided a way to increase productivity, maintain consistent quality, and reduce human exposure to hazardous environments (Huffman, 2015). At the same time, automation of work tasks is prone to disrupt the labor market, making people redundant at one place but usually creating new opportunities in another (Autor, 2015). In a way, the production of logs in the forest can also be seen as such manufacturing, and thus suitable for automation for the reasons mentioned above. However, automation endeavors are complex in forest environments because they are rough, remote, and exposed to the elements (Lindroos *et al.*, 2019). Forest operations are often compared to space or military missions– complex tasks in harsh environments. A more down-to-earth analogy is the mining industry, which (like the space and military sectors) has already worked with automated and tele-operated machinery for decades (Andersson, 2013). A concept used in the mining industry in particular is combination of automated work elements with tele-operation, thereby creating a very efficient system as a whole. Instead of waiting for full automation of roundwood harvests, the forest industry could exploit this approach by automating relatively simple tasks while exploiting the possibilities of tele-operation for the others. For example, in forwarding work the driving could be distinguished from the crane work and either teleoperated or autonomous. A common feature of all industries that are compared to the forest industry is that they can, and have, spent large amounts of resources on research and development of various aspects of automation. Such resources have been hard to raise in the low-cost oriented forest industry, but that might need to change. For countries with a mature forest industry like Sweden, the next technological development leaps in harvest operations are likely to involve increased levels of tele-operation and automation (Lindroos *et al.*, 2019). In the studies underlying this thesis, teleoperation and automation were investigated in a forwarding context, the studied concept is called *tele-extraction*, and if not otherwise specified the focus is on tele-extraction within the Nordic CTL harvesting method.

1.5 Aims and objectives

Overall aims of studies this thesis is based upon were to simulate and evaluate combinations of teleoperation and automation of forwarding within the cut-to-length harvesting method, and to discuss their potential application internationally.

Specific objectives of studies I-IV were:

I. to evaluate the economic potential of semi-automated tele-extraction with teleoperation of loading and unloading compared to standard extraction within the Nordic CTL two-machine harvesting system.

II. to evaluate the economic potential of semi-automated tele-extraction with teleoperation of driving work elements compared to standard extraction within the Nordic CTL two-machine harvesting system.

III. to compile data on annual volumes of industrial roundwood harvested by the main harvesting methods in the major roundwood-producing countries, and assess effects of possible explanatory variables on levels of mechanization and choices of methods.

IV. to create a globally consistent raster dataset of slope classes on forest land and make this freely available online. A secondary objective was to present data on global and national forest land distribution in relation to a number of slope classes, ranging from relatively flat to very steep, as well as forest area per slope class, on a national level.

2. Materials and methods in brief

To simulate future CTL harvesting systems, two studies (reported in Papers I and II) were conducted to evaluate the economic potential of different configurations of a novel concept called semi-automated tele-extraction or simply tele-extraction. To evaluate the potential application of such a concept in other countries, further studies involved global mapping of harvesting methods and reasons for the variations (Paper III), and global analysis of the slopes of forest land (Paper IV).

2.1 Papers I and II

To analyze forwarding work in Study I, Discrete Event Simulation (DES) was applied. Since the aim was to compare standard forwarding and a new concept called tele-extraction, two models were created using AnyLogic software. One mimics regular forwarding in Swedish conditions and the other models the new tele-extraction concept, also in Swedish conditions, with operators working at distance and only during terminal work elements (loading and unloading). Both models included five main work elements, as well as randomly occurring and separately recorded downtime.

- Driving empty
- Loading (including simultaneous driving and crane work, included in terminal time)
- Driving while loading (driving between log piles, included in terminal time)
- Driving loaded
- Unloading (including driving while unloading, included in terminal time)

The main conceptual difference between the simulation-models was that the tele-extraction model (unlike the standard model) incorporated seize and release of operators from an operator pool, the scope of which depended on the work-element being addressed. In addition, the size of the operator pool was varied to analyze effects of different operator/machine-ratios.

2.1.1 Data

To run the simulations, actual stand-data recorded in harvests by forest companies in three regions of Sweden were used as inputs for both models. These data included information on one-way extraction distances and harvested volumes for every stand, which were applied in the models' time consumption-functions. Statistics on downtime for forwarders were provided by SCA in Umeå and used to customize probability functions for downtime intervals and lengths in the models. Furthermore, statistics of machine driving speeds and time consumption for unloading provided by Manner *et al.* (2016) were used to create probability functions for the models. For cost calculations, estimations of cost components for large forwarders were provided by SCA in Umeå (Table 2).

Table 2. Forwarding cost estimates for a large forwarder (SCA, 2020).

Type of cost	Cost (USD/SMH*)
Fixed machine cost	29.5
Variable machine cost	50.4
Operator cost	46.1
Total	126

*SMH is Scheduled Machine Hours, including downtime (Productive Machine Hours × 0.86)

2.1.2 Modelling

The models were built as DES models with single forwarder loads as the units of observation/entity. The size of the loads was fixed at 22 m^3 sub (under bark), thus enabling conversion from total harvested volumes to numbers of loads in the input-data as well as calculations of productivity and costs post-simulation. The actual time consumption functions for driving and loading work elements were collected from Nurminen *et al.* (2006) with simplifications and adjustments similar to those of Lindroos (2012).

Simplifications in the model were setting driving distance without load equal to driving distance with load, and assigning all harvested wood to a single sawlog assortment. To account for variation in distances between loading and landing sites for material harvest from the same stand, a random element was introduced for driving distances with the same average distance within stands.

In addition to the model structure in Study I with teleoperated loading and unloading, and autonomous driving, new configurations of the tele-extraction concept were modelled in Study II. These were designated Teledrive A (with automated loading and unloading, but tele-operated driving empty, loaded, and between log-piles), Teledrive B (with automated loading, driving between log-piles, and unloading, but tele-operated driving empty and loaded), and finally, Full Auto as an end-point reference with all work elements fully automated.

The base DES model used in this study was the same as that developed for the first simulation study. To enable evaluation of new configurations of the tele-extraction concept, structural changes were made to the model. To model the Teledrive A configuration with automated crane work and tele-operated driving (including driving between log-piles), a local loop was created that repeated loading and driving between log-piles until a pre-set and load-specific number of loading cycles was reached. This structure enabled seize and release of the operator for every shift between loading and driving between log-piles work elements.

When modelling the Teledrive B configuration, the local loop described above could be removed since both loading and driving between log-piles work elements was automated, so no seize and release of operators was needed.

For Full Auto, all seize and release activities, as well as certain time measurements regarding operators were deactivated. Thus, time consumptions (and productivity) were similar to those of standard forwarding, the difference was in cost since the operator cost was removed.

2.1.3 Post-processing of results

All post-processing of the simulation output was performed with automated combinations of spreadsheets and R-scripts. The number of forwarder loads and their attributed data in each simulation constituted a vast amount of output, which could not be produced with the built-in logging functions in

AnyLogic. Custom-built R-scripts were therefore used to pick specific output data that were needed and transform the data to desired tables and figures.

2.2 Paper III

2.2.1 Data gathering

One large part of the study consisted of data gathering concerning the distribution of harvested roundwood on harvesting method in the 31 largest wood producing countries. This information was gathered in four different ways. First, the data on harvested volumes per country were collected from the Food and Agriculture Organization (FAO) of the UN. Then, corresponding data on the shares of different harvesting methods were extracted from: papers and reports emanating from universities and institutes; harvesting equipment manufacturers' estimates; and estimates by forestry experts and researchers. If different sources gave diverging information for a country, the sources were weighted in accordance with their apparent reliability for that country. For example, manufacturer's representatives and researchers/experts often add indications of levels of certainty to their estimates.

In a second part of the study, data were gathered about the studied countries that could potentially explain the differences (through regression modelling) between harvesting methods in harvested volumes obtained in the first part. Data on the potential explanatory variables were sought in international online databases that contained normalized data for all studied countries.

2.2.2 Definitions

The concept of harvesting method was chosen as the unit of observation because it encompasses a limited number of possible alternatives, each of which can be strictly defined but still applied in almost all countries. Specific harvesting systems are also commonly used to classify harvesting operations, and that can sometimes be more appropriate, but for the scope of this study a more aggregated concept was needed. Harvesting method was combined with level of mechanization and three categories were defined:

Fully mechanized cut-to-length (CTL), *Fully mechanized full-tree/tree-length (FT/TL),* and *Other*. The definitions imply that all non- and partly mechanized harvesting was assigned to the category *Other*, thus enabling certain analyses of the level of mechanization.

2.2.3 Modeling

Ordinary least squares regression analysis was done with shares of roundwood volumes harvested by fully mechanized CTL, fully mechanized FT/TL, and mechanization (CTL + FT/TL) as response variables. All tested explanatory variables are listed in Table 3. The statistical software R was used for the data preparation and regression analyses.

Table 3. Variables tested in the regression analysis.

Variable	Source	Description
Diesel price (US$/L)	https://www.globalpetrolprices.com/diesel_prices/	Accessed 1 Nov 2018
Fossil energy consumption (%)	ourworldindata.org	Share of a country's energy consumption from fossil fuel
Human Development Index (HDI) (index between 0 and 1)	ourworldindata.org	A combined index of life expectancy, level of education and Gross Domestic Product
GDP (US$/capita)	ourworldindata.org	Gross Domestic Product for each country
Gross value from forestry (1000 US$)	(FAO 2015)	Gross value from forestry for each country
Publicly owned land (%)	(FAO 2015)	Share of the forest land that is publicly owned
Slope (%)	(Lundbäck et al. 2020a) and the online database: (Lundbäck et al. 2020b)	Shares of forest land in selected slope classes. Lundbäck et al. (2020a) used four: < 15°, 15°-20°, 20°-30° and >30°. Here, the classes were also combined to form new classes, so in total seven slope variables were tested.
Forest land/Total land (%)	(FAO 2015)	Forest land as a share of total land area
Interest rate (%)	https://tradingeconomics.com/country-list/interest-rate	The steering interest rate in January 2019 set by respective central banks
Social security rate (SSR) (%)	https://tradingeconomics.com/country-list/social-security-rate	Total Social Security Rate per country
PPP index (number of LCU units)	https://data.worldbank.org/indicator/PA.NUS.PPP	Global index of the number of units of local currency (LCU) corresponding to the same amount of goods or services as 1 US$ in the USA in 2011

2.3 Paper IV

The overall concept of the Geographic Information System (GIS) analysis reported in this paper was to compile data on terrain slope and forest cover to extract slope data for forested areas of the earth. To produce results with globally consistent levels of accuracy and comparability, the analysis was based on remote sensing data. Country borders were used to delimit results for each country and slopes were classified to make the results more useful, not least within forest operations. To handle and manipulate the large global datasets a number of tools and software were used, all open-source (Figure 4).

The data on terrain elevation originate from the German TanDEM-X mission (Rizzoli *et al.*, 2017), particularly the aggregated model with 90 m resolution due to ease of access and handling. The forest cover data used were the widely spread 'Hansen dataset', consisting of NASA satellite data processed into a forest cover raster dataset with 30 m resolution (Hansen *et al.*, 2013). The input data were treated with a sequence of manipulations (Figure 4) and ultimately converted into two main results: the shares of forest land per country in each of four slope classes, and total forest area per country. The forest areas were calculated for comparison with those in other sources of information, mainly FAO (2010), to obtain an idea of the accuracy of the country-wise forest/non-forest data produced.

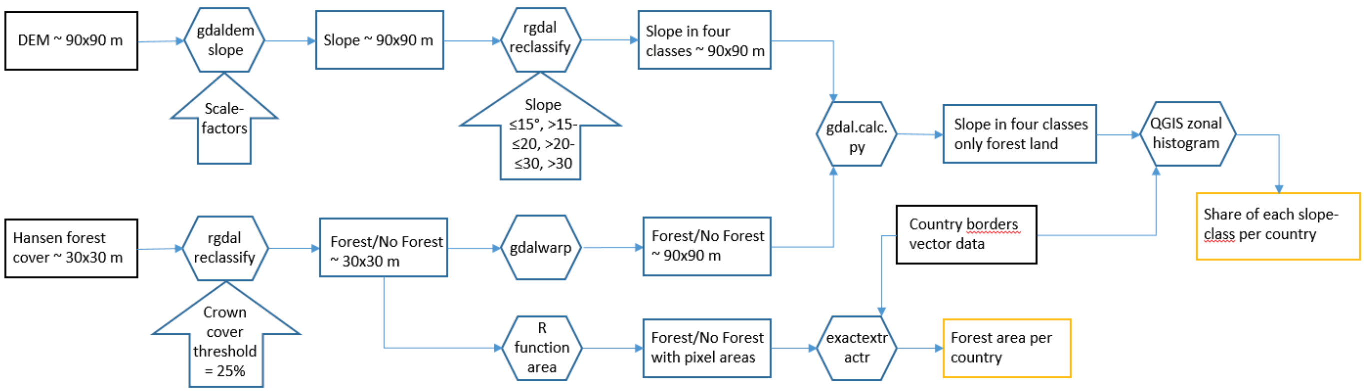

Figure 4. Flowchart of the steps in the GIS-analysis. Black borders indicate input data and orange borders indicate end-results. Rectangles and hexagons indicate the state of data and tools used, respectively.

3. Results

3.1 Simulations of tele-extraction (Papers I and II)

Simulation of standard forwarding with one machine and one operator in the north region resulted in a productivity of 32 m^3/hour and total cost of about 3.64 USD/m^3 with an average one-way extraction distance of 350 m. These results provided a benchmark for all further simulations in the north region. The Teleload configuration offered the lowest potential cost reduction, between 6% and 10% depending on the region. Both teledrive configurations inevitably had higher potentials since the most time-consuming work elements (loading and unloading) were autonomous, and when driving while loading was also automated (in Teledrive B) the potential cost reductions approached 20%. The Full Auto configuration yielded the absolute maximum cost reduction: 38% (Figure 5).

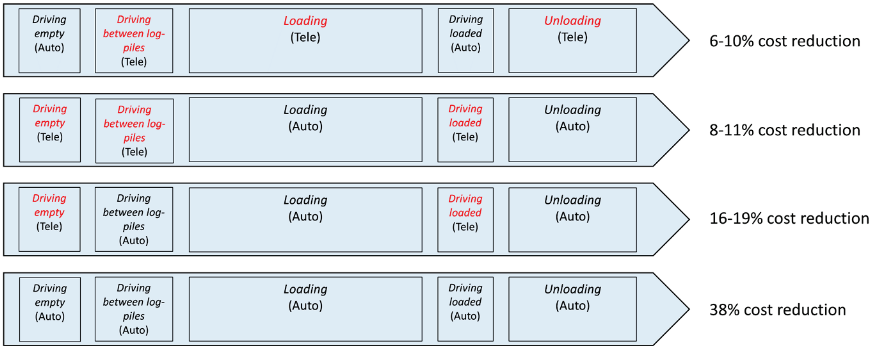

Figure 5. Reductions in cost compared to standard forwarding for three configurations of tele-extraction and Full Auto (which offered the highest absolute potential reduction). Work elements in red are tele-operated in the corresponding configurations. The length of the boxes around each work element is proportional to the average time consumption of the work element according to Manner *et al.* (2016).

For the north region, the optimal number of operators per machine was found to be 0.5/0.6 for Teledrive A, 0.4 for Teledrive B, and 0.7 for Teleload (Table 4). Productivity decreased together with the number of operators since the access to available operators became a bottleneck, but the threshold number beyond which productivity rapidly declined varied among the configurations (Table 4). For Teledrive A, productivity started to decline steeply at about 0.4 operators per machine and then sunk quickly with fewer operators, the corresponding drops for Teledrive B and Teleload were at about 0.2 and 0.6 operators per machine, respectively. A common feature for all these configurations was that the optimal number of operators per machine was just higher than the number at which its steep decrease started (Table 4). Results for the middle and south regions followed similar patterns to the north region, with slightly lower productivity and higher cost.

Table 4. Productivity and costs for Teleload, Teledrive A, and Teledrive B with indicated numbers of operators per machine, ranging from full teleoperation/standard forwarding with one designated operator for each machine to fully autonomous operation with no operators involved. Lowest average costs are indicated with bold numbers. IQR is the Interquartile Range.

Number of operators per machine	Full Tele (1)	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1	Full Auto (0)
Teledrive A											
North Region											
Productivity average (std. dev.)	30.47 (11.21)	30.44 (11.23)	30.44 (11.20)	30.17 (11.02)	29.23 (10.61)	26.92 (9.53)	22.76 (7.83)	17.02 (5.73)	10.38 (3.36)	4.18 (1.20)	31.44 (10.87)
Productivity median (IQR)	34.09 (14.86)	34.10 (14.80)	34.06 (14.83)	33.71 (14.63)	32.52 (13.98)	29.53 (12.92)	24.52 (10.92)	18.01 (8.23)	10.81 (4.88)	4.29 (1.71)	34.74 (14.49)
Cost average (std. dev.)	3.73 (.71)	3.59 (.71)	3.45 (.71)	3.32 (.70)	**3.23** (.71)	**3.23** (.72)	3.37 (.75)	3.79 (.83)	4.91 (1.08)	9.10 (2.03)	2.25 (.69)
Cost median (IQR)	3.55 (.80)	3.40 (.79)	3.26 (.79)	3.14 (.79)	3.05 (.80)	3.05 (.82)	3.20 (.88)	3.63 (1.02)	4.77 (1.40)	8.94 (2.73)	2.08 (.77)
Teledrive B											
North Region											
Productivity average (std. dev.)	31.09 (11.13)	31.09 (11.20)	31.04 (11.17)	30.98 (11.21)	30.86 (11.02)	30.24 (10.66)	28.45 (9.66)	24.55 (7.87)	18.03 (5.41)	9.42 (2.70)	31.44 (10.87)
Productivity median (IQR)	34.57 (14.85)	34.59 (14.87)	34.53 (14.86)	34.50 (14.90)	34.24 (14.62)	33.42 (14.14)	30.94 (13.14)	26.10 (11.00)	18.74 (7.75)	9.66 (3.88)	34.74 (14.49)
Cost average (std. dev.)	3.67 (.70)	3.53 (.70)	3.39 (.70)	3.26 (.70)	3.12 (.70)	3.01 (.70)	**2.96** (.70)	3.04 (.72)	3.40 (.77)	4.80 (1.05)	2.25 (.69)
Cost median (IQR)	3.49 (.78)	3.35 (.78)	3.21 (.78)	3.07 (.79)	2.94 (.78)	2.83 (.78)	2.79 (.79)	2.87 (.82)	3.26 (.93)	4.68 (1.38)	2.08 (.77)
Teleload											

North Region											
Productivity average (std. dev.)	30.99 (11.30)	30.93 (11.21)	30.44 (10.89)	29.00 (9.91)	26.27 (8.17)	22.42 (5.88)	18.13 (3.85)	13.65 (2.31)	9.14 (1.18)	4.56 (.43)	31.44 (10.87)
Productivity median (IQR)	34.58 (14.98)	34.43 (14.88)	33.81 (14.34)	31.79 (13.00)	28.27 (10.49)	23.63 (7.26)	18.86 (4.78)	14.01 (2.88)	9.29 (1.49)	4.62 (.56)	34.74 (14.49)
Cost average (std. dev.)	3.68 (.70)	3.54 (.70)	3.43 (.70)	**3.39** (.70)	3.43 (.70)	3.59 (.69)	3.87 (.68)	4.37 (.68)	5.38 (.70)	8.45 (.80)	2.25 (.69)
Cost median (IQR)	3.50 (.79)	3.36 (.79)	3.25 (.79)	3.21 (.79)	3.26 (.78)	3.42 (.77)	3.71 (.76)	4.22 (.78)	5.25 (.81)	8.33 (.98)	2.08 (.77)

Machine utilization was very tightly connected to productivity and as it decreased with reductions in access to operators, the utilization of the operator pool rose, approaching 100% (Figure 6). The saved operator cost, resulting from fewer operators in the operator pool, was countered by increases in fixed hourly machine costs due to low machine utilization. The best trade-off in terms of number of operators per 10 machines depended on the configuration (Table 4 and Figure 7). With the optimal number of operators for each configuration, the extraction distance affects the potential reduction in cost compared to standard forwarding (Figure 8). In general, the longer the extraction distance the larger the potential for tele-extraction with the Teleload configuration, since the autonomous driving will be a larger part of the total time per forwarder load. The opposite applies to Teledrive A and B since shorter extraction distances in those configurations lead to shorter tele-operated times (Figure 8). The potential reduction in cost for the Full Auto configuration was naturally independent of extraction distance since no operators are involved at all (black stars in Figure 8).

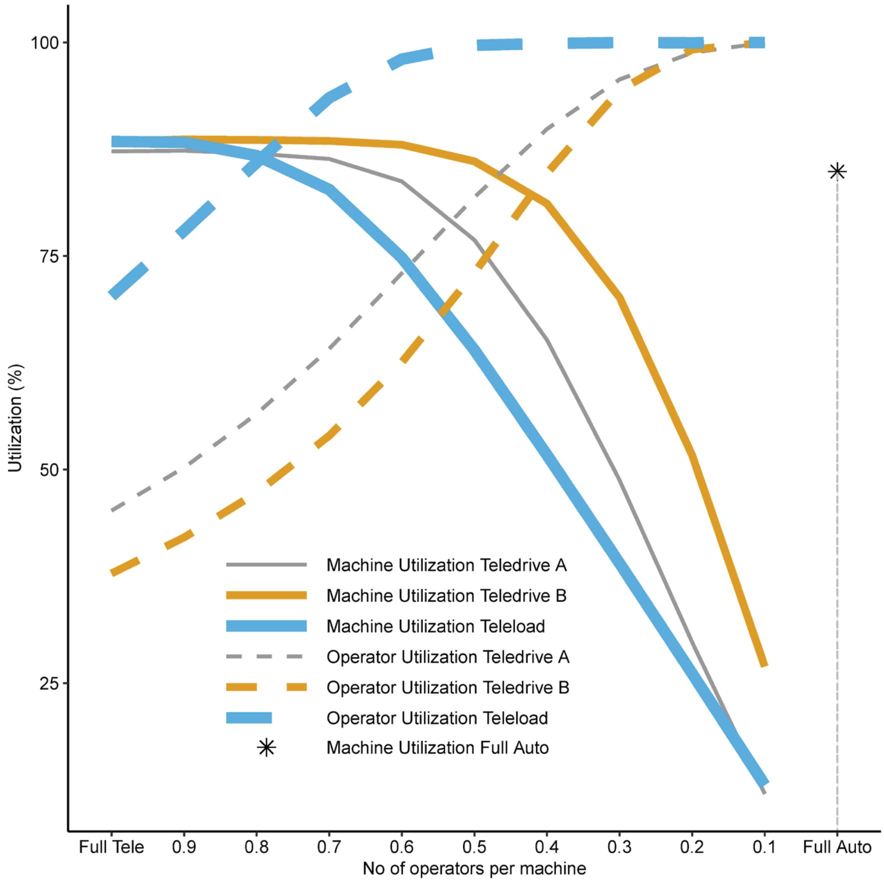

Figure 6. Average utilization of machines and operator pool in the north region for indicated numbers of operators per machine (x-axis) and configurations (Teledrive A, Teledrive B, Teleload, Full Tele as the baseline, and Full Auto, marked by the black star indicating the upper reference point).

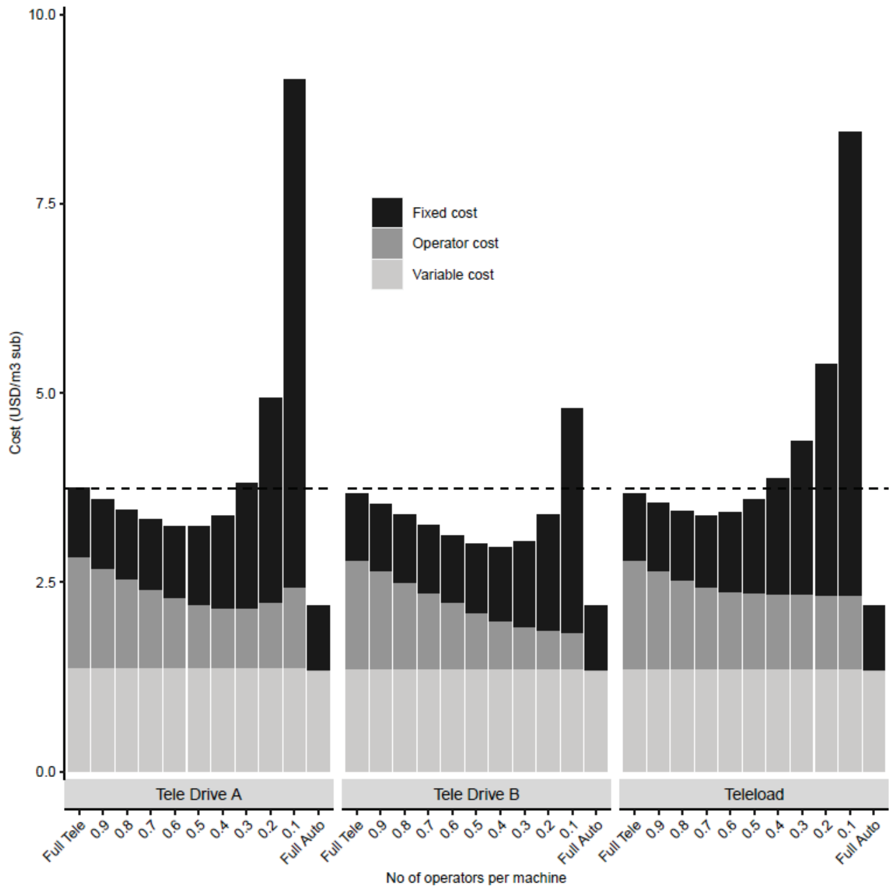

Figure 7. Average simulated forwarder cost (USD/m^3 sub) per cost category for the north region with indicated numbers of teleoperators per machine (x-axis) and configuration (Teledrive A, Teledrive B, Teleload, Full Tele as the baseline, and Full Auto, indicating the upper reference point regarding cost reduction).

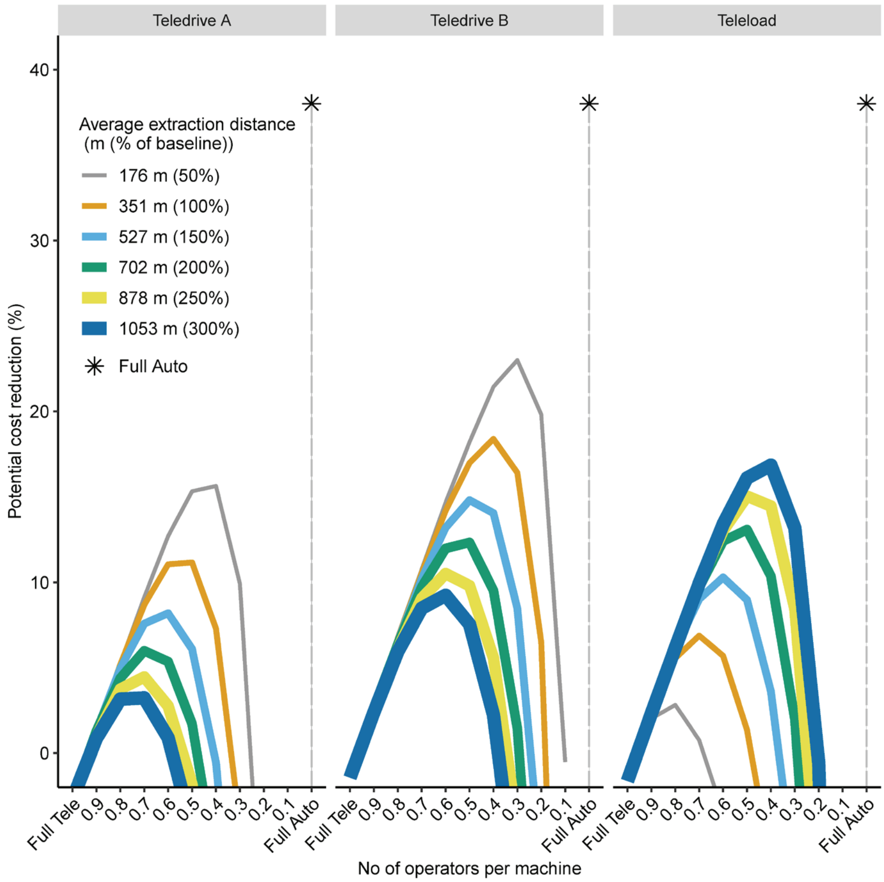

Figure 8. Simulated potential cost reductions for tele-extraction compared to standard forwarding in the north region, with indicated numbers of teleoperators per machine (x-axis), relatively adjusted extraction distances, and indicated configurations (Teledrive A, Teledrive B, Teleload, Full Tele as the baseline, and Full Auto, marked by the black stars indicating the upper reference point). The lines approaching the x-axis continue with negative economic impact on operations when the number of operators per machine declines. Every data point in the figure was obtained from a separate simulation run, each including about 150 000 forwarder loads, summing to over 27 million observations for the data presented in the whole figure.

3.2 Harvesting methods worldwide (Paper III)

Total harvests in the countries included in this study (31) amounted to 1.38 billion m^3 of industrial roundwood, 74% of the global harvest, in 2016. Over two thirds of that volume was harvested with fully mechanized methods (Table 5). Fully mechanized cut-to-length (CTL) was most common, accounting for 37% of the average harvested volume (Table 5). Since there have been variations of definitions of harvesting methods and harvesting systems in contemporary and historical literature, a classification decision was required. This resulted in a proposed structure of classification (Figure 9) in line with those of (Gerasimov & Sokolov, 2014; Lindroos *et al.*, 2017). The definition of harvesting method in Paper III, and this thesis, is formulated as follows:

´The harvesting method is defined by the shape of the roundwood logs at different stages in the wood supply chain. Trees can be fully converted to salable logs at the stump (cut-to-length harvesting method), delimbed at the stump but cross-cut somewhere else (tree-length harvesting method), or felled at the stump with all further processing somewhere else (whole-tree harvesting method).

The categories used in Study III (Table 5) were then defined as a combination of harvesting method and the level of mechanization, with ‘Other’ as a mixed category covering all elements of the classification scheme (Figure 8) that did not meet criteria for either of the first two categories. This means that a high value for ‘Other’ in Table 5 may stem from a low level of mechanization, high share of non-ground based harvesting, or some combination of these (as illustrated by the data for Ukraine and Austria).

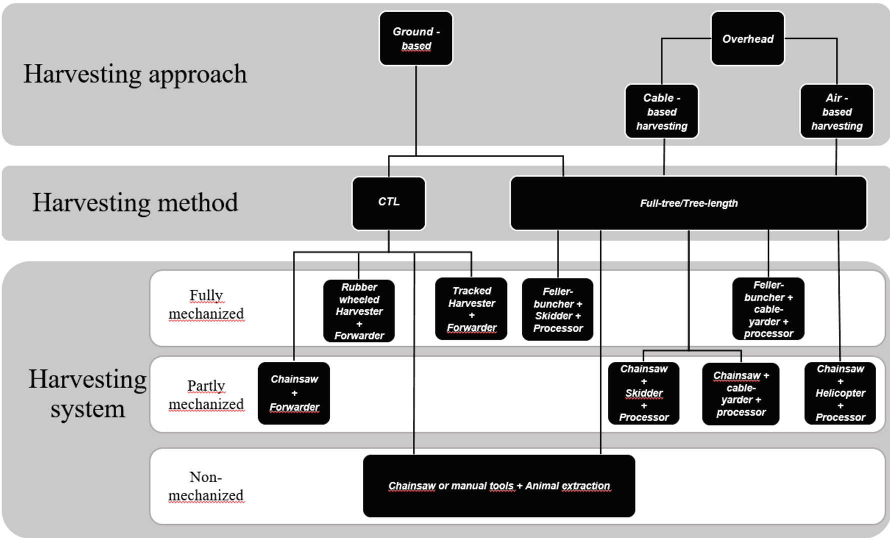

Figure 9. Classification of harvesting operations and their level of mechanization. The specific harvesting systems in the bottom of the figure are merely examples, many more are not included in the figure (Lundbäck *et al.*, 2021a).

Table 5. Annual volumes of industrial roundwood harvested[1] in included countries and the shares harvested by indicated categories of methods (Lundbäck *et al.*, 2021a).

Country	Annual harvest (M m^3 solid under bark)[1]	Fully mechanized CTL (%)[2]	Fully mechanized FT/TL (%)[3]	Other (%)[4]
Austria	12.2	35	<1	65
Belarus	11.3	10	10	80
Bulgaria	3.5	< 5	< 5	95
Czech Republic	14.1	30	10	60
Estonia	6.6	80	5	15
Finland	54.3	95	<1	<5
France	25.1	55	10	35
Germany	42.8	65	10	25
Ireland	2.7	98	0	2
Italy	2.1	60	<1	40
Latvia	11.4	70	5	25
Lithuania	4.7	50	5	45
Norway	10.3	95	<1	<5
Poland	36.8	20	10	70
Romania	11.0	5	5	90
Slovakia	8.8	< 5	< 5	95
Spain	13.3	60	<1	40
Sweden	67.2	95	<1	<5
Turkey	20.4	2	6	92
UK	8.7	90	0	10
Ukraine	8.2	< 5	< 5	95
Europe	*375.5*	*59*	*5*	*36*
Eastern Canada	57.9	75	20	5
Western Canada	99.9	5	80	15
USA	356.6	15	70	15
North America	*514.4*	*20*	*66*	*14*
Brazil	145.1	45	25	30
Chile	44.6	25	25	50
Uruguay	11.3	75	<1	25

South America	*201.0*	*42*	*24*	*34*
Russia	198.2	35	10	55
Malaysia	13.9	<1	<1	>95
Australia	30.1	45	50	5
New Zealand	28.7	10	55	35
South Africa	14.4	30	60	10
Weighted totals[5]	1 376	37 %	33 %	30 %

[1] Based on data compiled in the *FAO Yearbook of Forest Products 2016* (FAO 2016)

[2] Fully mechanized CTL – Ground-based cut-to-length operations in which all steps are mechanized, called ‘CTL at stump’ in Canada.

[3] Fully mechanized FT/TL – Ground-based full-tree or tree-length operations in which all steps are mechanized, and stems are bucked no earlier than at landings.

[4] Other – All other types of operations, such as cable- or air-based harvesting approaches, partly mechanized harvesting systems and harvesting systems with simple equipment.

[5] The average shares for all countries were weighted with harvested volume.

A regression model (Model 1, with R^2 value 0.64) was created to explain how the share of CTL was related to other nation-level data. According to the model, high diesel price and high Gross Domestic Product (GDP) were associated with high share of CTL while steep terrain (large share >20°) was associated with low share of CTL (Table 6, Figure 10).

Table 6. Summary statistics for fully mechanized CTL Model 1 (with no interaction variable). (Lundbäck *et al.*, 2021a).

Variable	Parameter estimate	SE	p-value	VIF	R^2-adj (%)	RMSE	RMSECV
Full model	-	-	<0.001	-	63.9	18.52	21.20
Intercept	-27.37	13.37	0.050	-	-	-	
Diesel price	49.76	10.91	<0.001	1.31	-	-	
Slope >20°	-0.9282	0.226	<0.001	1.01	-	-	
GDP per capita	0.0006317	0.0002774	0.031	1.31	-	-	

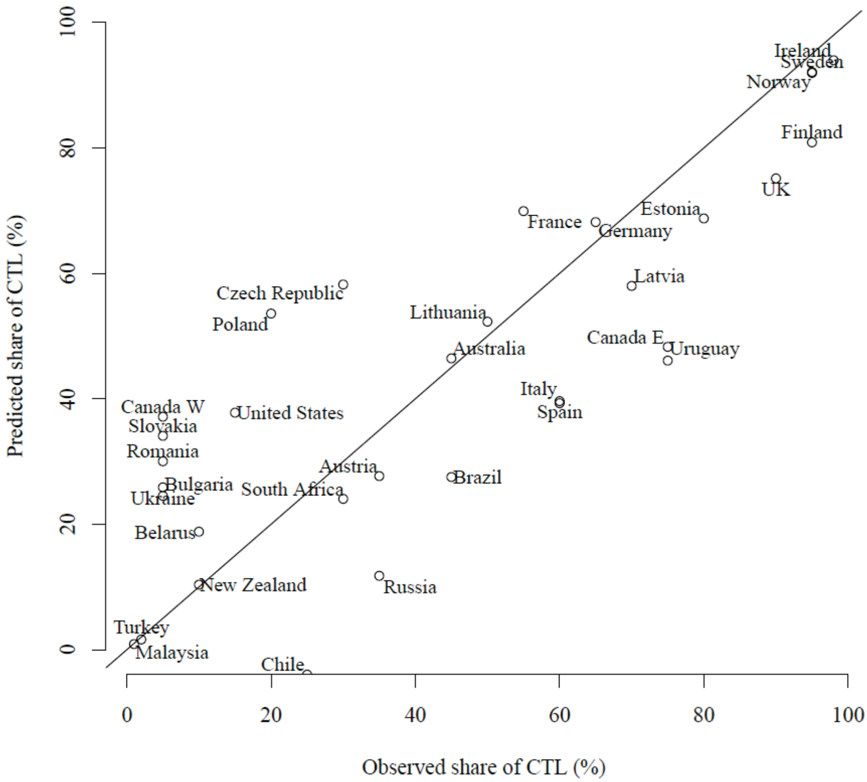

Figure 10. Shares of volume of industrial roundwood harvested by CTL in indicated countries, according to regression Model 1, versus observed shares. The line through the origin has a slope of one. Countries above it have higher modeled values than observed values, and vice versa for countries below the line (Lundbäck *et al.*, 2021a).

3.3 World-wide slope mapping of forest land (Paper IV)

The total area of forest land, according to the applied forest cover data (Hansen *et al.*, 2013) is 4.15 billion ha, or 32% of the world's land area. There is great variation in forest area between the continents, Russia alone has 790 million ha, 82% of the forest land is on slopes less than 15°, and the rest on steeper slopes (Figure 11).

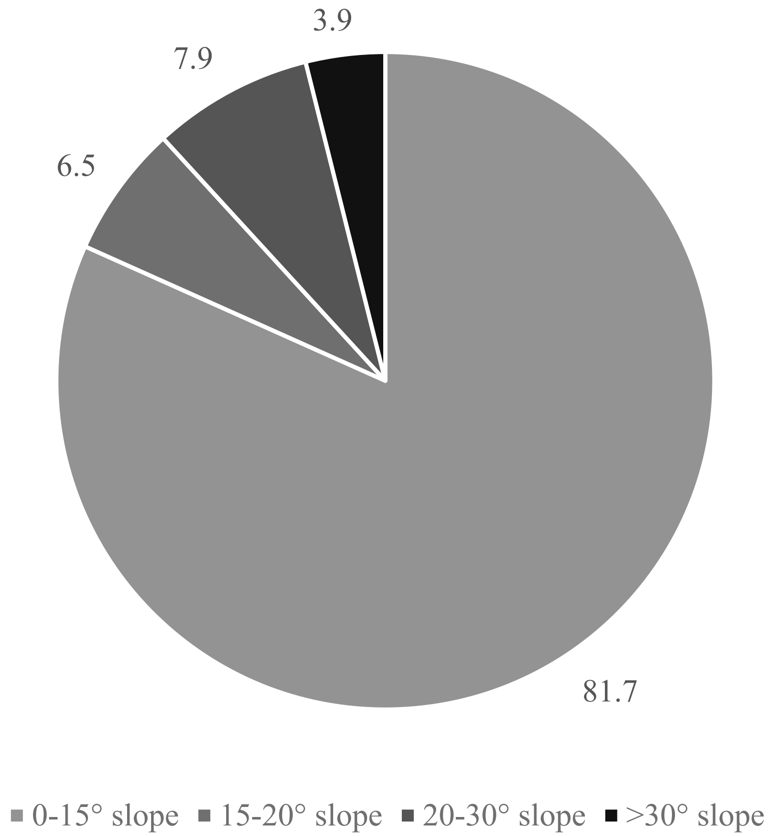

Figure 11. Distribution of the world's forest land in four slope classes (%) (Lundbäck *et al.*, 2021b).

Large areas of forest land with steep slopes are in the mountains of Asia, Europe, and North America, while flat forested land is common in Russia, Africa, and the Amazon rainforest. Of the 10 largest roundwood producing countries China, India, and Chile have the highest shares of forest land (about half) with >15° slopes. In Russia, Sweden, Finland, Canada, the USA, and Brazil forest land is relatively flat (Figure 12). Apart from the numerical figures of area within slope classes per country, the study also resulted in a global raster dataset with about 90×90 m resolution, and information on the slope class of each pixel. This dataset is accessible online (Lundbäck *et al.*, 2020), can be visualized with customized geographic backgrounds and offers an overview of the data for large or small user-defined areas, for example Europe (Figure 13).

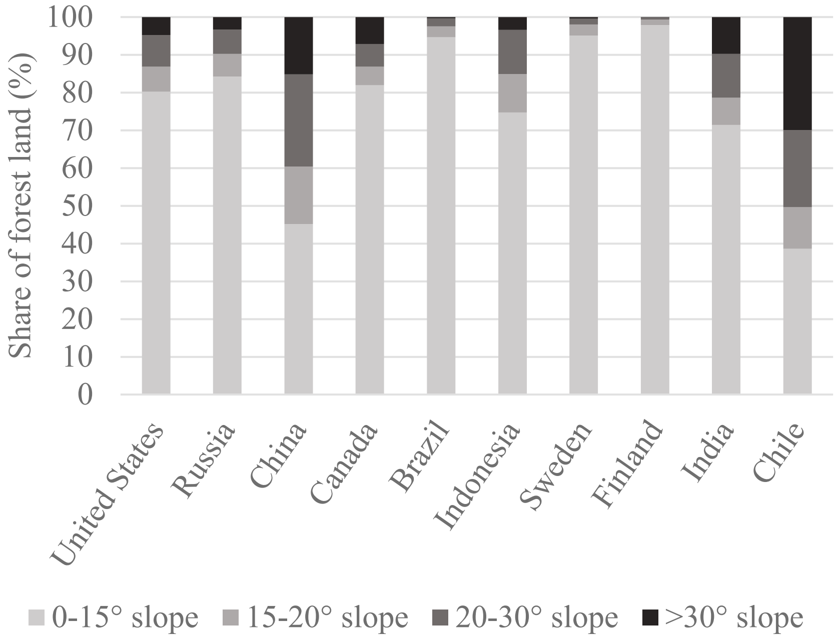

Figure 12. Distributions of forest land in four slope classes in the 10 countries that annually harvest 70% of the world's industrial roundwood (the USA, Russia, China, Canada and Brazil together account for 50% of the world's harvest). Annual harvest decreases from left to right (Lundbäck *et al.*, 2021b).

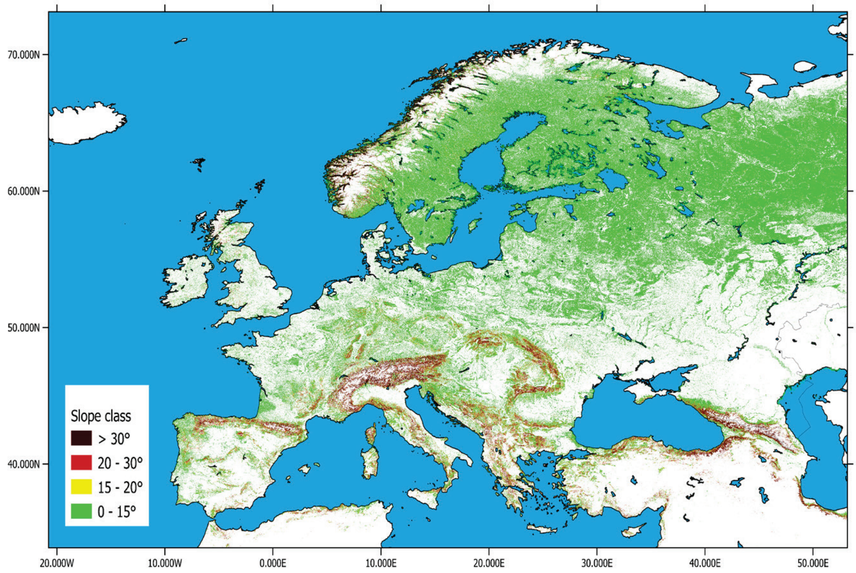

Figure 13. Part of the global map of the classified slopes in Europe generated in the study (Lundbäck *et al.*, 2021b).

4. Discussion

4.1 Organizational aspects of tele-extraction

Before more detailed discussions, an account of how a tele-extraction system would be set up and work is warranted. Forwarding is not an isolated activity but part of the timber supply chain. In Sweden, the forwarder is commonly part of a harvesting system that also includes a harvester and in total 4–5 operators working in shifts. The harvesting team usually stays relatively close together, with ideally just a few days of harvested wood in the forest at any given time for the forwarder to extract. If the forwarder was operated from long distance and partly autonomously, some miscellaneous but regular work elements would have to be adapted accordingly, for example refueling and greasing without physical onsite involvement of the operator. The harvester operator might be able to solve some problems, like minor breakdowns, within a reasonable time, leading merely to short delays for the harvester. However, introduction of forwarders without onsite operators would require many changes, of various magnitudes, to the machines to avoid kinds of interruptions or breakdowns that can be easily fixed by the operator today, but would lead to major delays in a teleoperation context. If the tele-extraction system initially relied on the harvester operator for certain work elements, the working times and shifts of teleoperators would have to differ from those of onsite operators to ensure that the forwarder was in operation for more hours per day close to the end of a harvest site. That would be essential to avoid the forwarder being left alone, too far from the harvester operator to fix issues that might arise quickly, or finishing its operations at one site while the harvester moves to the next harvest site, which is the standard procedure today in Sweden. With loss of the connection of particular operators with particular machines, the timing of the harvester operations would probably become a simple scheduling problem.

4.1.1 Operator work schedule

In a tele-extraction system like the one studied, each operator will be faced with a somewhat unpredictable mix of busy and idle time windows (Figure 14). The patterns and lengths of busy and idle time blocks will vary depending on how the system is configured, i.e. which work elements are controlled by operators. The patterns and lengths will also vary with the combination of harvest plots that are handled within the tele-extraction system. Since the operators will move between different machines, the total mix of extraction distances and harvested volumes will determine the workflow for a specific operator, rather than the schedule for a specific machine.

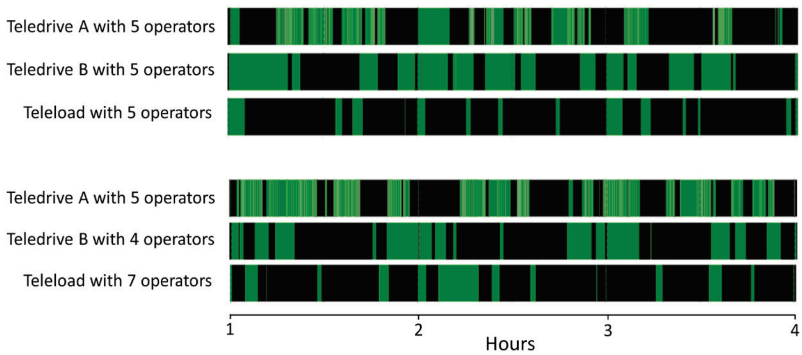

Figure 14. Gantt chart showing times during a few hours of operation at the beginning of the simulations when an operator was busy and idle in black and green, respectively. Teledrives A, B and Teleload was simulated with five operators on the ten machines as well as their respective optimal number of operators per machine; 0.5, 0.4, and 0.7.

Longer continuous busy time blocks were obtained in the Teleload simulation (Figure 14), because the terminal activities (loading and unloading) are teleoperated in Teleload, and consume large amounts of time compared to driving. Increasing the temporal resolution to examine activity patterns within hours shows that many short, busy periods occur in the operations with the Teledrive A configuration (Figure 15). This was expected, because of the frequent alternation between loading crane movements (autonomous) and driving between the log piles to be loaded (teleoperated), but makes Teledrive A more difficult to implement than the other configurations. Another operator-related factor is that it might be challenging to implement teleoperation in all machines completely according to current production needs, or at least it would put high demands on operator support systems to avoid the operators being regularly delayed or losing productivity due to fatigue.

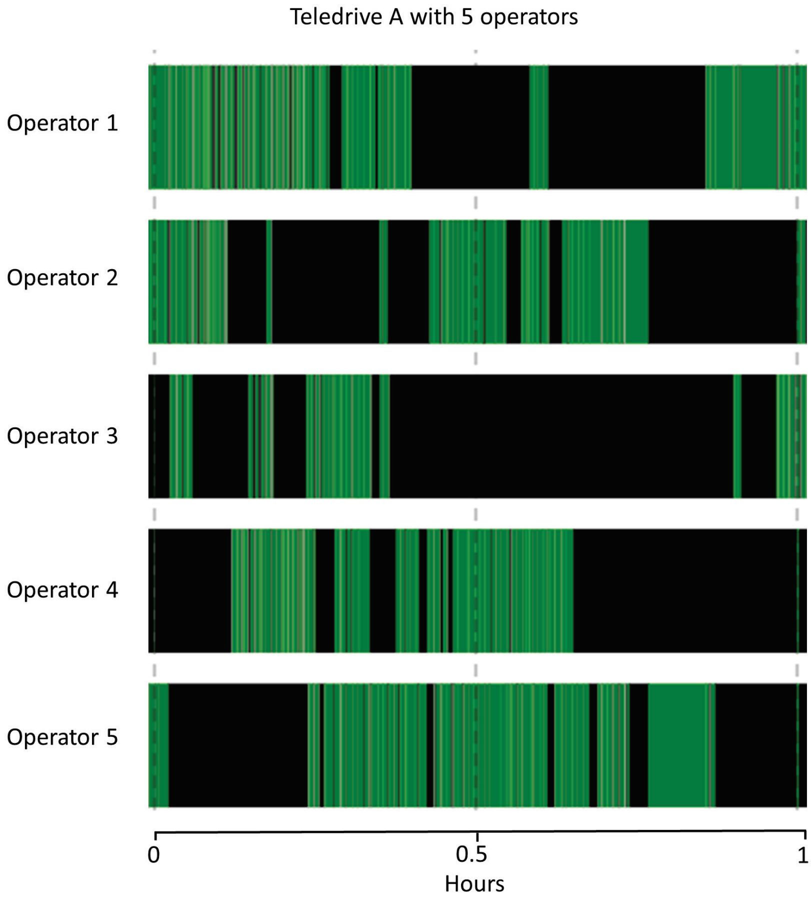

Figure 15. High-resolution visualization of a one-hour output of the Teledrive A simulation with five operators. The grey zones in the green areas indicate very short time windows for driving between log piles (operator busy) and loading (operator idle).

The risk of short but numerous delays was particularly clear in the Teledrive A configuration, (Figure 15). In Study II, the effect of the probable need of a human operator to spend a certain time assessing the situation and deciding where to drive etc. was evaluated by introducing a delay every time an operator entered a machine to drive to the next log pile into the simulations. The results indicated that average delays of 10 s (ranging randomly from 5 to 20 seconds) decreased productivity and increased costs by about 2 percentage points, shrinking the potential cost reduction for Teledrive A from 10% to 8% compared to standard forwarding. These results accentuate the need for good operator support systems, minimizing such delays.

In an attempt to quantify effects of limitations in the free assignment of operators to machines originally simulated, a Teleload scenario with 0.5 operators per machine was tested with the operator pool modified so that one operator was only accessible for two machines, the next operator for two other machines, and so on. This was intended to reflect a situation where a single operator could only keep track of two machines at once, without being delayed by extra time for planning and/or recalling what to do next. The results show that locking certain operators to machines increased costs by 13% compared to regular Teleload with free assignment and the same number of operators (5). Adding 13% of extra cost to costs of the best Teleload configuration in the north region (with 0.7 operators per machine) results in costs of 3.83 $/m3 harvested roundwood, which is actually higher than the cost of standard forwarding (3.64 $/m3). Assessing whether or not two machines per operator is relevant for practical work is beyond the scope of this thesis. However, the results indicate that the freedom for machines to 'seize' any idle operator according to current need is an important element of tele-extraction and crucial to attain the potential cost reductions.

There is potential to increase utilization of machines in cases of operator overcapacity. Even if not tested in studies underlying this thesis, an imaginable illustrative scenario is that 0.7 operators per machine may be a *feasible* economic optimum (similar to the optimum obtained for Teleload in the north region in Study I) while the *true* optimum is somewhere between two discrete levels, for example 6.5 operators. Clearly, the feasibility of having a pool of 6.5 operators would depend on the scale of the whole tele-extraction fleet (the number of machines). With the parameters of the studies this thesis is based upon and a fleet of 10 machines, 6.5 operators would be for the true optimum of 0.65 per machine, and if full-time employment is specified that would be impossible, hence the feasible optimum would be 7 operators. Some extra operator idle time blocks would then be available, but with unpredictable intervals and lengths. If some of those time blocks could be used for some of the delays that are operator-related, but in standard forwarding also stop the machine (i.e. small delays that were included in the downtime in the simulations), implementation of tele-extraction could theoretically increase machine utilization.

4.1.2 Organization of tele-extraction machine fleets

In an international perspective, not all harvest operations are organized as in Sweden, with teams of 4–5 operators working shifts with one harvester and one forwarder. Larger teams with more machines at the same harvesting site are likely to favor the tele-extraction system since maintenance personnel are usually already available onsite. It is easier to justify the inclusion of dedicated personnel for maintenance and repairs financially for a large fleet of machines operating close to each other at big harvest sites, for example in fast-growing pulpwood plantations. This raises the possibility that the future organization of harvest operations in Sweden may substantially change if tele-extraction would be implemented. Maybe the development towards teleoperation and automation will force a shift in ownership and financial responsibility for equipment from the small contractors to large forest companies (as was the case during mechanization in the 1960s to 1980s in Sweden) or even to equipment manufacturers. There are no presumptions in the simulation studies underlying this thesis about who would own or be the overall operator of a tele-extraction system, but there are many assumptions about the functionality of teleoperation and autonomous operation that might have different effects depending on who is running the operation. For example, the cooperation between harvester and forwarder regarding transfer of data on harvested volumes and geographic areas might be impaired if the forwarder is part of a bigger fleet owned by a forest company or equipment manufacturer while the harvester is owned and operated by a small contractor. This and similar imaginable obstacles could probably be overcome in a country like Sweden with a very extensive and well-structured common data organization for forestry, but might be more difficult in many other countries.

One possible developmental trajectory is towards tele-extraction systems that are highly autonomous overall, but with a few operators that act mostly as supervisors and only intervene when difficulties beyond the systems' operational parameters appear. That presupposes the possibility of performing all work elements autonomously in normal conditions, which is probably quite far in the future. Another imaginable possibility is that specific technology may be developed to automate specific work elements while the other work elements are teleoperated. The configurations presented in this thesis suggest and illustrate such a division of work elements. In practice, a third developmental trajectory is perhaps most likely, at least in the initial phase, involving automation of all or most work elements in easy conditions, with teleoperation when conditions become more difficult.

4.1.3 Implications for hourly operator costs

In a future of potentially changed working conditions, in which forwarder operators can be situated anywhere while operating the machines, the possibility that the work could be internationally outsourced to low-wage countries should be considered. Any reductions in wage levels would increase the cost reductions, so there would be obvious temptations for employers to shift teleoperated work to India, for example. On the other hand, wage levels could potentially be higher as any tele-extraction system still works in a local context, so there are needs for cooperation with harvester operators, adaptations to local forest conditions, and hence potentially for knowledgeable and skilled operators with local attachments. Therefore, there are clear reasons to test effects of both lower and higher hourly operator costs than those applied in the main simulations.

To investigate the sensitivity of the simulation results to the level of hourly operator cost, the operator cost was increased or reduced by about 10% for operations in the north region with the optimal number of operators per machine for each of the three configurations, giving six new simulations in total. For both Teleload and Teledrive configurations, the change in hourly operator cost led to about 3% increases or reductions in cost per m^3 of roundwood. The size of the change depends slightly on the operator time, as a percentage of the total time for a full load cycle, which differs among the configurations, but the range stayed within 2.6 to 3.9% in these simulations. In such cases, a higher operator cost will increase the potential cost reduction for tele-extraction because it is operator time that is removed when shifting from standard forwarding to tele-extraction. However, if the work is outsourced, as mentioned above, tele-extraction is a prerequisite to access the low-waged workforce of another country, so comparisons of standard forwarding and low-wage variants are irrelevant.

4.2 Technical aspects of tele-extraction

Relating to technological development, there is strong indications that the coming developments leaps (Figure 2), and/or disruptive changes (Christensen, 2013) in Sweden, will soon occur in the realms of teleoperation and automation, including emergence of all the general technology required (which was not considered in detail in this thesis or the underlying studies). Examples include digitalization by incorporation of remote sensing data into the working environment (the forest) of the machines of the future (Heppelmann *et al.*, 2022), development of algorithms that can utilize common sensor equipment for navigation purposes (Chiang *et al.*, 2020), and the development and implementation of more smart planning tools and operator support systems (Flisberg *et al.*, 2021).

4.2.1 Terrain and level of automation

The studies underlying this thesis yielded results based on specific configurations of the tele-extraction concept, but nothing restricts future implementation of a tele-extraction system to one configuration or another. Assuming a relatively short time span between automation of the first and last work element in forwarding, the local terrain conditions are likely to dictate the level of automation. It will probably be higher if the terrain is flat, firm and smooth (facilitating driving), and both the logs and assortments are easy to identify, than if conditions are more demanding. So, it seems likely that systems will be developed that can run autonomously but require teleoperation when conditions become difficult in some way. Such setups would have similarities to other applications of teleoperation in cases where semi-automation is more feasible or desirable than full automation (cf. Materna *et al.*, 2017). Forest operations also have the advantage, compared to (for example) self-driving cars or military applications, that it is not usually problematic to immediately stop operations and wait for an available operator. An example of a case where a teledrive approach would be suitable is a site where an extraction trail between a roadside and harvest plot is very steep while the harvest plot itself is on flat ground with homogeneous trees, suitable for autonomous operation. In contrast, a teleload approach may be more suitable for a harvest plot with mixed tree species and many assortments, carelessly spread out by the harvester, and perhaps also covered by snow, but with a very flat, wide, firm, clear and obstacle-free extraction trail to and from the plot. In practice, a mix of these two endpoints would probably become quite common, letting the machine call for an operator only when needed and managing by itself otherwise.

4.2.2 Communication systems and level of automation

The level of automation is also tightly connected to the demands placed on a communication system for teleoperation. Systems with high levels of automation, in which the operators mostly take high-level decisions that the machines largely execute autonomously, can be operated with weaker connections, lower sensitivity to interruptions and lower bandwidths than systems with lower levels of automation (see Table 1). In tele-extraction contexts, an example of a high-level decision-making interface is a 'click and pick' function for operators to use during the loading work element, enabling them to see all log piles within reach of the crane, click on the next one that should be loaded, then let the machine execute the loading autonomously. Such a system could be operated in settings with quite sparse network reception since an interruption during the actual loading would not be critical. Waiting times would only occur if the operator needed to wait for reception to transmit commands to the machine. Depending on how the machines develop in the future, there might be various other cases of this kind of high-level decision-making by operators, and it may be particularly useful in forest operations due to the remote and large working areas.

4.2.3 Risks with technically complex and online tele-extraction

A downside of introducing more digital and connected control systems is, of course, higher risks of unexpected malfunctions or even hostile digital attacks, with wood supply adding to the large array of potential targets of attacks and disturbance by hackers. Going online and digitalization also raise risks of the creation of complex systems, with 'legacy' elements of previous systems that nobody any longer really knows how to fix when something goes wrong (Sarter *et al.*, 1997). A general issue in today´s technological development is that developers and innovators frequently generate new applications by combining existing technologies in new ways, meeting new needs. When the function of a system or technology is crucial for people's health or lives, for example in healthcare or aviation, there is a weakness built into this kind of innovation since the developers do not necessarily know exactly how the components work in detail, only that their outputs make the new application work (until something fails).

4.2.4 Backup systems

To handle serious breakdowns or other extraordinary events, there is a need for some kind of simplified manual control system, especially if the design of a tele-extraction forwarder does not include any kind of operator cab. The machine could have various kinds of malfunction in the tele-link, or get stuck in a way that cannot be handled via teleoperation, or a hydraulic hose may break in the forest. For such events, it would be convenient if a person could plug in some kind of basic radio or wire control device to, at least, be able to drive the machine while walking along, completely overriding the regular teleoperation system. This kind of backup control system is likely to become obsolete when the technology has developed sufficiently, but will probably be necessary during the first years of implementation.

4.2.5 Removal of the operator's cabin

Under the assumption, made in Studies I and II, that forwarders in a tele-extraction system are teleoperated at all times when they do not work autonomously, i.e. there is never a need for an onsite operator, an interesting possibility to consider is removal of the operator cab and associated systems for operator comfort. According to technical specifications for the largest forwarder from Komatsu, the cabin, including damping equipment, weighs about 1 700 kg. Extra technical equipment for managing the teleoperation might well be expensive, but would probably not be particularly heavy. Thus, not exceeding the original total weight of the forwarder, approximately 2 m^3 more roundwood could be accommodated, assuming that the load space distributes weight on both front and rear axles, so weight rather than volume is the limiting factor for the load sizes. Alternatively, the total weight could be decreased while maintaining the same load volume, which might be favorable for operations on (for example) soft ground.

To quantify the effect of increasing the load volume from 22 to 24 m^3, simulations were ran for all three configurations (Teleload and Teledrive A and B) and for 0.1 to 1 operators per machine. Results indicate that this would reduce costs of each configuration and number of operators combination, by 3 to 7%. With the optimal number of operators per machine in each configuration, the reduction in cost ranged between 3.7 and 5.0%. The improvement in cost efficiency has nothing to do with the tele-extraction system *per se*, except that it would not be possible to remove the cab without teleoperation.

4.2.6 More than one assortment

In all simulations, operations with only one assortment were modelled, i.e. no extra time for sorting or mixing loads was included in the time consumption for the loading or unloading work elements. For Teleload, this was addressed by an analysis where the time for loading and unloading was increased by 33%. This decreased the potential cost reduction from 7% to 5.3% (see Study I). In contrast, in new simulations of the Teledrive A and B configurations, 33% increases in terminal times increased cost reductions from 11 to 13% and from 18.5 to 20%, respectively. This is because operation during the terminal time is autonomous in the Teledrive configurations, so increasing the terminal time's share of total time consumption per load can reduce operator involvement, and hence costs. The result was sufficiently strong for the Teledrive A case to reduce the optimal number of operators per machine from 0.6 to 0.5. The general conclusion of these sensitivity analyses is that increases in work time assigned to loading and unloading, for example due to more assortments, increase the profitability of making terminal work autonomous. It should also be noted that the 33% increase in terminal time increased the differences in potential cost reductions of the Teledrive and Teleload configurations, rather than reducing them.

4.3 Sustainability aspects of tele-extraction

The concept of sustainability is often divided into three 'pillars': economic, environmental, and social. The economic implications of tele-extraction are extensively addressed in this thesis and the underlying studies, but its implications for environmental and social sustainability also warrant attention, and thus are considered in this section.

4.3.1 Environmental sustainability

Environmental sustainability is a wide concept. In this thesis, the United Nation's Sustainable Development Goal (SDG) 9 (*Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation*; (United Nations, 2021)) is highly relevant. Further, target 9.4 (*by 2030 upgrade infrastructure and retrofit industries to make them sustainable, with increased resource use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes, all countries taking action in accordance with their respective capabilities*) is particularly relevant. Key associated objectives are to minimize CO_2 emissions per unit added value in industrial processes, such as timber harvesting. Implementation of the tele-extraction concept would have several effects on CO_2 emissions. First, it would eliminate journeys to and from harvesting sites for operators of the forwarders (which may be several hundred km), thereby reducing emissions from car traffic. The potential savings in CO_2 emissions this could provide were not quantified in the studies this thesis is based upon, but could be included in future life cycle assessments of the tele-extraction concept. Second, removal of the operators' cab and increasing forwarders' payloads, would increase efficiency by decreasing numbers of loads per harvest site and CO_2 emissions per extracted m^3.

Apart from CO_2 emissions, various forms of ground disturbance, like compaction and rutting, are probably the most important environmental aspects of all kinds of roundwood extraction and forwarding. SDG 15 (*Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss*) is also highly relevant to the sustainability of forest management. In this context, target 15.2 (*promote the implementation of sustainable management of all types of forests, halt deforestation, restore degraded forests and substantially increase afforestation and reforestation globally*) is particularly important, and a key element is to avoid damage to forest ecosystems. Here too a potential benefit of tele-extraction compared to standard forwarding is removal of the operator cab. Instead of replacing the weight of the cab with payload, the total weight could be decreased without losing as much payload as would be the case with standard forwarding. This could also potentially allow modification of the log bunk's design to improve the weight distribution between front and rear axles, thereby further reducing damage to the ground.

4.3.2 Social sustainability

In Sweden, attracting workers to operate forest machines has become a major issue in recent decades. The work is demanding, with shift work, long travel to and from the workplace, occasional overnight stays at the harvest site, and work in darkness and isolation. These demands have probably led to, or at least reinforced, gender and age inequalities. In the general gender pattern of work, males spend more time commuting to and from work while females do more household work and related travel (Solá, 2016). Similar gender patterns in commuting for work and household-related travel have been demonstrated more quantitatively by Fan (2017) in an American context. Historical factors could also contribute to these inequalities. For example, in previous times males exclusively did the hard manual harvesting during the winter, at least partly due to the need for physical strength. This no longer applies and males have no advantages for operating today's machines, but there are still historical traces in gender patterns, including the higher proportions of males than females in harvesting operations. Although the work itself does not favor men above women, aspects such as remote workplaces, long travel to and from work, and other elements of strong tradition probably hinder a shift to greater gender equality. Changes including shifts to long-distance tele-operation of forest machines might be radical enough to address this, possibly more profoundly than ever before. If the work becomes more office-like with less interaction with physical workplaces and better possibilities for convenient commuting, that might remove some of the gender bias and male-association from employment as a forest machine operator. Although gender equality has not traditionally been considered in the technical development of roundwood harvest systems, it is clearly included in both the UN's SDGs (target 5.4) and sector-specific literature, such as work by Marchi *et al.* (2018), although in the latter case implicitly in terms like 'social well-being' and 'people and society'.

Future work forces may, as stated above, be attracted by regular office hours and similar commuting patterns to those in most other occupations, leading to possibilities of a family life with equal opportunities not only for men and women, but also for young and old operators. Moreover, tele-operation could ease knowledge transfer from experienced to beginner operators as a routine part of everyday work, since operators would sit together.

Implementation of a tele-extraction system would potentially have several positive effects on the forest industry: higher efficiency, more comfortable and convenient working conditions for operators, and a better balance between available candidates and workforce requirements. However, the effects may not all be positive, as the detachment and diminishment of the forwarding workforce (important elements of the tele-extraction idea) also have some adverse implications. Perhaps most importantly, efforts to decrease the number of people needed to perform a certain task (extracting logs in this case) always raise the question of how the people who would otherwise have had a job will make a living. This is especially relevant in rural parts of Sweden, and probably other countries, where most of the forest harvesting naturally occurs. There are good grounds for seeing teleoperation and automation as threats to rural development, in a similar manner to effects of the mechanization of harvesting and dramatic associated reductions in needs for workers in Sweden during the second half of the 20th century. Shifts towards situating central operator offices in cities where it is easy to find workers, or even outsourcing to low-wage countries on the other side of the earth, has obvious drawbacks in human and societal terms. However, they might be essential to maintain the international competitiveness of the Swedish forest industry.

4.4 Discussion of research methodology

4.4.1 Studies I and II

Much of this thesis is based on simulation studies of forwarder work. Some of the main advantages of simulations are that they can easily incorporate random elements that cannot be predicted in a deterministic way, effects of waiting times and queues, and possibilities to study the behavior of a model during runtime. Runtime studies enable rapid familiarization with, and development of trust in, a model since the mechanisms responsible for the results become apparent. Since the core objective of the simulations was to identify effects of lack of operator capacity on productivity and costs, Discrete Event Simulation (DES) was deemed a suitable simulation method. DES is particularly appropriate for simulating waiting times arising from interactions between discrete work elements and access to resources needed to complete the work elements (Banks *et al.*, 2005). In Studies I and II, the work elements considered were those involved in forwarding, i.e. driving empty, loading, driving while loading, driving loaded, and unloading, and the resource was the operator pool. There seemed to be few, if any, options apart from DES for identifying system effects on aspects such as the work elements requiring teleoperation and optimal number of operators in an operator pool. To implement the DES model in Studies I and II, AnyLogic simulation software was used. Other software packages are available that have previously been used for forestry applications, and could probably have produced similar results. However, after completing the simulations, it can be concluded that AnyLogic not only enabled efficient simulations, but also provided great possibilities to adapt the reporting of results and output format due to its general Java language foundation and extensive scope for adding customized code in all parts of a simulation model. Finally, AnyLogic has advantages for development efforts outside the DES realm, as it provides possibilities to use other simulation methods, as well as hybrid modelling.

Inconsistencies in baseline simulations

There was a consistent difference in time consumption per load between simulations of standard forwarding and tele-extraction configured with 10 operators (Full Tele) for a set of 10 machines. Differences also occurred between Teledrive A, B, and Teleload, all while having 10 operators (see Figure 7). In theory, there should not be such differences since there are never waiting times due to lack of operator capacity when every machine have access to one full operator at all times. Nevertheless, a 1% increase in time consumption was present in the Full Tele case, regardless of other parameter inputs. To exclude the possibility that the difference was due to differences in model structure, i.e. the tele-extraction model seized and released operators even when there was one operator per machine, a highly simplified mini model was constructed with two identical sets of source-delay-sink structures. In this mini model, one of the paths incorporated seize and release functionality while the other was straightforward with no such functionality. Results of this test showed no difference in time consumption, so the model structure could be ruled out as source of error in that sense. Analyses of the mini model mentioned also showed that introduction of random elements affected the variance of the average time consumptions in a manner leading to variances from different probability density functions

(PDFs) being added to each other. However, that never affected the average time consumption per forwarder load, since each load was subject to the same number of PDFs in both models.

Another tested hypothesis regarding the difference in time consumption was that some bias may have been introduced by 'parallelization' linked to the tele-extraction model simulating operations of 10 forwarders instead of one (despite the total number of loads during a simulation being similar in the models). In more detail, the built-in global pseudo-random generator of the simulation software, consisting of a long but deterministic string of numbers with a 'random' or fixed starting point (seed), may not have been enough to truly randomize the parallel streams of forwarder loads. The 'random' starting point may, for example, be based on the current system time in the computer on which the simulations run, which theoretically could result in similar seeds for several parallel streams of forwarder loads (the only prerequisite being that the first load of each stream reaches its first PDF at the same time). To overcome this potential issue, custom randomization functions were set for most PDFs of each forwarder instead of using the global common function. Effects of both random seeds and seeds fixed at different levels were tested for these custom randomization functions. These measures did not have any effect on the difference in time consumption.

Finally, both models were run with no downtime (random) functions at all, and this resulted in much smaller differences in time consumption per load (0.05% rather than 1.2%), so this identified the major contributor to the difference. The reason for this is not obvious; each load seemed to be exposed to an equal amount of downtime risk during its lifetime in the model. However, there was clearly a difference between one downtime function engaged for a long time in the standard forwarding model, and 10 downtime functions engaged in parallel for a shorter time in the tele-extraction model. The conclusion is that the cost comparisons could probably have been made between different tele-extraction configurations with Full Tele as the benchmark resembling standard forwarding. That would have increased the potential gain in cost efficiency by around another percent unit compared to the gains presented in Papers I and II.

Running simulations with new data

Thanks to an unexpected opportunity, a new dataset of harvest areas from a forest company in central Sweden became available while this thesis was being written. After a brief cleaning of the data; deletion of areas with zero volume or extraction distance, and checking minimum and maximum values for relevant variables, around 5 000 harvest areas or 450 000 forwarder loads were adapted to the standard forwarding simulation model and run. The results validated the datasets as the resulting productivity and cost estimates were very similar, for example average productivity varied between 29 and 31 m3/SMH for the three original regions and the new dataset. A validation of this kind is not the same as, for example, a validation of a regression model, where one dataset is used to create the model and, in some cases at least, another is used to validate the consistency of the model's behavior over different datasets. The underlying regression models for predicting time consumption by the work elements included in the simulation models were already well established, validated and ready to use. Moreover, since there are so many forwarder loads per simulation, all time measurements stabilize during the simulations and the difference in productivity or cost between different simulations with the same input data is less than a percentage point. Therefore, use of a new dataset, with no extreme outliers, is not expected to change outputs of the simulations substantially.

4.4.2 Study III

Data gathering

In the data-gathering of study III (presented in the paper entitled "Worldwide trends in methods for harvesting and extracting industrial roundwood"), a very wide approach to forest harvests was adopted, with comparisons of harvest operations in countries in many parts of the world. The data on shares of volumes harvested by specific harvesting methods were estimates, based on information drawn from several sources: machine manufacturers' knowledge of the world market, research colleagues around the world, and literature. Since there was no single source of sufficient knowledge to obtain such data, some kind of triangulation (Thurmond, 2001) was needed. The challenges in gathering data probably account for the previous paucity of knowledge of geographic distributions of harvesting methods, and volumes harvested by them, and although the approach presented in Study III is far from perfect, it constitutes a step forward. The harvested volumes data were gathered solely from the FAO and data for explanatory variables used in the modelling were gathered from various international online databases. For the datasets of explanatory variables, only those including data for all studied countries could be used, although data on more variables were found for some of the countries. An alternative approach would have been to gather data on harvested volumes and explanatory variables individually per country, and in support of such an approach some of the levels of annual harvest differed from levels known by the authors. However, despite some discrepancies there are also major advantages in using data that have been subjected to at least some attempted normalization across countries by a subject-specific organization.

Definitions

In Study III, harvesting methods were categorized according to the divisions between CTL and FT/TL as well as between fully mechanized and not fully mechanized operations. This resulted in the three categories *fully mechanized CTL*, *fully mechanized FT/TL*, and *Others*. The categories were set in discussions with machine manufacturers to enable data gathering in relevant ways, and are not completely self-explanatory in relation to the classification scheme presented in the study (Figure 9). In the classification, the level of mechanization is only considered on the harvesting system level, not harvesting method or harvesting approach. Conceptually, a harvesting method can also be fully, partly, or non-mechanized, without specifying the harvesting system, which is in fact what was done in Study III. For completion, the classification scheme could have included the level of mechanization as a separate dimension, regardless of the harvesting approach, harvesting method, or harvesting system. In conclusion, despite its imperfections, Study III contributed to the literature on harvesting methods and systems (Sundberg, 1988; Gerasimov & Sokolov, 2014; Lindroos *et al.*, 2017; Robert *et al.*, 2017) by presenting a systematic, condensed classification scheme in a single figure.

Modelling

In the modelling in this study, effects of a number of variables that could potentially explain differences in harvesting method were investigated, including some for which records of their parameters in all the studied countries were available, some for which parameters were only available for certain countries, and some that were not easily quantified at all. One in the third category was some measure of average or maximum tree size. Tree size is believed to have a major impact on the kind of harvesting equipment that can be used, for purely physical reasons, but no robust way to quantify tree size in a homogeneous manner across countries was found during the study. Further studies should include assessment of the possibility to apply some kind of remote sensing data to address this issue, as was done for terrain slope. Effects of variations in the sawmilling equipment and/or their regulations regarding timber dimensions in different countries also warrant attention, as they could potentially lead to a tree size variable substantially affecting outputs of harvesting method models.

4.4.3 Study IV

The global analysis of slope of forest land essentially involved using existing datasets on forest cover (Hansen *et al.*, 2013) and elevation (Rizzoli *et al.*, 2017), and overlaying them to create a new dataset with new information. The ingoing datasets were both produced from radar images and widely used all over the world. The analysis would have been straightforward and quite fast if it were done for a single country, but handling global datasets introduces challenges associated with large file sizes, projections, and computational time. To overcome the challenges and complete the analysis, a programmatic approach to the workflow was both unavoidable and desirable. The GDAL library was chosen as the core instrument for analyses of the raster datasets as it reputedly has good functionality and high computational efficiency, it can be operated through various interfaces and is, for example, a substantial part of the QGIS program package (QGIS Development Team, 2019). For this study, R was used as the interface to call GDAL functions from the console in a PC, which was successful in terms of computational efficiency, avoiding resource-consuming visualizations and it enabled easy incorporation of other tools (such as certain raster calculation tools developed in R and customized loops) into the workflow. The bulk of the work could not have been done with a traditional interface although results from different steps in the analysis were visualized in QGIS for validation of the work method and visualization of the end-products. A downside of this approach was the relatively steep learning curve for handling the different tools in a programmatic setting, but no good alternative was available and the knowledge gained can be used in other, future projects.

As with many large-scale or global mapping efforts there was, of course, a trade-off between the scope and resolution of the results in this analysis. Trials with data of varying resolution for Sweden and Austria (a subset of countries representing both flat and steep land) helped to gain confidence in using the 90×90 m height data to calculate national-level shares of land within slope classes. The increased value of using finer-grained data did not exceed the extra effort in data handling and computation. However, the operational use for a dataset with 90×90 m resolution is very limited; each pixel covers almost a hectare and the average slope for that area does not provide much guidance for navigating in the terrain with a machine. However, the intended use of the results was not to assist operational path planning, but to characterize the large-scale differences between countries and regions in order to explain or predict other phenomena, such as the dominating harvesting method. Although there is also a need for more detailed digital renditions of the forest terrain to develop new technology, the wide use of a globally consistent and ratable dataset is evident in the diverse subjects of the articles citing this study so far.

4.5 Potential worldwide application of tele-extraction

Since more than a third of the harvested volume in the 31 main roundwood-producing countries is harvested with fully mechanized CTL technology (involving forwarders), and over 80% of the forest area in the world has less than 15° slopes, and is relatively easy for autonomous machines to navigate, there seems to be a global potential for the CTL tele-extraction system. To pinpoint a few countries that might be most likely to implement tele-extraction systems, a subset of the countries in Study III was extracted. Since tele-extraction, as simulated in the studies this thesis is based upon, concerns forwarding, clearly countries that already harvest high shares of total volumes with CTL technology are likeliest to adopt it. Thus, the criteria for inclusion in the subset were CTL shares above 50%, according to both recorded values and predictions by the regression model (Table 6). The subset consist of 10 countries, all European (Figure 16, Table 7).

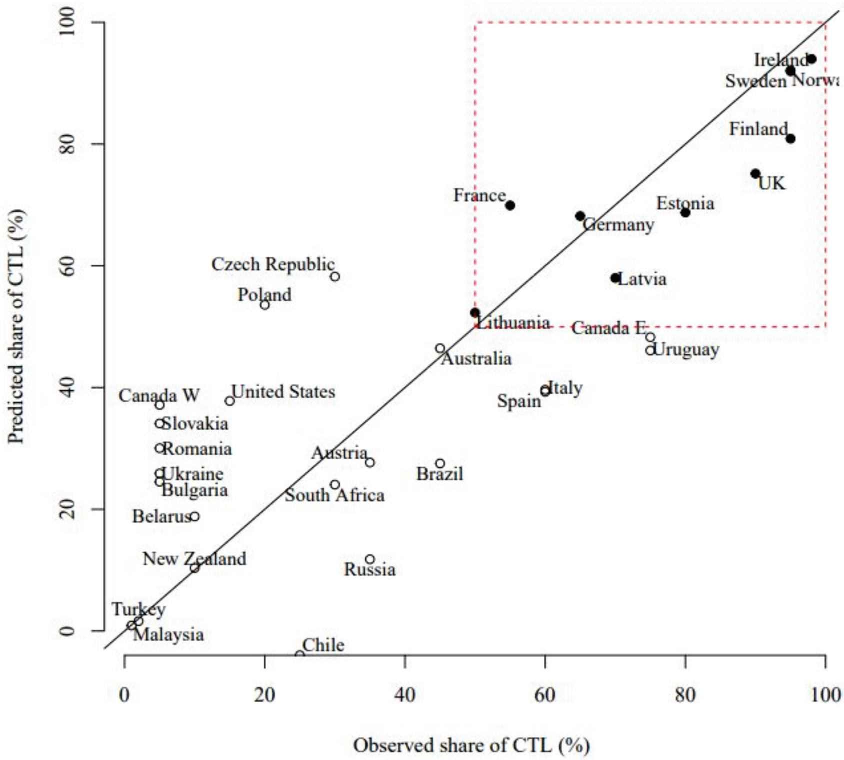

Figure 16. Shares of volume of industrial roundwood harvested by CTL in indicated countries, according to regression model 1, versus observed shares. The line through the origin has the slope of one. Countries in a subset with both observed and predicted shares of CTL of at least 50% are indicated with black dots and the red rectangle. Based on Figure 10.

Table 7. Annual harvested volumes and shares of the volumes harvested by fully mechanized CTL (cf. Table 5) in countries with both observed and predicted shares > 50%.

Country	Annual harvest (M m^3 solid under bark)	Share of fully mechanized CTL (%)	Harvested volume with CTL (M m^3 solid under bark)
Sweden	67.2	95	63.8
Finland	54.3	95	51.6
Norway	10.3	95	9.8
Germany	42.8	65	27.8
France	25.1	55	13.8
UK	8.7	90	7.8
Ireland	2.7	98	2.6
Estonia	6.6	80	5.3
Latvia	11.4	70	8.0
Lithuania	4.7	50	2.4
Totals*	234	83	193

* Totals of the volume columns are sums of the volumes for the individual countries, and for the third column (share of CTL), the total is the countries' volume-weighted average.

The 10 countries together have an annual harvest of 234 Million m^3, accounting for about a tenth of the global annual harvest. When the shares of volumes harvested by CTL in each country are considered, the total volume is 193 M m^3 (Table 7). By a rough estimation, perhaps half of that 193 M m^3 (about 95 M m^3) might be suitable for tele-extraction. If eastern Canada, which very nearly met the criteria (Figure 16), is also included this value increases to 138 M m^3. This is more than the combined present annual harvest in Sweden and Finland and about 7% of the annual global harvest of industrial roundwood. How realistic this estimate is, and the timeframe that it might become reality, are difficult to tell.

4.5.1 Tele-extraction in other harvesting methods than CTL

Although CTL harvesting is common in many countries and on the rise with mechanization in even more, it is relevant to discuss the potential of tele-extraction, or similar approaches, within other harvesting methods than CTL. The use of skidders is very common around the world in various harvest operations, not least in so-called 'hot' systems including several cooperating machines. There might be even more potential for increasing cost efficiency in such a system than in CTL forwarding, if skidders could be teleoperated from an operator pool and partly autonomous. Based on common knowledge of occasionally increased waiting times in hot machine systems, it would be advantageous if idle skidders did not have to carry the operator cost and the operator could work with other machines. In a wider perspective, common operator pools for several types of machines, working according to current need within a certain geographic area, would be able to be kept busy in case of breakdowns or other events that shut down a whole fleet of 5–10 machines and the same number of operators in normal conditions.

4.6 Development implications

The main message from this thesis is that a system like tele-extraction offers potential cost reductions. The level of cost reductions depends on how the system is configured, and characteristics of the targeted harvesting plots, with extraction distance as an important factor. Many assumptions are made in this thesis about technical development of support systems for operators and machines, which (of course) must be realized before a tele-extraction system can be implemented. However, the development and implementation of such support systems is also beneficial in today's forwarding work, making it easier to offset investments along the way to tele-extraction and ultimately full automation. Another important aspect is that the simulations presented in this thesis were tailored to a Swedish context, but (as discussed above) it seems likely that tele-extraction would also be beneficial in various other countries around the world.

4.6.1 Cost-efficient ranges of site and organizational conditions

When manufacturers or forest companies are considering a new phase of technology development, the ranges of conditions in which they can provide at least a minimum level of cost savings warrant attention. These ranges may be influenced by both site-related factors (e.g., extraction distance) and organizational factors (e.g., number of operators per machine). In the examples presented below (from Figure 17) a minimum level of 5% cost savings is assumed.

Regarding extraction distances, the Teledrive A configuration could meet the minimum cost savings goal with distances under 500 m while for Teledrive B the envelope could potentially be extended to distances under 1000 m. In contrast, the Teleload configuration required distances over 350 m. Within the noted ranges for extraction distances the 5% cost reduction goal generally allowed a *maximum* of 0.8 operators/machine, but the *minimum* number of operators per machine varied. These minimum and maximum thresholds are relevant when considering staffing requirements for teleoperation centers.

For Teledrive A, the envelope of cost savings when working with a 500 m extraction distance extended down to 0.5 operators per machine, while the corresponding envelope with a 200 m extraction distance extended down to 0.3 operators per machine. For Teledrive B, the envelope of cost savings when working with a 1000 m extraction distance extended down to 0.5 operators per machine. The corresponding envelopes for 500 and < 200 m extended to 0.3 and 0.2 operators per machine, respectively. For the Teleload configuration, the envelope of cost savings at the minimum distance of 350 m was relatively narrow; ranging from 0.8 to 0.6 operators per machine. At 500 m, the envelope extended down to 0.5 operators per machine and at 1000 m the envelope extended to 0.25 operators per machine.

As noted above, maximum staffing for meeting a 5 % cost-savings goal within the relevant range of site conditions was stable at 0.8 operators per forwarder. As operations reach towards higher levels of cost savings, the lower limits for minimum staffing ranged from 2 to 5 operators per machine (Figure 17).

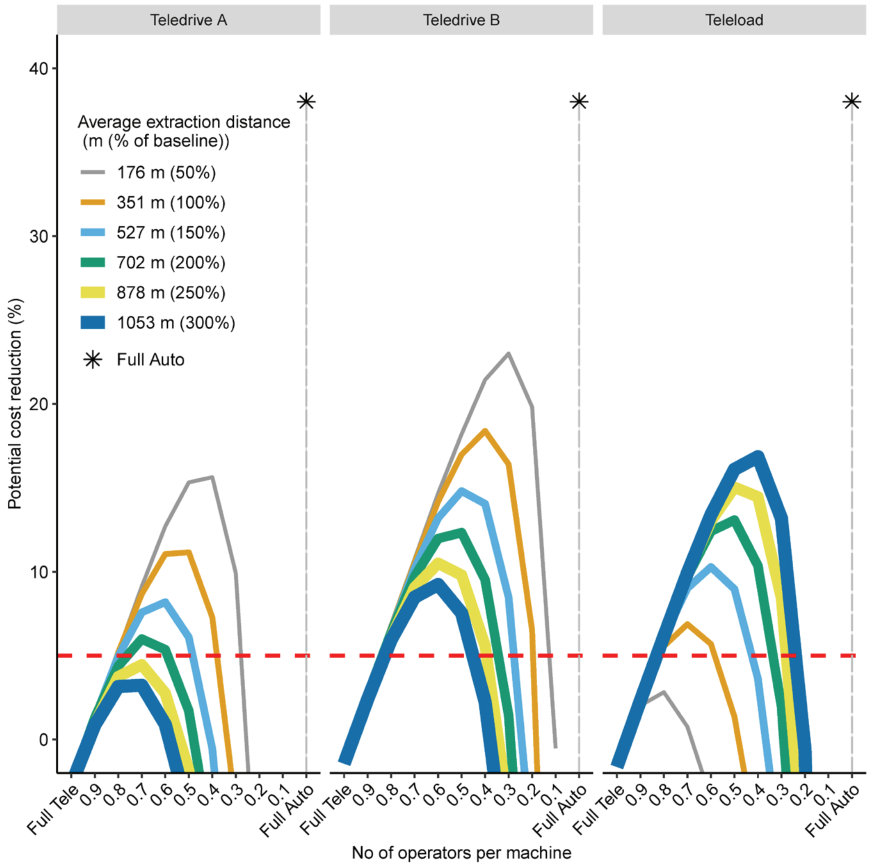

Figure 17. Simulated potential cost reductions for tele-extraction compared to standard forwarding in the north region, with varying numbers of teleoperators per machine (x-axis), relatively adjusted extraction distances, and indicated configurations (Teledrive A, Teledrive B, Teleload, and Full Auto as black dots indicating the upper reference point). The red horizontal line indicates the level where 5% cost reduction is achieved.

4.7 Conclusion

The overall conclusion of this thesis is that there is potential to increase cost efficiency by between 6 and 19% in Swedish CTL forwarding if tele-extraction is applied. The size of the potential savings depends on the configuration of the tele-extraction system; automation of the most time-consuming work elements, such as loading, has the highest potential since it can cut most operator time. Furthermore, there is potential for implementation of tele-extraction in at least 10 countries with a high share of mechanized CTL harvesting (potential volume: roughly 100 000 to 150 000 m^3 sub).

4.8 Future research and ways forward

The results presented in this thesis may facilitate development of future harvesting equipment in two ways. First, results of the simulations provide a roadmap of productivity and costs for different configurations of the tele-extraction concept, providing a gauge of the cost savings that potential developmental trajectories could provide. Second, the developed models, including the structure for reporting results etc., form a testbed for addressing future research questions. One identified need is to tweak the simulations of Swedish operations by adding more detail as more knowledge is acquired, for example regarding differences in time consumption for a work element depending on whether it is performed by a standard operator, teleoperated, or run autonomously. Other important steps to accelerate development are to apply costs, productivity functions, and stand data from other countries and simulate the tele-extraction concept in those contexts. An interesting type of case is a large-scale pulp wood plantation, where a fleet of machines already works in close proximity to each other, enabling use of on-site maintenance equipment and personnel and perhaps short-distance teleoperation with the operator pool situated at the landing. Implementation would be more straightforward and feasible sooner in such a case than in most others with more demanding obstacles and greater technical challenges, frequently including (for example) long-distance teleoperation in remote areas.

The worldwide analyses conducted in the studies underlying this thesis would also benefit from expansion and improvement in the future to guide efforts of manufacturers and developers. Mapping of shares of volumes harvested by different methods and systems could potentially become a routine task, perhaps on regional level, to establish up-to-date knowledge of levels of mechanization and harvesting methods used, thus providing robust foundations for further efforts. More analyses similar to the terrain slope analysis in Study IV might contribute to future digitalization of harvest operations, for example, some measure of tree size that could be derived from global coverage satellite data would add much useful information for predictions of technical development. Future digitalization is also likely to focus on separate countries, using available LIDAR data to classify terrain roughness and forests in ways that set foundations for automation of machines. There is no reason to delay this since the results can be directly implemented in the form of operator support systems while waiting for the day of full automation.

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Popular science summary

In Sweden, as good as all industrial roundwood is brought from the stump to the nearest forest road with help of forwarders, purpose built and highly productive machines. Forwarders are also used for about one third of the global annual harvest (about 700 000 000 m^3). The forwarders have of course been improved in many ways since their introduction, but their conceptual function have basically stayed the same and further improvement in productivity and cost efficiency is not easy. Looking at other industry sectors that, alike the forest industry, are on constant hunt for cost reductions, application of fully or partly automated systems is state-of-the-art. For example, extraction of ore from underground mines have undergone a shift to teleoperation and automation during the last decades, leading to improved productivity, increased personnel safety, and increased cost efficiency. As data transfer-technology (5g) becomes better and the development of sensor equipment and software for computer-vision rushes, it is becoming realistic with teleoperation and automation also in forestry applications.

Focusing on forwarding, that have many similarities with loading-hauling-dumping within mining, this thesis have examined theoretical potential of increased cost efficiency in a new concept for forwarding, called tele-extraction, were the forwarders are either working autonomously or being controlled remotely by a pool of operators. In this way, fewer operators are needed to operate the same number of machines, how many fewer depending on which work elements are automated and which are tele-operated, leading to fewer wages to pay. The thesis does not consider whether or not all necessary technology exist, the effect of centralising and diminishing operator crews on rural development, or the cognitive implications of operating many different forwarders remotely, but is a strategic foresight of what would be the economic effect if implementing a tele-extraction system,

assuming it is possible to do. The overall result showed that there is potential for increased cost efficiency of between 6% and 19% if tele-extraction is applied. The size of the potential savings was dependent on the configuration of the tele-extraction system, automation of more time consuming work elements, such as loading, gave larger potential since more operator time was deliberated. Furthermore, there is potential for implementation of tele-extraction in at least ten countries with a high share of roundwood volumes handled by forwarders, the potential volume is roughly between 100 000 000 and 150 000 000 m^3 solid under bark.

Populärvetenskaplig sammanfattning

I Sverige körs så gott som allt industriellt avverkat virke från stubben till närmaste skogsbilväg med hjälp av skotare, högproduktiva maskiner specialbyggda för ändamålet. Skotare används också för cirka en tredjedel av den globala årliga avverkningen (ca 700 000 000 m^3). Skotarna har naturligtvis förbättrats på många sätt sedan de introducerades, men deras konceptuella design och funktion har i princip förblivit densamma och ytterligare förbättringar av produktivitet och kostnadseffektivitet är inte lätta att uppnå. Om man tittar på andra industrisektorer som liksom skogsindustrin är på ständig jakt efter minskade kostnader, så är användningen av helt eller delvis automatiserade system redan på plats. Till exempel har utvinning av malm från underjordiska gruvor genomgått en snabb och tydlig övergång till fjärrstyrning och automation de senaste decennierna, vilket har lett till förbättrad produktivitet, ökad personalsäkerhet och ökad kostnadseffektivitet. I takt med att dataöverföringsteknik som 5g byggs ut och utvecklingen av sensorutrustning och mjukvara för ”seende maskiner” rusar, blir det realistiskt med fjärrstyrning och automation även i skogsbruket.

Med fokus på skotning, som har många likheter med lastning-körning-dumpning inom gruvdrift, har denna avhandling undersökt teoretisk potential för ökad kostnadseffektivitet i ett nytt koncept för skotning, kallat tele-skotning, där skotarna antingen arbetar autonomt eller fjärrstyrs av en pool av operatörer. På så sätt behövs färre operatörer för att köra lika många maskiner, hur många färre beroende på vilka arbetsmoment som är automatiserade och vilka som är fjärrstyrda, vilket leder till färre löner att betala. Avhandlingen tar inte hänsyn till huruvida all nödvändig teknologi redan finns eller inte, effekten på landsbygdsutvecklingen av att centralisera och minska operatörskollektivet eller de kognitiva implikationerna av att köra många olika skotare på distans, utan är en strategisk framtidsbild av den ekonomiska effekten av implementering av ett tele-skotningssystem, förutsatt att det är möjligt att göra. Det övergripande resultatet visade att det finns potential för minskade kostnader på mellan 6% och 19% om tele-skotning tillämpas. Storleken på kostnadsminskningarna var beroende av hur teleskotningssystemet konfigureras, automatisering av mer tidskrävande arbetsmoment, såsom lastning, gav större potential eftersom mer operatörstid frigjordes. Dessutom finns det potential för implementering av tele-skotning i minst tio länder med en hög andel rundvirke som hanteras av skotare, den potentiella volymen är ungefär mellan 100 000 000 och 150 000 000 m^3 fast under bark.

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III

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Worldwide trends in methods for harvesting and extracting industrial roundwood

Mikael Lundbäck, Carola Häggström, and Tomas Nordfjell

Department of Forest Biomaterials and Technology, Swedish University of Agricultural Sciences, Umeå, Sweden

ABSTRACT

Globally, almost 2 billion cubic meters of industrial roundwood are harvested yearly. Two of the most common methods of harvest and extraction are cut-to-length (CTL) and full-tree or tree-length (FT/TL). The aim of this study was to compile data on annual volumes of industrial roundwood harvested by the main methods in forestry countries. To quantify the effect of potential explanatory variables, the data were subjected to linear regression analysis, using shares of roundwood volumes harvested by fully mechanized CTL and/or FT/TL as response variables. Generally, high diesel price and Gross Domestic Product appear to favor CTL, while high shares of steep terrain (>20°) in forest land decrease the leve l of both mechanization and CTL, and low Social Security Rate (SSR) favor FT/TL. Two models were created for CTL, one with an R^2 of 0.64 and another more complex with an R^2 of 0.75. A separate model for mechanization (CTL and FT/TL together) showed an R^2 0.57. The CTL models could potentially be used to predict shares of roundwood volumes harvested by CTL in countries not included in this study. Predictions for countries with large harvested volumes, e.g. China and India, are presented here, but they require validation, as does the model's applicability for countries with small harvested volumes. Countries with less than 10% of steep slope forests are almost exclusively mechanized according to the model. For FT/TL, the proposed model is probably not sufficiently robust for prediction, but it highlights SSR as one important explanatory variable.

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Introduction

Globally, 1.9 billion solid cubic meters under bark (m^3) of industrial roundwood is harvested annually (FAO 2016), and 1 billion m^3 is harvested in the five largest producers: the USA, Russia, China, Canada, and Brazil. Another 250 million m^3 is produced by Sweden, Indonesia, Finland, and India, while about 200 countries account for the rest, each producing less than 50 million m^3 per year (FAO 2016). The wood is harvested and extracted in various ways (c.f. Heinimann 2004; Heinrich and Arzberger 2004; Arets et al. 2011; Hiesl 2013; Moskalik et al. 2017), but no analysis of the global variations in harvesting methods has been previously presented and there is no clear consensus even regarding some of the key terms. However, it is known that diverse ecological, legal, social, and economic factors form frameworks for commercial activities such as harvesting roundwood that affect choices of harvesting methods and systems (Nordfjell et al. 2004; Ghaffariyan 2014). For example, Nordfjell et al. (2004) suggest the following six important factors: "1) terrain conditions, 2) tree sizes, 3) silvicultural strategy, 4) density in the remaining stand, 5) labor cost and 6) object volume (the total harvested volume in a stand)". Although factors such as *density in the remaining stand* and *object volume* indicate that choices may be stand-specific, they can also be treated as averages for regions or countries.

Definitions

The terms "harvesting method" and "harvesting system" are commonly used in the forest operations literature, but definitions and conceptions of the terms vary. For example, Sundberg (1988) and Robert et al. (2017) use the terms interchangeably. In contrast, Gerasimov and Sokolov (2014) and Lindroos et al. (2017) clearly distinguish between *harvesting methods*, defined according to the state of harvested material at roadsides, and *harvesting systems*, defined according to the combinations of machinery, workforce, and tools used. However, in contexts where stands on steep terrain are frequently harvested, there is also a need to distinguish ground-based harvesting from cable-based and air-based harvesting (cf. Visser et al. 2014). Furthermore, the level of mechanization adds another dimension that may affect the terms used. Therefore, there is a need for a globally applicable framework to systematically classify and exemplify the key terms. Use of the framework presented in Figure 1 is proposed here.

In the proposed framework, all kinds of harvesting are first classed in terms of the "*harvesting approach*," depending on whether the operations are all ground-based or some of the operations involve use of cables or aerial systems (designated "ground-based," "cable-based," and "air-based," respectively). They are then further classified in term of *harvesting method*, depending on the state of harvested wood at landings, for example salable logs and full stems in the cut-to-length and full tree (tree-length) methods, respectively. Finally, the concept *harvesting system* refers to the specific combination of machinery, workforce and tools used, i.e. what Lindroos et al. (2017) and others also refer to as the harvesting system. The comprehensiveness of the examples in Figure 1 is high at the top of the figure and low at the bottom, i.e. there are many

CONTACT Mikael Lundbäck mikael.lundback@slu.se Department of Forest Biomaterials and Technology, Swedish University of Agricultural Sciences, Umeå, Sweden.

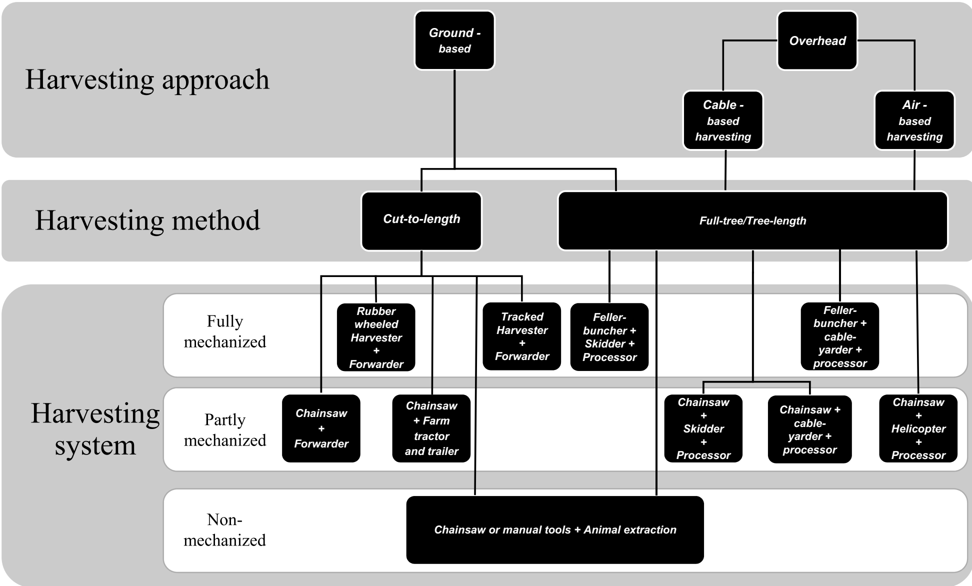

Figure 1. Framework including examples of the most common harvesting operations classified according to the concepts "Harvesting approach," "Harvesting method," and "Harvesting system." The examples of harvesting systems are biased toward the most mechanized harvesting systems; a wide range of partly mechanized harvesting systems are not included here.

more harvesting systems than those included in the figure, a few more harvesting methods, and perhaps only one more imaginable harvesting approach (water-based).

The choice of harvesting method

Theoretically, the variation in harvesting trees among countries could be considered in terms of any of the three concepts in the proposed framework (Figure 1). However, in many countries only ground-based harvesting approaches are used, so global comparison of harvesting approaches would not be very informative, and harvesting systems are too diverse for international-level generalizations (if a single machine or tool is changed the harvesting system also changes, by definition). Thus, the harvesting method is the most convenient and potentially informative conceptual level for comparison.

Regarding factors that influence the choice of harvesting method listed by Nordfjell et al. (2004), acquiring or analytically applying national-level information on tree sizes, silvicultural strategies, density in remaining stands, and object volumes (total harvested volumes in stands) may be difficult. However, two terrain-related factors that most clearly affect the harvesting of roundwood generally on the national level are the shares of steep terrain and soil with low bearing capacity in the total forest land area. For the harvesting method specifically, the share of steep terrain is probably most important, and this variable can be assessed relatively conveniently (Lundbäck et al. 2020a). The financial factor labor cost can also be assessed at a national level, and high labor costs would generally be expected to favor harvesting methods often performed by harvesting systems with low labor intensiveness, such as mechanized CTL (Asikainen et al. 2011). Although labor costs play an important role in choices of harvesting methods according to Nordfjell et al. (2004), there are also other harvesting costs, regardless of whether forest owners themselves, small contractors or large forest companies do the harvesting. One is the cost of diesel, as nearly all harvesting operations around the world involve use of diesel engines, and there is a clear difference in diesel consumption between most full tree harvesting methods and most CTL harvesting methods. This is because CTL harvesting generally involves use of fewer and smaller machines, resulting in around 40% less diesel consumption per unit harvested roundwood (Zhang et al. 2016). Effects of these, as well as several other economic variables, and countries' amounts of forestland, relative to their total areas, were tested in this study.

Aims of the study

The aims of this study were to compile data on annual volumes of industrial roundwood harvested by the main harvesting methods in the major roundwood-producing countries, and assess the effects of possible explanatory variables on level of mechanization and choices of methods. Since the focus was on harvesting roundwood for industrial use, methods for harvesting and extracting material from forests for use as firewood or other applications throughout the world were not mapped or analyzed.

Materials and Methods

This section first describes the collection of data on industrial roundwood volumes harvested by each of the harvesting methods considered and then the methods used to analyze effects of potential explanatory variables on the volumes.

Collection of data on harvested roundwood volumes

All countries that produced at least 5 million m^3 of industrial roundwood per year for which data on volumes harvested by the considered methods could be obtained were included in the study. It was not possible to obtain estimates of volumes harvested by these methods for a number of countries with an annual harvest over 5 million m^3, most importantly China and India (Table 1), so they were excluded from the modeling. However, some countries that produced less than this threshold were also included because they are well suited for the intended analyses of harvesting methods in terms of available data and frequency of inclusion in studies of forestry operations. The included countries are listed in Table 4.

We estimated each of the countries' volumes of roundwood harvested annually by the following three pre-defined categories of methods, reflecting the main differences between cut-to-length and full-tree/tree-length operations, as well as the level of mechanization:

Fully mechanized CTL – Ground-based cut-to-length operations in which all steps are mechanized, known in Canada as ”CTL at stump”.

Fully mechanized FT/TL – Ground-based full-tree or tree-length operations in which all steps are mechanized, defined by bucking no earlier than at landings.

Other – All other operations, such as cable- or air-based harvesting approaches, partly mechanized harvesting systems and harvesting systems with simple equipment.

Four sources of material were used to obtain the harvested volumes and their distributions in the three categories. First, official global statistics on harvested volumes from the Food and Agriculture Organization (FAO) of the United Nations. Second, peer-reviewed papers and reports from research institutes and universities. Third, manufacturers' estimates of the distributions. Fourth, corresponding estimates by forestry experts.

Official statistics of annual roundwood production were obtained from the *FAO Yearbook of Forest Products 2016 (FAO 2016)*.

Literature was systematically searched to find published material concerning harvesting methods in the studied countries. The same relevant keywords were applied in Web of Science and Google Scholar searches for all studied countries. In addition to articles found through this search, some articles found in their reference lists and search engines' recommendations, such as “related articles,” were included in the review. All included literature is listed in the supplementary material.

Estimates of total demand for various types of forest machines and volumes harvested by associated categories of methods in the countries included were mainly provided by Komatsu Forest in Umeå, Sweden. As the head office for a worldwide organization of forest machine retailers, they have access to information that enables them to present highly educated estimates on this matter. To improve and validate the estimated distributions of harvesting methods further, researchers engaged in forest operations research in various parts of the world helped to fill blanks and refine some of the estimates. Substantial contributions have been made by experts and researchers from Australia, New Zealand, and Canada. In addition, researchers from the USA, Scandinavian countries, South Africa, and Eastern European countries have helped efforts to validate the estimates. The most significant contributors are listed in the supplementary material.

To create data for Table 4, the different sources of information have been weighted together in a way that give the most certain figures for a specific country a higher weight than other weaker figures. When the different sources of information were weighted together, more emphasis is put on more recent literature and experts with country-specific knowledge.

Explanatory variables for mechanization and choices of harvesting methods

The shares of fully mechanized CTL and fully mechanized FT/TL as well as the combination of the two were chosen as response variables for ordinary least squares (OLS) linear regression analyses. For this, open source statistical software R (versions 3.5.1 and 4.0.2) was used.

Potential explanatory variables were chosen (Table 2) for which cause-effect relationships could be theoretically explained and/or relevant data were available for all the studied

Table 1. Countries with annual harvests over 5 million m^3 (FAO 2016), but lacking estimates of volumes harvested by thecategories of harvesting methods considered in the study.

Country	Annual harvest of industrial roundwood (M m^3 under bark)
China	164.4
Indonesia	74.0
India	49.5
Japan	21.3
Thailand	14.6
Argentina	11.8
Portugal	11.0
Nigeria	10.0
Vietnam	6.7
Myanmar	6.0
Mexico	5.4

Table 2. Variables tested in the regression analysis.

Variable	Source	Description
Diesel price (US$/L)	https://www.globalpetrolprices.com/diesel_prices/	Accessed 1 November 2018
Fossil energy consumption (%)	ourworldindata.org	Share of a country's energy consumption from fossil fuel
Human Development Index (HDI) (index between 0 and 1)	ourworldindata.org	A combined index of life expectancy, level of education and Gross Domestic Product
GDP (US$/capita)	ourworldindata.org	Gross Domestic Product for each country
Gross value from forestry (1000 US$)	(FAO 2015)	Gross value from forestry for each country
Publicly owned land (%)	(FAO 2015)	Share of the forest land that is publicly owned
Slope (%)	(Lundbäck et al. 2020a) and the online database: (Lundbäck et al. 2020b)	Shares of forest land in selected slope classes. Lundbäck et al. (2020a) used four: < 15°, 15°-20°, 20°-30° and >30°. Here, the classes were also combined to form new classes, so in total seven slope variables were tested.
Forest land/Total land (%)	(FAO 2015)	Forest land as a share of total land area
Interest rate (%)	https://tradingeconomics.com/country-list/interest-rate	The steering interest rate in January 2019 set by respective central banks
Social security rate (SSR) (%)	https://tradingeconomics.com/country-list/social-security-rate	Total Social Security Rate per country
PPP index (number of LCU units)	https://data.worldbank.org/indicator/PA.NUS.PPP	Global index of the number of units of local currency (LCU) corresponding to the same amount of goods or services as 1 US$ in the USA in 2011

countries. Data for all variables included in the models were collected from different sources and compiled to enable further analyses (Table 3).

To refine each model, correlation matrices between new candidate variables and residuals of the existing model were generated to see how much (if at all) they improved the model. A high correlation between residuals of the existing model and a potential new variable was used as an indicator for its inclusion, as residuals of a model represent the unexplained part of the variation. Residual plots were examined to check that residuals met requirements of approximation to a normal distribution, homoscedasticity, etc., for the regression analysis.

The final models are trade-offs between high R^2 values at a 5% significance level, low numbers of variables, interpretability and relevance to the aims of the study. Fivefold cross-validation with three repetitions was applied at the end of the process to validate the models as good as possible with available data. This is an internal validation approach that is suitable when there are relatively few observations since it does not rely on splitting the gathered data into training and control sets before the start of the analysis. Instead, the dataset is split into five subsets (hence fivefold) after the regression model has been constructed, which are subsequently used as control datasets. This whole process is then repeated, in this case three times. The results are displayed, in terms of root mean square error of cross–validation (RMSECV) values, in Tables 5–8.

The CTL models were applied to the countries in Table 1 after completion of their construction. This application was not validated since there are no true observations for comparison of the predictions, but rather an application of the models that requires evaluation in future research.

Results

The total annual harvested volume of industrial roundwood in the countries included in this study amounted to 1.38 billion m^3, 74% of the total global harvest, in 2016. The results indicate that over two thirds of this volume was harvested by fully mechanized methods (Table 4).

Factors affecting the level of mechanization

A model was constructed with the level of mechanization (expressed as fully mechanized CTL and fully mechanized FT/TL combined) as response variable. R^2 = 0.57 (Table 5). High GDP per capita is associated with a high level of mechanization while a high share of steep terrain (slope >20°), and publicly owned forest land is associated with a low level of mechanization (Table 5, Equation 1, and Figure 2).

$$\begin{aligned} &\mathit{Level\ of\ mechanization}(\%) = 64.7493503 + 0.0010198* \\ &\mathit{GDP\ per\ capita}(\mathit{US\$}) - 0.9135723 * \mathit{Slope} > 20^{\circ} \\ &\mathit{in\ forest\ land}(\%) - 0.4186511 * \mathit{Share\ of\ forest\ land} \\ &\mathit{puplicly\ owned}\ (\%) \end{aligned} \tag{1}$$

Factors affecting use of the CTL harvesting method

Two models were constructed with fully mechanized CTL (CTL hereafter) as the response variable. The first model is simpler, with R^2 0.64 (Equation 2) while the other is slightly more complex due to inclusion of an interaction variable, R^2 0.75 (Equation 3). According to Model 1, high diesel price and high Gross Domestic Product (GDP) are associated with a high share of CTL, while a large share of steep terrain (slope, >20°) is associated with a low share of CTL (Table 6 and Equation 2, and Figure 3). Table 6

$$\begin{aligned} &\text{Share of fully mechanized CTL}(\%) = -27.37 + 49.76* \\ &\text{Diesel price}(\text{US\$/Litre}) - 0.9282*\text{Slope } 20^{\circ}\text{ in forest land}(\%) \\ &+0.0006317 * \text{GDP per capita}(\text{US\$}) \end{aligned} \tag{2}$$

$$\begin{aligned} &\text{Share of fully mechanized CTL}(\%) = -64.8047 + 59.0055* \\ &\text{Diesel price}(\text{US\$/Litre}) + 0.7721*\text{Slope} < 15^{\circ}\text{ in forest land}(\%) \\ &- 0.407*\text{Dieselprice}(\text{US\$/Litre})*\text{Share of forest land} \\ &\text{publically owned}(\%) \end{aligned} \tag{3}$$

Table 3. Variable data used in the models.

Country	Diesel price ($/L)[a]	GDP/capita (1000 $)[b]	Share of forest land with slope >20° (%)[c]	Share of forest land with slope <15° (%)[c]	Share of forest land publicly owned (%)[d]	Diesel price × Share of forest land publicly owned[e]	Social Security Rate, SSR (%)[f]
Australia	1.14	45	6	90	73	83.2	11.5
Austria	1.51	45	53	35	19	28.7	39.6
Belarus	0.69	19	0	100	100	69.0	35.0
Brazil	0.97	13	2	95	62	60.1	39.8
Bulgaria	1.32	18	32	50	88	116.2	32.4
Eastern Canada	1.01	43	3	94	91	91.9	13.8
Western Canada	1.01	43	26	67	91	91.9	13.8
Chile	0.96	21	50	39	25	24.0	24.6
Czech Republic	1.48	31	8	82	77	114.0	45.0
Estonia	1.60	26	0	100	41	65.6	35.4
Finland	1.70	38	1	98	30	51.0	32.5
France	1.79	39	16	77	25	44.8	59.2
Germany	1.52	47	10	82	52	79.0	40.2
Italy	1.77	35	49	37	34	60.2	39.4
Ireland	1.82	56	4	93	53	96.5	14.8
Latvia	1.42	23	0	100	52	73.8	35.1
Lithuania	1.27	26	0	100	61	77.5	41.9
Malaysia	0.52	23	15	70	95	49.4	20.0
New Zealand	1.16	34	44	41	60	69.6	11.0
Norway	1.98	76	39	50	12	23.8	22.3
Poland	1.37	26	4	93	82	112.3	36.1
Romania	1.48	19	34	48	67	99.2	37.3
Russia	0.67	23	10	84	99	66.3	30.0
Slovakia	1.49	27	33	49	50	74.5	48.6
South Africa	1.19	12	31	59	60	71.4	2.0
Spain	1.48	32	35	51	29	42.9	36.3
Sweden	1.88	44	2	95	25	47.0	38.4
Turkey	1.08	19	51	33	100	108.0	37.5
United Kingdom	1.77	39	8	86	28	49.6	25.8
Ukraine	1.12	10	10	85	100	112.0	22.0
United States	0.87	53	13	80	42	36.5	15.3
Uruguay	1.23	20	0	99	1	1.2	35.8

[a]https://www.globalpetrolprices.com/diesel_prices/(Accessed November 2018).
[b]https://ourworldindata.org (Accessed January 2019).
[c](Lundbäck et al. 2020a).
[d](FAO 2015).
[e](FAO 2015) The interaction between diesel price and share of forest land publicly owned has no unit, and it is not interpretable as numbers as such but rather describes the behavior of Model 2.
[f]https://tradingeconomics.com/country-list/social-security-rate (Accessed January 2019).

According to Model 2, high diesel price and high share of forest land with slopes <20° are associated with a high share of CTL. The model shows that the third variable "Share of forest land that is publicly owned" also helps to explain the share of CTL, but its effect depends on the diesel price. At a given diesel price, an increase in publicly owned land has a negative effect on the share of CTL (Table 7 and Equation 3, and Figure 4).

Factors affecting use of the FT/TL harvesting method

The data acquired in this study cannot explain variations in the share of fully mechanized FT/TL as good as variations in the share of CTL with the applied modeling technique. The best linear function found only included the variable Social Security Rate (SSR), a low SSR indicating a high share of FT/TL. The R^2 value of this model is 0.36 (Table 8, Equation 4, and Figure 5).

$$\text{Share of fully mechanized FT/TL}(\%) = 48.0224 - 1.0805 * \text{SSR}(\%) \tag{4}$$

Model visualization

The relations between the level of mechanization and three explanatory variables included in the model are visualized in Figure 2. The share of forest land with slope >20° is put on the x-axis and show a clear effect of slope on the level of mechanization. Also, a change between the extreme values of the variables GDP/capita and share of forest land publicly owned show a big difference in the level of mechanization (Figure 2). Countries with less than 10% of steep slope forests (>20°) are almost exclusively mechanized according to the model (Figure 2)

The relationship between the share of CTL and three explanatory variables included in Model 1 are visualized in Figure 3.

Table 4. Annual volumes of industrial roundwood harvested[a] in included countries and the shares harvested by the categories of methods described in this paper.

Country	Annual harvest (M m^3 solid under bark)[a]	Fully mechanized CTL (%)[b]	Fully mechanized FT/TL (%)[c]	Other (%)[d]
Austria	12.2	35	<1	65
Belarus	11.3	10	10	80
Bulgaria	3.5	<5	<5	95
Czech Republic	14.1	30	10	60
Estonia	6.6	80	5	15
Finland	54.3	95	<1	<5
France	25.1	55	10	35
Germany	42.8	65	10	25
Ireland	2.7	98	0	2
Italy	2.1	60	<1	40
Latvia	11.4	70	5	25
Lithuania	4.7	50	5	45
Norway	10.3	95	<1	<5
Poland	36.8	20	10	70
Romania	11.0	5	5	90
Slovakia	8.8	<5	<5	95
Spain	13.3	60	<1	40
Sweden	67.2	95	<1	<5
Turkey	20.4	2	6	92
UK	8.7	90	0	10
Ukraine	8.2	<5	<5	95
Europe	*375.5*	*59*	*5*	*36*
Eastern Canada	57.9	75	20	5
Western Canada	99.9	5	80	15
USA	356.6	15	70	15
North America	*514.4*	*20*	*66*	*14*
Brazil	145.1	45	25	30
Chile	44.6	25	25	50
Uruguay	11.3	75	<1	25
South America	*201.0*	*42*	*24*	*34*
Russia	198.2	35	10	55
Malaysia	13.9	<1	<1	>95
Australia	30.1	45	50	5
New Zealand	28.7	10	55	35
South Africa	14.4	30	60	10
Weighted totals[e]	1,376	37%	33%	30%

[a]Based on data compiled in the *FAO Yearbook of Forest Products 2016* (FAO 2016).
[b]Fully mechanized CTL – Ground-based cut-to-length operations in which all steps are mechanized, called "CTL at stump" in Canada (see Figure 1).
[c]Fully mechanized FT/TL – Ground-based full-tree or tree-length operations in which all steps are mechanized, and stems are bucked no earlier than at landings (see Figure 1).
[d]Other – All other types of operations, such as cable- or air-based harvesting approaches, partly mechanized harvesting systems and harvesting systems with simple equipment (see Figure 1).
[e]The average shares for all countries were weighted with harvested volume.

Table 5. Summary statistics for the model on level of mechanization.

Variable[a]	Parameter estimate	SE	*p*-Value	VIF	R^2-adj (%)	RMSE	RMSECV
Full model	-	-	<.001	-	57.4	19.63	20.67
Intercept	64.7493503	15.88	<.001	-	-	-	
GDP per capita	0.0010198	0.0002834	.0012	1.21	-	-	
Slope >20°	−0.9135723	0.2423362	<.001	1.04	-	-	
Publicly owned land	−0.4186511	0.1439266	.007	1.25	-	-	

[a]See Table 2 for definitions.

The figure shows (*inter alia*) that changing the diesel price from the lowest to highest value completely shifts the scale of the response variable, regardless of GDP and share of land with >20° slope. Model 2 also indicates the same pattern, but the slope variable is expressed in the opposite direction, a high share of terrain with slope <15° increases the share of CTL (Figure 4). Furthermore, the interaction variable adds another dimension to the interpretation. The FT/TL model solely shows the relationship between SSR and the share of FT/TL (Figure 5), a high SSR being associated with a low share of FT/TL.

When the predicted level of mechanization and shares of CTL and FT/TL are plotted against the recorded data (Figure 6 to Figure 9), it is visible that some countries have a good alignment between predicted and recorded values while other countries are more far off. The difference between the two CTL models in terms of R^2 is also graphically expressed in this way (Figure 7 and Figure 8).

Application of models

Data for countries that were not included in the regression analysis (Table 1) are shown in Table 9 along with the predictions made by the CTL models.

Discussion

This study provides the first comparisons of estimated volumes of industrial roundwood by the harvesting methods considered in

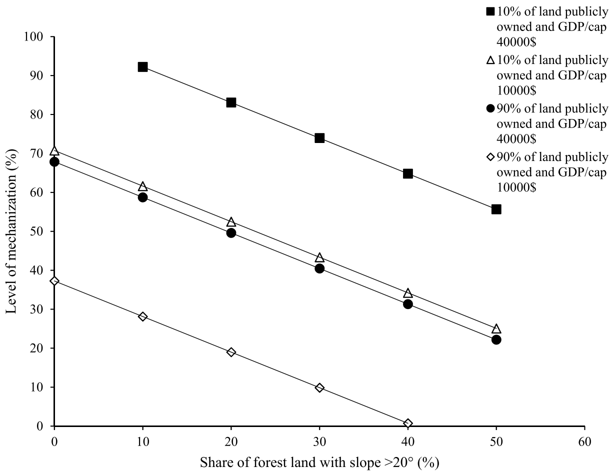

Figure 2. Shares of volume of industrial roundwood harvested fully mechanized at indicated shares of slope >20° according to the model. The four lines reflect shares with indicated combinations of extremes of the variables Gross Domestic Product per capita and forest land publicly owned. For example, the line with quadratic points indicates shares when 10% of the forest land is publicly owned and the GDP is 40,000$ per capita.

Table 6. Summary statistics for fully mechanized CTL model 1 (with no interaction variable).

Variable[a]	Parameter estimate	SE	*p*-Value	VIF	R^2-adj (%)	RMSE	RMSECV
Full model	-	-	<.001	-	63.9	18.52	21.20
Intercept	−27.37	13.37	.050	-	-	-	
Diesel price	49.76	10.91	<.001	1.31	-	-	
Slope >20°	−0.9282	0.226	<.001	1.01	-	-	
GDP per capita	0.0006317	0.0002774	.031	1.31	-	-	

[a]See Table 2 for definitions.

countries from all over the world. Overall, the estimates of distributions between CTL and FT/TL in this study, as well as the level of mechanization, are similar to results presented by the North European Regional Office of the European Forest Institute (EFINORD) (Jonsson et al. 2013) for the European countries represented in both studies. However, there are differences in definitions and categorization of the data between the two studies.

Implications of definitions and boundaries

The definitions of CTL and FT/TL

The categories of harvesting methods in this study are limited by the inclusion criteria that the cut-to-length and full-tree methods must be *fully mechanized* to qualify for categorization as CTL and FT/TL, respectively. The non-mechanized harvesting systems that are widely used in some countries will include

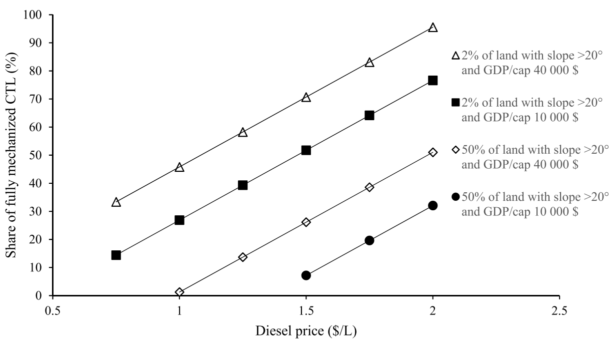

Figure 3. Shares of volume of industrial roundwood harvested by fully mechanized CTL at indicated diesel prices according to Model 1. The four lines reflect shares with indicated combinations of extremes of the variables Gross Domestic Product per capita and forest land with slope >20°. For example, the line with triangular points indicates shares when 2% of the forest land has slopes more than 20° and the GDP is 40,000$ per capita.

Table 7. Summary statistics for fully mechanized CTL model 2 (with an interaction variable).

Variable[a]	Parameter estimate	SE	*p*-Value	VIF	R^2-adj (%)	RMSE	RMSECV
Full model	-	-	<.001	-	75.0	15.43	17.51
Intercept	−64.8047	17.53	<.001	-	-	-	
Diesel price	59.0055	8.00	<.001	1.02	-	-	
Slope <15°	0.7721	0.14	<.001	1.02	-	-	
Diesel price * Publicly owned land (Interaction)	−0.407	0.10	<.001	1.01	-	-	

[a]See Table 2 for definitions.

elements of both CTL and FT/TL harvesting methods, but by definition they will be included in the ”other” category. Also, volumes harvested with partly mechanized systems were categorized as "other," creating an underestimation of the level of mechanization. The underestimation is likely to be small in countries with high level of mechanization and bigger in countries that are less mechanized.

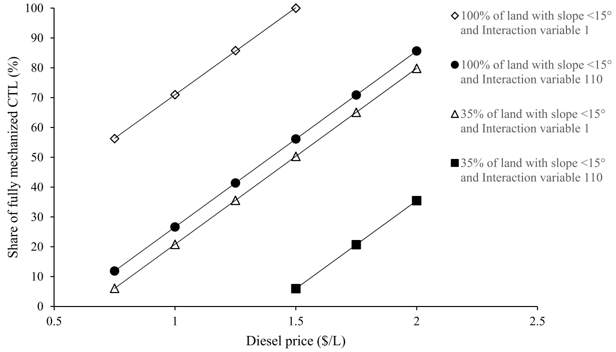

Figure 4. Shares of volume of industrial roundwood harvested by fully mechanized CTL at indicated diesel prices according to Model 2. The four lines reflect shares with indicated combinations of extremes of the interaction and share of forest land <15°.

Table 8. Summary statistics for the FT/TL model.

Variable	Parameter estimate	SE	*p*-Value	VIF	R^2-adj (%)	RMSE	RMSECV
Full model	-	-	<.001	-	36.0	17.32	17.84
Intercept	48.0224	8.27	<.001	-	-	-	
SSR[a]	−1.0805	0.252	<.001	-	-	-	

[a]See Table 2 for definition.

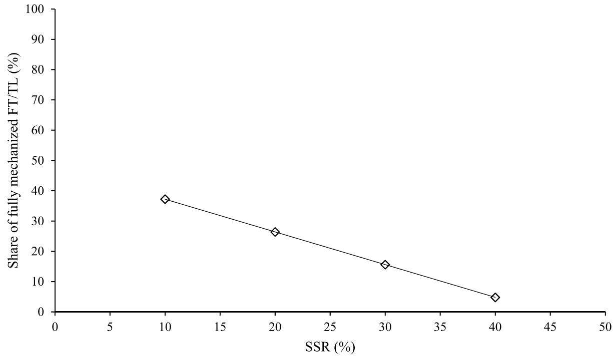

Figure 5. Shares of volume of industrial roundwood harvested by fully mechanized FT/TL at indicated levels of social security rate according to the model.

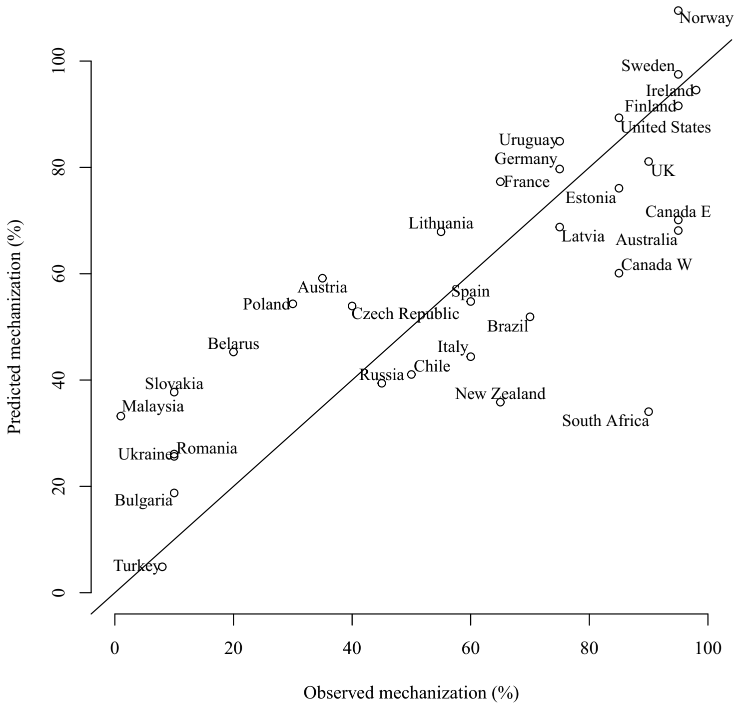

Figure 6. Shares of volume of industrial roundwood harvested fully mechanized in indicated countries according to the model versus observed shares. The line through the origin has the slope of 1. Countries above it have higher modeled values than observed values, and vice versa for countries below the line.

Global CTL vs FT/TL

The results imply that roughly equal volumes of roundwood are harvested by fully mechanized CTL and FT/TL, 37% and 33% of the total volumes, respectively (Table 4). This conflicts somewhat with the general notion that the FT/TL method is the dominant harvesting method or *group of harvesting systems* in the world (c.f. Drushka and Konttinen 1997). Much of the discrepancy is probably due to the comparison here being based on harvested volumes rather than numbers of machines sold (frequently applied metrics), as more machines are usually used per harvested m^3 in FT/TL harvesting systems. Another contributory factor is that FT/TL's dominance may have declined in recent years, and the CTL method may have gained ground during mechanization in previously less mechanized countries, the timespan between sources of information on this matter is large. A third factor is that the exclusion of all partly mechanized systems from these categories may have affected the distribution between CTL and FT/TL. Accordingly, observations in the literature (Demir 2010; Moskalik et al. 2017) and common knowledge of the authors suggest that harvesting systems in countries with a substantial share of the ”other" category (Table 4) probably involve more FT/TL than CTL. In some countries, e.g. Austria, Italy, and New Zealand, a large share of steep terrain is probably a major factor (Lundbäck et al. 2020a), due to the frequent requirement for cable-based harvesting systems, many of which involve manual/motor-manual work elements. In other countries, e.g. in eastern Europe, FT/TL methods were probably favored by the equipment available after World War II, but during further mechanization CTL is increasingly favored. This can be seen in Table 4 in the tendencies for shares of CTL to be higher in the more mechanized Baltic countries than in Eastern European countries and, according to Moskalik et al. (2017), shares of FT/TL to be higher in the less mechanized countries closer to Russia. Hence, CTL may also be favored during mechanization in other parts of the world. However, FT/TL methods still dominate in some countries, or parts of countries, that are important producers and have high levels of mechanization generally, including the USA and western Canada.

What decides the choice of harvesting method and harvesting system?

Explanatory variables, both those included in the models and potentially others, can be roughly placed in one of three groups representing physical, economic, and social/traditional dimensions of the framework affecting commercial activities such as harvesting roundwood (c.f. Nordfjell et al. 2004). All of these dimensions are, to a certain degree, represented in CTL models 1 and 2 and in the mechanization model (consisting of CTL and FT/TL), which is probably the reason for their quite good R^2 values (the physical, economic and social dimensions by the

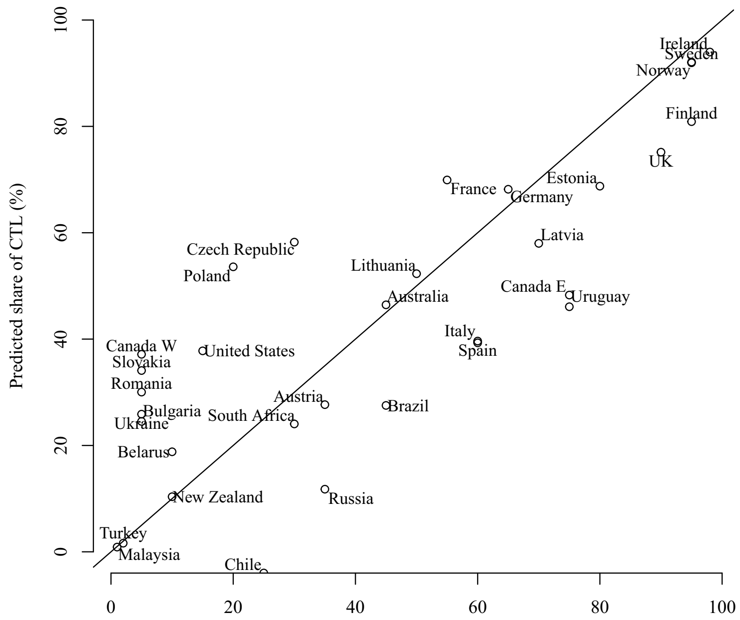

Figure 7. Shares of volume of industrial roundwood harvested by CTL in indicated countries according to Model 1 versus observed shares. The line through the origin has the slope of 1. Countries above it have higher modeled values than observed values, and vice versa for countries below the line.

slope-variables, diesel price, and GDP in Model 1, and these factors plus the share of publicly owned land in Model 2). None of these variables capture the full explanatory power of the respective dimensions, and some (e.g. GDP and share of publicly owned land) may encompass parts of both economic and social dimensions, but they proved to be useful to combine for these models.

Diesel price vs share of publicly owned land

One factor that apparently influences the share of CTL in a country is the amount of privately owned forest land, as a proportion of the total. More strictly, we found negative correlations between the share of publicly owned land and level of mechanization as well as share of CTL which are probably more than coincidental, but the causality is difficult to explain. A somewhat far-fetched hypothesis is that owners in countries with a large share of private forest owners are dependent on frequent income from their forests and thus more likely to perform thinnings. This may favor the CTL method since a forwarder with short logs can more easily move around in a remaining stand than a skidder with full-length stems.

Actually, the share of publicly owned land was the most strongly correlated variable with the share of CTL. However, diesel price was chosen as the first variable in the model since the cause-effect relationship is easier to explain and it was almost as strongly correlated with CTL. One main difference between most FT/TL and most CTL operations is that FT/TL operations generally involve more (and larger diesel engines). Thus, we hypothesized that CTL harvesting is likelier to be favored in countries with high diesel prices. This seem to hold also because the effect of diesel price was not significant for level of mechanization, implying that diesel price distinguishes between harvesting methods rather than levels of mechanization.

Share of steep terrain in forest land

The share of steep terrain in forest land is an important variable of the physical environment that must be considered when planning harvest operations (Nordfjell et al. 2004). The slope of the terrain together with its roughness, ground-bearing capacity and sizes of the trees often determine the harvesting systems that can be applied in a specific area or region. Terrain slope was considered the easiest of these factors to quantify on a global level according to Lundbäck et al. (2020a), and proved to explain a substantial part of the variation in level of mechanization and the share of CTL. Since all non- or partly mechanized systems as well as all cable-based systems were categorized as "others," quite a lot of steep terrain harvesting will fit in that category. That leaves much of the flat terrain in the fully mechanized categories and is a reason for the usefulness of share of steep slope as an explanatory variable. Regardless, effects of the other mentioned physical variables warrant attention in future research.

Gross domestic product and social security rate

Shares of harvesting methods and probably even more level of mechanization in a country are also influenced by demographic factors, partly because CTL and FT/TL harvesting

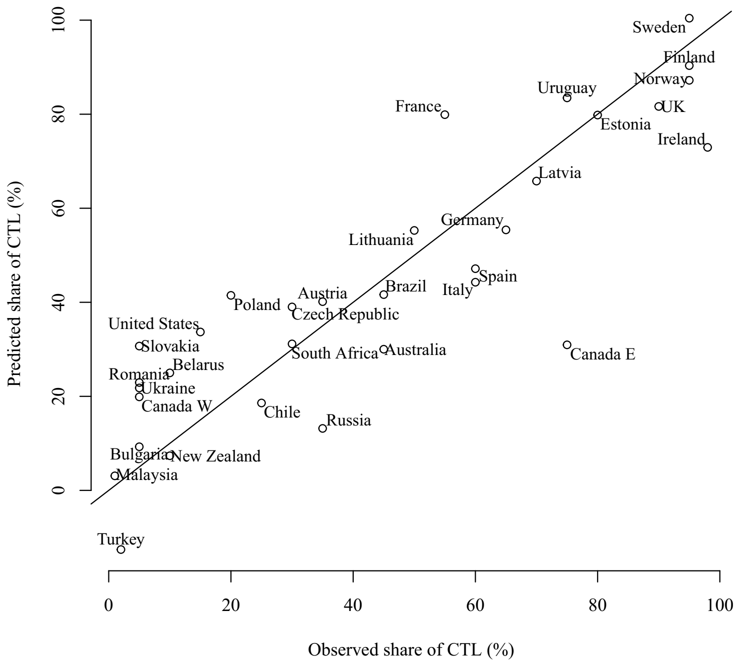

Figure 8. Shares of volume of industrial roundwood harvested by CTL in indicated countries according to Model 2 versus observed shares. The line through the origin has the slope of 1. Countries above it have higher modeled values than observed values, and vice versa for countries below the line.

methods differ in complexity of the machines and equipment typically used. It takes more training and education to effectively operate harvesters and forwarders than fellers, skidders, and processors because more decisions are made by the same person and the machines used in CTL operations are more technically complex. Further down on that scale is manual and motor-manual work which usually is less paid and traditionally takes less training/education. Together with the higher prices for CTL machines this results in workers being hired for longer terms and receiving higher salaries in CTL operations than in FT/TL operations (under otherwise similar conditions). We hypothesized that this effect would be demonstrable using some kind of economic national statistics. GDP per capita is a common measure of a country's economic output and general economic strength, but it provides no information specifically about the forest sector. Nevertheless, it improved Model 1's goodness. The finding that Social Security Rate (SSR) is an explanatory variable for FT/TL can probably be partly explained along the same lines.

Other variables

The Human Development Index (HDI) incorporates GDP, life expectancy, and level of education, so it embraces much more than GDP alone, but it did not improve the fit of the regression models. Like many available statistics for countries tested in this analysis (Table 2), it is probably too general and unable to distinguish differences specifically in the forestry sector between countries.

The variable fossil energy consumption did not improve the fit of the models either, probably because it is correlated to a certain degree with diesel price and partly explains the same variations. However, diesel price is much more helpful for explaining the share of fully mechanized CTL.

Many variables in official global statistics are available to test, but there also probably many concerning forestry that would be interesting to use, but no globally comparable data are available. One example is the size of harvested trees, as small equipment cannot handle trees larger than a certain size and large equipment cannot cost-effectively handle trees smaller than a certain size. Thus, a tree size variable would probably improve models. Another potentially useful variable may be some index linked to a country´s history of timber transportation by river, or lack of it. At least in parts of Scandinavia, the manual handling of logs and size of creeks in forests historically set some limits for both the length and weight of logs. Similar observations may also be informative for practices and harvesting methods in other countries.

Model 1 vs model 2 for CTL

The CTL regression analysis resulted in two models, because we sought both a simple model with high level of interpretability and (as in all regression analysis) as high as possible goodness of fit. Model 1 includes three variables, all of which affect the share of CTL in an intuitive way:

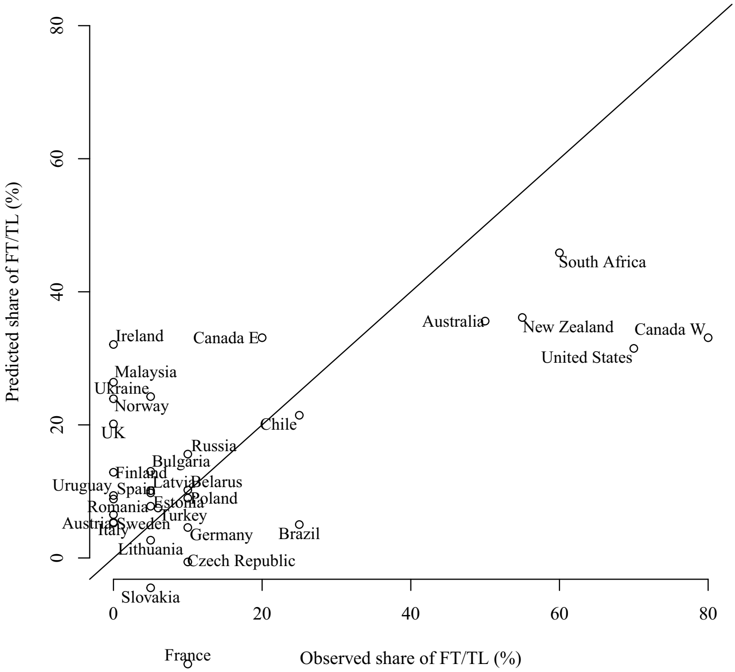

Figure 9. Shares of volume of industrial roundwood harvested by FT/TL in indicated countries according to the model versus observed shares. The line through the origin has the slope of 1. Countries above it have higher modeled values than observed values, and vice versa for countries below the line.

Table 9. Data and predicted shares of fully mechanized CTL for countries that were not included in the modeling but produce more than 5 million m^3 of industrial roundwood.

Country	Share of fully mechanized CTL Model 1 (%)	Share of fully mechanized CTL Model 2 (%)	Diesel price ($/L)	Share of slope >20° (%)	Share of slope <15° (%)	Share of forest land publicly owned (%)	Diesel price × Share of forest land publicly owned
Argentina	24.9	36.9	0.93	6.3	91.0	62	57.66
China	0.0	4.5	1.02	40.5	42.4	57	58.14
India	0.0	2.7	1.03	33.1	55.4	86	88.58
Indonesia	6.5	21.1	0.79	13.0	87.1	87	68.73
Japan	19.3	19.5	1.17	37.2	45.0	41	47.97
Mexico	13.6	47.3	1.08	24.5	63.2	1	1.08
Myanmar	0.0	0.0	0.67	28.7	55.8	100	67.00
Nigeria	0.6	17.4	0.57	4.1	93.0	100	57.00
Portugal	60.8	88.3	1.66	12.9	74.1	3	4.98
Thailand	10.3	3.1	0.91	18.0	66.4	100	91.00
Vietnam	0.0	0.0	0.8	33	49.7	68	54.4

diesel price and GDP per capita positively and share of forest land with slope >20° negatively. Model 2 is more elaborate since apart from another measure of steep slope it also considers the interaction between diesel price and share of forest land that is publicly owned. Model 2 is less straightforward to interpret; the share of publicly owned forest land affects the share of CTL but how much depends on the diesel price.

As discussed above, the share of forest land that is publicly owned is an indirect measure of part of the multi-dimensional framework that sets the choice of harvesting method in a given country. It probably incorporates elements of political history, economic development, forest politics, and both social and cultural aspects. Clearly, apart from being correlated to the share of CTL it is also correlated to GDP per capita and many of the other tested variables, which thus lack the orthogonality required for a parsimonious regression model. In model 2, it seems that GDP per capita is replaced by share of publicly owned forestland through the interaction variable.

Model performance

It is easy to compare recorded (Table 4) and predicted (Figure 7 and Figure 8) shares of CTL. However, the input data in the models clearly do not cover real situations of some countries well. For example, results for Canada are divided into eastern and western parts because CTL harvesting is much more dominant in the eastern parts. Our analysis is that the difference in share of CTL is largely due to the western parts of the country having a larger share of trees which are too big to handle with regular CTL harvesting equipment. In contrast, in eastern Canada there are large areas with relatively small trees, which are suitable for forwarders and thinning operations, both characteristics of the CTL category. However, tree size was not available as input to the models. Only national-level data for both diesel price and GDP per capita were available as input, so eastern and western Canada differ only in the slope variable in these regression models. Clearly, the difference in terrain slope between east and west (Table 3) does not provide reliable results of the share of CTL, as the predicted share of CTL is basically the same for eastern and western Canada.

The Scandinavian countries have very similar culture and traditions in harvesting wood and they all have a very large share of CTL. However, Model 1 differentiates Finland from the other two slightly but clearly, due to Finland's lower diesel price and GDP/capita (Table 3), although there are no real differences among them in share of CTL harvesting methods. This illustrates a weakness of all regression models: they are limited to the included variables and may therefore indicate erroneous differences or similarities in the response variable. Both models ignore effects of tradition, collaboration and so on, which are much stronger than effects of differences in diesel price and GDP per capita in the Scandinavian countries. Model 2 differentiates Norway most strongly from the other Scandinavian countries, corroborating the conclusion that the models exaggerate minor variation, and indicating that they may show the major patterns, but probably cannot be used to spot small differences between countries. In the case of Norway, their higher share of steep slope in forest land does not result in a lower share of CTL than the other Scandinavian countries simply because Norway harvests less of their total forest area annually; therefore, it is possible to find harvest areas with less slope.

The FT/TL models' performance is much poorer, in terms of R^2, than that of the other models. In large part because the small number of countries with a high share of fully mechanized FT/TL (only three observations exceeding 50%) makes it harder to fit a good regression model. An approach to use the difference between the models for level of mechanization and CTL was also attempted but did not result in an improved model.

Application in new countries

The application of the final Models 1 and 2 to the countries in Table 1 does not validate the models as there are no estimates of the shares of CTL for those countries. However, if these countries have a large share of motor-manual work today, the estimates indicate a likely path during a mechanization process.

Some predicted values are negative numbers, which is of course nonsensical for percentages. Therefore, all negative predictions were interpreted as a zero share of CTL, and corresponding countries are unlikely to have a substantial share of fully mechanized CTL according to the models. Of course other factors could favor CTL harvesting methods, but these countries are less likely to have high shares of CTL than other countries.

As a final remark regarding the usability of the models, they were constructed for countries with at least 5 million m^3 of annual harvest of industrial roundwood. Therefore, the models cannot be expected to perform well on new countries with smaller annual harvests, as they are beyond the model boundaries. Likewise, the models are not applicable for prediction of level of mechanization or shares of harvesting methods for non-industrial roundwood.

Future studies

Since the CTL models developed in this study explain 64% and 75%, respectively, of the variation in the share of fully mechanized CTL recorded in Table 4 there is still room for improvement. A variable that is highly likely to improve the models is, as discussed above, the average size of harvested trees in each country. Perhaps also the proportion of hardwood vs softwood and/or the proportion of intensive plantation forests in different countries would bring valuable information. Other variables, such as terrain roughness and more forestry-specific economic measures would probably also improve the CTL models. Suitable data on terrain roughness could potentially be obtained using a large-scale GIS approach and available fine-grained elevation models. The resolution would probably have to be much finer than for slope data (Lundbäck et al. 2020a), so there would be very high computing power requirements. However, it should not be neglected as an interesting topic for future research.

The lower R^2 of 36% for the FT/TL model shows it has even more scope for future improvement. Efforts could be made to improve explanation of either the *fully mechanized* share of FT/TL, as in this study, or the overall division between CTL and FT/TL, regardless of the level of mechanization. However, the last option poses new challenges in gathering sufficient data for the response variables. Machine manufacturers probably know less about the proportion of overall FT/TL than about the fully mechanized FT/TL in a country since the non- or partly mechanized volumes are handled with their specific machines to a lesser extent.

Conclusions

The general conclusion of this study is that it is possible to explain parts of the variation between countries in the level of mechanization and harvesting methods. The main explanatory variables identified are: diesel price, share of steep terrain in forest land, GDP per capita, the share of forest land that is publicly owned, SSR and the interaction between diesel price and the share of forest land that is publicly owned.

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ORCID

Mikael Lundbäck http://orcid.org/0000-0002-1842-7032

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IV

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Global analysis of the slope of forest land

Mikael Lundbäck[1,*], Henrik Persson[2], Carola Häggström[1] and Tomas Nordfjell[1]

[1]*Department of Forest Biomaterials and Technology, Swedish University of Agricultural Sciences, Skogsmarksgränd, Umeå SE-901 83, Sweden*
[2]*Department of Forest Resource Management, Swedish University of Agricultural Sciences, Umeå SE-901 83, Sweden*

*Corresponding author Tel: +46 90 786 8182; E-mail: mikael.lundback@slu.se

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Forests of the world constitute one-third of the total land area and are critical for e.g. carbon balance, biodiversity, water supply and as source for bio-based products. Although the terrain within forest land has a great impact on accessibility, there is a lack of knowledge about the distribution of its variation in slope. The aim was to address that knowledge gap and create a globally consistent dataset of the distribution and area of forest land within different slope classes. A Geographic Information System (GIS) analysis was performed using the open-source QGIS, GDAL and R software. The core of the analysis was a digital elevation model and a forest cover mask, both with a final resolution of 90 m. The total forest area according to the forest mask was 4.15 billion hectares whereof 82 per cent was on slope < 15°. The remaining 18 per cent was distributed over the following slope classes, with 6 per cent on a 15–20° slope, 8 per cent on a 20–30° slope and 4 per cent on a slope > 30°. Out of the major forestry countries, China had the largest proportion of forest steeper than 15° followed by Chile and India. A sensitivity analysis with 20 m resolution resulted in increased steep areas by 1 per cent point in flat Sweden and by 11 per cent points in steep Austria. In addition to country-specific and aggregated results of slope distribution and forest area, a global raster dataset is also made freely available to cover user-specific areas that are not necessarily demarcated by country borders. Apart from predicting the regional possibilities for different harvesting equipment, which was the original idea behind this study, the results can be used to relate geographical forest variables to slope. The results could also be used in strategic forest fire fighting and large-scale planning of forest conservation and management.

Introduction

Of the earth's land area, 31 per cent is covered by forests (FAO, 2010; Keenan *et al*., 2015). Forests play a key role in regulating the earth's climate through the carbon cycle; more carbon is sequestered and stored per hectare (ha) in forests than other types of land cover (Eliasch, 2012). Forest cover has increased by ∼7 per cent since the 1980s (Song *et al*., 2018). Nevertheless, every year, ∼3.7 billion m^3 of roundwood is harvested around the world, and of those forests, according to Curtis *et al*. (2018), 70 per cent are later reforested while 30 per cent remain deforested (see also Global Forest Watch, 2020). Out of the total global harvest, 1.9 billion m^3 are classified as industrial roundwood (FAO, 2016). There are 31 countries that harvest at least 10 million m^3 of industrial roundwood per year, and together they harvest ∼1.7 billion m^3 or 90 per cent of the total annual harvest in the world (FAO, 2016). Five countries harvest more than half of the total harvested volume in the world: the USA, Russia, China, Canada and Brazil (FAO, 2016). Industrial roundwood is harvested and extracted in numerous ways around the world. There are many reasons for the choice of harvesting systems, equipment and methods in different countries (see Gibson *et al*., 1986; Nordfjell *et al*., 2004; Ghaffariyan, 2014). Typically, the physical properties of the land to be harvested play a major part in determining the most suitable equipment and methods. See for example the systematic, Geographic Information System (GIS) based approach in Kühmaier and Stampfer (2010).

Certain key physical properties are commonly recorded in most countries before harvesting begins (Sessions, 2007; Uusitalo, 2010). In the Nordic countries and Canada those physical properties are organized in a structured and harmonized manner into a 'terrain classification system' (Anon., 1969; Samset, 1975; Mellgren, 1980). Physical properties have historically been used to determine which areas are suitable for harvesting machinery at all, and for accessible areas, a given classification describes the level of difficulty that machinery would experience when negotiating the terrain. Since machinery came to be widely used in forest harvesting, the capabilities of all machines have increased and thus affected such classifications in terms of what is difficult and what is possible (Malmberg, 1980; Nordfjell *et al*., 2010). In the Swedish terrain classification system there are three properties: (1) ground conditions, (2) surface structure and (3) slope (Berg, 1992). The *ground conditions* property describes the load-bearing capacity of the ground and is determined largely by the soil type, moisture content and vegetation type (Malmberg, 1989). Favourable ground conditions have good load-bearing capacity and indicate the possibility of harvesting at many different times of the year and in most kinds of weather conditions without negative impacts on the soil, whereas more problematic ground conditions restrict the characteristics of the machines that can be used (available driving force, ground pressure, ground clearance and traceability, etc.) as well as the season and weather conditions when harvesting is possible (Malmberg, 1989; Han *et al*., 2009). The second property, *surface structure,* describes the level of difficulty with respect to number and size of rocks and other obstacles within a harvest area (Malmberg, 1989). Surface structure does not usually affect the season when harvesting can be undertaken but indicates which machinery to use and its productivity on the specific site. Like ground conditions, surface structure can place specific demands on the machine characteristics ground clearance and traceability.

The third property, slope, is defined as the average terrain slope within a particular harvest area. Slope is measured in degrees, or as a percentage calculated as the change in elevation divided by the relevant horizontal distance. Slopes approached in different directions affect the harvesting equipment in different ways; for example, an uphill slope requires sufficient driving power and traction, a downhill slope requires good braking and a side slope can cause a vehicle to overturn if the machine is not sufficiently stable. A stable machine is ideally low and wide; however, there is a trade-off with turning radius and ground clearance. The maximum slope that can be negotiated with certain machinery can vary due to surface structure, vehicle–terrain interaction and operator skill level (Visser and Stampfer, 2015). Usually, tracked machines can handle steeper slopes than wheeled machines as long as the surface structure is not too rough (Nordfjell *et al*., 2004). If the terrain becomes too steep even for tracked machines, the last option is cable- or air-based systems (Greulich, 1999; Nordfjell *et al*., 2004). According to the International Labour Organization's code of practice for forestry work, rubber-wheeled harvesters and forwarders should not operate on terrain steeper than 35 per cent (∼19°), tracked harvesting equipment should not be used on land exceeding 40 per cent (∼22°), and no ground-based equipment at all, even that designed specifically for steep terrain, should work beyond 50 per cent (∼27°) (ILO, 1998).

Apart from the definite limits in slope for different kinds of equipment, there are also cases when work is still possible, but it has to be carried out with extra care. For example, a forwarder extracting timber can handle much steeper slopes upwards and downwards than sideways, and therefore strip roads may have to be oriented parallel to the slope. Furthermore, the maximum side slope is less when the forwarder is loaded than unloaded. Specific limits for side slope with and without loads were specified for forwarders in the 1960s and 70s in Sweden, as outlined in 'Driving in Steep Terrain' (Malmberg, 1980). The specific limits state that driving across a side slope steeper than 15° should be avoided, and if unavoidable, extra detailed planning of the work is required (Malmberg, 1980). For a fully loaded forwarder and/or rough terrain, the limit for a side slope is even less. In addition, guidance has been provided for soil preparation/scarification in the Swedish context: the maximum slope for downhill work is given as ∼22°, and ∼ 17° for uphill work (Rülcker, 1991).

A global dataset containing slope classes for the forest land of different countries would be useful in strategic wood harvest planning and many other applications. Modern remote sensing data and methods facilitate a wide range of analyses, not only in research related to climatology and geology, but also in the field of forest operations (Talbot *et al*., 2017). An overall picture of forest operations in mountainous areas is presented by Heinimann (2004). Therein, 28 per cent of the world's forests are classified as mountainous, although the slope that counts as mountainous is not defined (Heinimann, 2004). Another application of large-scale slope data is in predicting and fighting wild fires affecting forest land: foreseeing difficulties with accessibility due to steep forest terrain could potentially increase efficiency when deploying fire-fighting resources. Analysis of remote sensing data is, in general, a desirable approach when the results ought to be consistent and comparable between different geographical regions and countries. Manually collected information, for example country reports of forest area, forest volume, etc. to FAO, have a tendency to be more or less inconsistent in quality and resolution (Matthews and Grainger, 2003). Due to the expected demands of comparability in future statistical analyses and modelling studies, the GIS approach comes out as a relevant choice of method.

The aim of this study was to create a globally consistent raster dataset of slope classes on forest land and make this freely available online. A secondary aim was to present data on global and national forest land distribution in relation to a number of slope classes, ranging from relatively flat to very steep, as well as forest area per slope class, on a national level.

Methods

The overall concept of this analysis was to combine data on terrain slope with data on forest/non-forest land cover, to assess slope data within forested areas. The terrain slope-data were separated into four classes. The slope of the forest areas was extracted by country.

A GIS analysis was performed. To manipulate and modify the data, several open-source tools and software were used (Table 1): QGIS (Development Team, 2019), GDAL (GDAL/OGR contributors, 2019) and R (Core Team, 2018). The core of the analysis was based on elevation data from the German TanDEM-X mission (Rizzoli *et al*., 2017) as well as forest cover data from NASA satellites (Hansen *et al*., 2013). A vector dataset including country borders was also used for the division of data into countries (Esri®, 2019).

To calculate slope, the digital elevation model (DEM) developed from the TanDEM-X mission (Rizzoli *et al*., 2017) was used. The original elevation model has a resolution of 12 m, but it has subsequently been aggregated to 90 m resolution and made available freely for scientific use by Deutsche Zentrum für Luft- und Raumfahrt (DLR). For this study, the freely available 90-m resolution data were used.

Table 1 Software and tools used in the analysis and a short explanation of their application

Tool	Application	Reference
GDAL		
gdaldem slope	Slope calculation from elevation data	(GDAL/OGR contributors, 2019)
gdalinfo	Various applications when information from one raster was transferred to another, for example resolution	(GDAL/OGR contributors, 2019)
gdalwarp	For aggregation of forest cover data to resolution of slope data	(GDAL/OGR contributors, 2019)
gdal.calc.py	Combining the slope data with the forest cover data using raster multiplication	(GDAL/OGR contributors, 2019)
QGIS		
zonal histogram within QGIS	Applied to count the number of pixels with certain values within countries	(QGIS Development Team, 2019)
R:		
rgdal reclassify	Reclassification of slope data into classes	(Bivand *et al*., 2019)
R function area	To compute the area of each pixel in a raster, considering the data are unprojected	(Hijmans, 2019)
R function exactextractr	Used to extract sum of area-pixels within countries, similar to zonal statistics	(Baston, 2019)

To convert the elevation data to slope data, a corresponding slope raster was computed from the DEM using a method of eight grid points with unequal weights (Horn, 1981). This is the standard method applied for slope calculations in GDAL. Scale factors were applied to compensate for the fact that the horizontal positions of pixels in the DEM were presented in degrees while the elevation was in metres. To avoid projecting the global DEM on a flat surface, as one would do with smaller study areas, *different* scale factors were used for every change in latitude. The following formula was used for the scale factors:

$$\text{Scale factor} = 111\,320 * \cos \frac{\text{latitude} * \pi}{180}, \quad (1)$$

where 111 320 is a constant representing the number of metres in one degree longitude at the equator. The scale factor changed gradually according to equation 1 while moving towards the poles because one degree equals fewer and fewer metres in the east–west direction when moving away from the equator.

All slope pixels were placed in one of four slope classes. The classes were defined by slope intervals: ≤15°, >15 to 20°, >20 to 30° and >30°. The four slope classes are of unequal width. The first one (0–15°) is wider, while the next (15–20°) is narrower. This division was based on how harvesting equipment generally negotiates different levels of slope: basically, most machines can handle a slope ∼15°, while a slope of 17° can start to get challenging for some systems, especially on side slopes and with a load. This explains the choice of the first class (0–15°). A slope of 20–22° is commonly considered to be the limit for rubber-wheeled harvesters and forwarders, which is the rationale for designating the next class (15–20°). However, this limit can be pushed substantially with the help of cable-assist systems (Visser and Stampfer, 2015). Tracked machines, for example harvesters with self-levelling carriages, can usually handle slopes ∼30° before they start to loose grip (Cavalli and Amishev, 2019) and beyond that special features have to be added, for example wheels mounted on individually movable arms and cable assist. On this basis, the classes of 20°–30° and >30° were selected.

To calculate the share of forest land in each slope class, the Hansen forest cover data for the year 2000 (Hansen *et al*., 2013) were used. The Hansen forest cover data are a raster dataset with pixel values between 0 and 100 corresponding to a crown cover percentage within each specific pixel. To create a binary forest/non-forest (FNF) mask, a threshold of 25 per cent crown cover was applied for each pixel in the Hansen forest cover data. With that threshold, the calculation of forest area per country shows good overall alignment to FAO (2010) forest cover data. A lower threshold of 10 per cent was tested because it corresponds to FAO's definition of forest land. The lower threshold however, when applied on the Hansen forest cover data, resulted in significant overestimations of forest land in certain large countries such as Canada. The FNF mask was aggregated from the original 30 × 30 m resolution to 90 × 90 m to correspond to the slope data.

The intersection of 'slope' and 'forest' rasters was computed in the GDAL raster calculator. The number of pixels in a certain slope class was divided by the total number of forest land pixels in each country by also applying the Esri® (2019) vector data for country borders. The operation was repeated for each slope class in all countries. For this, the QGIS tool *Zonal histogram* was used.

Finally, the forest area was calculated for the FNF mask, pixel by pixel using the area function of the R raster package (Hijmans, 2019). With this function, the area was defined vertically from above and the function handles unprojected raster data in such a way that the areas could be calculated with approximations only within each pixel instead of over two digit numbers of latitudes. Due to the data structure of the DEM, a more standard tool would only use four different scale factors for the area calculation,

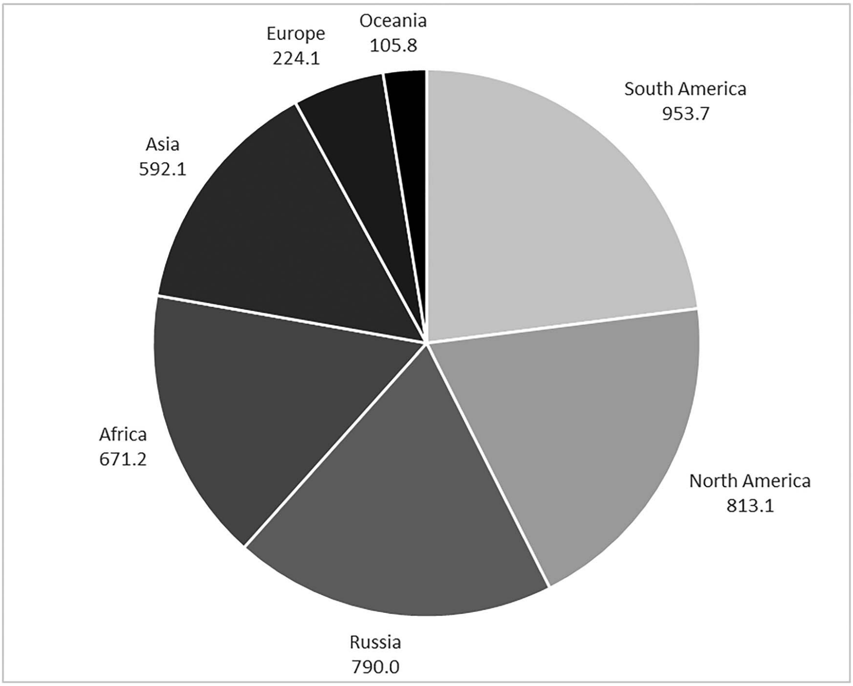

Figure 1 Forest area (Million ha) per continent calculated from the forest mask. Russia is displayed separately due to its size and presence in both Europe and Asia.

while the area function uses one for each latitude. The result is a value of area for each pixel, which was then summarized per country polygon using the *exact extract* function (Baston, 2019). All aggregated results per continent were computed, with Russia in a separate category due to its size and because it spans two continents, thus, Russia's forest areas are not part of Europe's or Asia's in the results.

Results

The total forest area according to the applied forest mask is 4.15 billion ha, corresponding to 32 per cent of the total land area of the earth. The forest area on the six continents varied between 106 million ha in Oceania and 954 million ha in South America. Russia alone has 790 million ha (Figure 1).

There is great variation in slope distribution between countries (Table 2). Of all the world's forests, 82 per cent were found on slopes between 0 and 15 degrees. The remaining 18 per cent was distributed in a declining pattern over the steeper slopes. The second slope class 15–20° supported a smaller percentage of the forest land than the third due to its narrower interval, 5° compared with 10° (Figure 2). Large areas of steep forests are typically found in the mountains, whereas flat terrain forests are found in, for example, Russia, Africa and the Amazon rainforest (Figures 3 and 4). In the 'High Coast' region of Sweden (Figure 3d), some very steep areas can be found close to rivers. In the same way, it is also possible to find flat forest areas in an overall steep landscape, for example south eastern China (Figure 4c). The distribution of slope in forest land varies greatly between continents, with Asia and Africa being the two extremes. Africa has a large share of forest land on flat terrain and almost no forest on very steep terrain (>30°). In contrast, Asia has <60 per cent of its forest land on flat terrain and ~10 per cent on very steep terrain (Figures 3–5).

The 10 countries that harvest the most roundwood each year account for ~70 per cent of the total global harvest (FAO, 2016). Finland, Sweden and Brazil all have at least 95 per cent of their forest land within the lowest slope category (0–15°). The forest land in the US, Russia and Canada shows common patterns of distribution over the four slope classes, having between 80 and 90 per cent of their forest area on slopes ~15° (Figure 6). There are three countries that stand out with a low (~50 per cent) share of forest land on slopes between 0 and 15°: Chile, China and India (Figure 6). Even more extreme are Latvia, Belarus and Uruguay with 99–100 per cent of their forest land in the lowest slope category (Table 2).

Table 2 The forest area and share of forest land within each of four slope classes (%) for every country

Country	Forest area (1000 ha)	0–15° slope (%)	15–20° slope (%)	20–30° slope (%)	>30° slope (%)
Afghanistan	264	8.3	6.1	27.0	58.6
Albania	715	24.3	18.7	34.1	22.8
Algeria	1333	44.9	21.8	26.6	6.7
Andorra	20	5.6	7.5	31.6	55.3
Angola	63 277	97.3	1.6	1.0	0.1
Anguilla	2	99.6	0.4	0.1	0.0
Antigua and Barbuda	19	88.2	5.7	5.7	0.4
Argentina	40 128	90.8	2.9	3.8	2.5
Armenia	346	20.5	17.5	39.3	22.7
Aruba	0.04	100.0	0.0	0.0	0.0
Australia	46 011	79.3	8.7	9.5	2.6
Austria	4380	35.6	12.1	24.5	27.8
Azerbaijan	1324	39.9	14.0	26.2	19.9
Bahamas	263	99.9	0.0	0.0	0.1
Bangladesh	2049	89.1	5.7	4.4	0.8
Barbados	5	94.6	5.0	0.4	0.0
Belarus	9278	100.0	0.0	0.0	0.0
Belgium	891	92.3	4.7	2.7	0.4
Belize	1731	89.3	5.5	4.4	0.8
Benin	609	99.6	0.2	0.2	0.0
Bermuda	0.1	99.5	0.0	0.0	0.5
Bhutan	2622	9.6	10.9	35.5	44.0
Bolivia	65 091	88.2	3.5	5.3	3.0
Bosnia and Herzegovina	2750	51.1	17.1	22.1	9.7
Botswana	55	96.0	2.3	1.7	0.1
Brazil	526 085	95.3	2.6	1.8	0.3
British Virgin Islands	5	26.1	23.8	46.6	3.5
Brunei	528	89.9	4.8	4.7	0.6
Bulgaria	4193	56.3	16.7	20.6	6.4
Burkina Faso	1	99.8	0.1	0.2	0.0
Burundi	848	72.5	13.8	12.2	1.5
Cambodia	9216	92.8	3.8	3.0	0.4
Cameroon	34 196	93.9	2.9	2.7	0.5
Canada	427 259	88.7	3.7	4.1	3.5
Eastern Canada	187 688	95.5	2.6	1.5	0.4
Western Canada	238 814	81.2	4.9	6.9	7.0
Cape Verde	7	26.6	23.4	34.2	15.8
Cayman Islands	9	99.9	0.0	0.0	0.1
Central African Republic	51 683	99.8	0.1	0.1	0.0
Chad	954	99.0	0.5	0.5	0.0
Chile	18 080	47.3	11.9	19.6	21.3
China	170 712	42.4	17.1	25.7	14.8
Colombia	82 315	81.4	5.8	8.7	4.1
Comoros	133	68.0	14.5	12.0	5.5
Congo	28 817	98.1	1.3	0.5	0.0
Costa Rica	3920	70.4	11.8	13.5	4.3
Croatia	2444	75.5	11.3	10.3	2.9
Cuba	4008	86.5	5.7	6.4	1.4
Cyprus	131	37.5	21.6	33.1	7.8

Continued

Table 2 Continued

Country	Forest area (1000 ha)	0–15° slope (%)	15–20° slope (%)	20–30° slope (%)	>30° slope (%)
Czech Republic	3108	81.1	10.6	7.3	1.0
Denmark	654	99.2	0.6	0.2	0.0
Djibouti	0.0001	100.0	0.0	0.0	0.0
Dominica	68	46.5	19.0	24.2	10.3
Dominican Republic	2626	71.4	11.8	13.1	3.8
Ecuador	19 115	72.0	8.8	13.0	6.1
Egypt	353	100.0	0.0	0.0	0.0
El Salvador	1029	71.7	13.8	12.2	2.2
Equatorial Guinea	2639	89.8	5.0	4.5	0.7
Eritrea	0.01	27.3	18.2	45.5	9.1
Estonia	2634	99.9	0.1	0.0	0.0
Ethiopia	15 494	79.5	9.3	9.1	2.2
Falkland Islands (Islas Malvinas)	2	59.1	18.3	20.8	1.7
Fiji	1502	72.6	15.0	10.6	1.7
Finland	21 625	98.2	1.2	0.5	0.1
France	17 200	74.0	8.5	11.0	6.5
French Guiana	8187	96.9	2.3	0.7	0.0
Gabon	24 607	94.1	3.9	1.9	0.1
Gambia, The	21	100.0	0.0	0.0	0.0
Gaza Strip	0.04	100.0	0.0	0.0	0.0
Georgia	3204	29.1	12.4	26.9	31.6
Germany	12 695	81.2	8.4	7.7	2.7
Ghana	7915	96.7	2.0	1.1	0.1
Gibraltar	0.1	38.0	14.7	30.7	16.6
Glorioso Islands	0.02	100.0	0.0	0.0	0.0
Greece	3994	40.9	19.5	27.7	11.8
Grenada	26	72.3	14.5	11.0	2.1
Guadeloupe	90	75.6	10.6	10.4	3.5
Guatemala	7820	72.1	10.0	12.8	5.1
Guernsey	1	91.3	3.2	2.1	3.4
Guinea	11 316	93.1	4.1	2.3	0.5
Guinea-Bissau	1409	99.9	0.0	0.0	0.0
Guyana	19 059	95.6	2.3	1.7	0.4
Haiti	887	60.0	15.4	18.3	6.3
Honduras	7849	60.3	17.9	18.3	3.5
Hungary	2053	89.9	6.0	3.6	0.4
India	41 758	55.4	11.5	18.9	14.2
Indonesia	160 216	78.5	8.6	9.9	3.0
Iran	1806	28.8	16.2	31.1	23.9
Iraq	21	70.0	3.7	12.2	14.1
Ireland	867	90.3	5.0	3.5	1.2
Isle of Man	14	74.0	11.7	10.3	4.0
Israel	33	68.2	15.0	14.3	2.5
Italy	9650	37.3	16.2	25.2	21.3
Ivory Coast	17 978	98.6	0.8	0.5	0.1
Jamaica	764	73.4	11.9	11.2	3.6
Japan	26 046	45.2	17.6	25.2	12.0
Jersey	2	84.7	6.5	6.9	2.0
Jordan	3	49.9	28.9	20.8	0.5
Kazakhstan	4455	51.9	11.2	20.3	16.6
Kenya	3950	85.3	6.9	6.1	1.6

Continued

Table 2 Continued

Country	Forest area (1000 ha)	0–15° slope (%)	15–20° slope (%)	20–30° slope (%)	>30° slope (%)
Kyrgyzstan	745	14.5	9.7	28.6	47.2
Laos	19 326	52.5	18.1	23.8	5.5
Latvia	3564	99.8	0.2	0.0	0.0
Lebanon	73	33.4	20.4	29.5	16.7
Lesotho	12	46.0	16.2	26.6	11.2
Liberia	9432	97.4	1.7	0.8	0.1
Libya	11	69.1	13.7	12.7	4.5
Liechtenstein	10	25.5	6.8	20.0	47.7
Lithuania	2352	99.6	0.3	0.1	0.0
Luxembourg	103	74.6	12.8	11.0	1.6
Macau	0.01	77.8	22.2	0.0	0.0
Macedonia	843	30.6	21.4	35.4	12.6
Madagascar	18 549	80.1	10.7	7.8	1.4
Malawi	2235	78.5	11.0	9.2	1.3
Malaysia	29 266	74.4	12.8	11.4	1.4
Maldives	0.02	76.0	0.0	0.0	24.0
Mali	104	95.6	3.0	1.4	0.1
Malta	0.1	75.0	3.8	3.0	18.2
Martinique	70	71.5	13.0	10.5	5.0
Mauritania	0.04	100.0	0.0	0.0	0.0
Mauritius	82	81.2	7.5	8.5	2.7
Mayotte	30	81.4	12.6	5.5	0.6
Mexico	55 339	63.2	12.3	17.3	7.2
Moldova	375	92.1	6.2	1.6	0.2
Monaco	0.2	19.5	21.5	46.3	12.7
Mongolia	4487	49.5	25.2	21.7	3.6
Montenegro	658	41.8	17.4	25.4	15.3
Montserrat	4	46.9	19.7	25.4	8.0
Morocco	756	45.3	18.5	26.7	9.4
Mozambique	37 030	96.4	1.8	1.6	0.2
Myanmar (Burma)	43 413	55.8	15.5	21.2	7.5
Namibia	14	91.8	2.6	4.6	0.9
Nepal	5315	25.9	10.9	30.4	32.8
Netherlands	624	99.6	0.2	0.1	0.2
Netherlands Antilles	7	94.7	3.7	1.4	0.2
New Caledonia	1423	55.0	16.3	22.3	6.5
New Zealand	10 960	41.3	14.0	23.1	21.6
Nicaragua	7878	88.4	6.6	4.5	0.5
Niger	0.01	100.0	0.0	0.0	0.0
Nigeria	12 883	93.0	2.9	3.5	0.6
North Korea	5384	23.5	20.0	41.2	15.3
Norway	11 358	58.4	12.0	14.8	14.8
Oman	0	0.0	33.3	0.0	66.7
Pacific Islands (Palau)	28	97.8	1.4	0.2	0.6
Pakistan	1152	10.2	9.0	29.2	51.6
Panama	5580	73.4	12.3	11.6	2.6
Papua New Guinea	42 413	70.5	10.0	13.8	5.7
Paraguay	24 954	99.7	0.2	0.1	0.0
Peru	78 043	82.1	4.9	7.7	5.2
Philippines	18 332	65.2	13.6	15.9	5.3
Poland	10 590	92.1	4.0	3.4	0.6

Continued

Table 2 Continued

Country	Forest area (1000 ha)	0–15° slope (%)	15–20° slope (%)	20–30° slope (%)	>30° slope (%)
Portugal	2478	74.1	13.0	11.1	1.8
Puerto Rico	520	73.1	14.1	11.5	1.4
Reunion	177	67.8	11.5	7.9	12.9
Romania	8057	52.8	16.8	21.5	8.8
Russia	789 986	84.8	5.7	6.2	3.3
Rwanda	697	65.9	16.4	15.8	2.0
San Marino	1	49.6	29.9	14.0	6.5
Sao Tome and Principe	14	50.0	14.2	19.9	16.0
Saudi Arabia	0.01	100.0	0.0	0.0	0.0
Senegal	170	99.9	0.0	0.0	0.0
Serbia	3178	51.9	19.0	22.9	6.2
Seychelles	1	99.5	0.0	0.0	0.5
Sierra Leone	6045	94.4	3.5	1.9	0.2
Singapore	14	98.4	0.3	0.0	1.2
Slovakia	2399	49.3	18.9	23.6	8.3
Slovenia	1330	48.9	15.2	20.8	15.1
Solomon Islands	2411	64.1	14.4	16.1	5.5
Somalia	140	96.7	1.3	1.3	0.7
South Africa	7082	70.9	12.6	12.5	4.0
South Korea	5357	33.1	23.1	35.0	8.7
Spain	11 888	54.7	16.3	20.8	8.2
Sri Lanka	4038	86.2	6.2	6.1	1.5
St. Kitts and Nevis	8	49.7	18.7	23.9	7.8
St. Lucia	50	66.4	18.4	12.1	3.1
St. Pierre and Miquelon	4	91.0	5.0	3.5	0.6
St. Vincent and the Grenadines	26	50.2	20.0	20.8	8.9
Sudan	17 181	98.4	0.6	0.8	0.2
Suriname	13 853	95.6	2.7	1.6	0.1
Swaziland	584	78.1	12.2	8.8	0.9
Sweden	27 826	94.6	3.1	1.8	0.5
Switzerland	1575	30.2	11.0	22.4	36.4
Syria	117	47.3	19.7	24.5	8.4
Taiwan	2331	23.3	12.2	30.4	34.0
Tajikistan	78	13.9	7.8	31.2	47.1
United Republic of Tanzania	34 029	91.8	4.3	3.4	0.5
Thailand	20 422	66.4	15.5	15.7	2.3
Togo	800	90.7	4.8	3.9	0.6
Trinidad and Tobago	377	87.0	6.0	6.0	0.9
Tunisia	243	73.3	15.9	9.5	1.3
Turkey	10 879	42.0	18.6	26.5	12.9
Turkmenistan	13	74.9	4.5	10.2	10.4
Turks and Caicos Islands	7	100.0	0.0	0.0	0.0
Uganda	10 000	94.4	2.4	2.6	0.7
Ukraine	11 587	85.5	5.3	6.6	2.6
UK	3809	80.9	8.0	7.5	3.6
US	284 896	80.4	7.1	8.4	4.1
Uruguay	1739	98.8	0.9	0.3	0.0

Continued

Table 2 Continued

Country	Forest area (1000 ha)	0–15° slope (%)	15–20° slope (%)	20–30° slope (%)	>30° slope (%)
Uzbekistan	133	51.4	6.1	19.4	23.1
Vanuatu	1040	70.9	11.4	12.8	4.9
Venezuela	56 997	84.7	6.7	6.5	2.1
West Bank	1	69.9	15.9	12.9	1.2
Vietnam	16 847	49.7	17.2	24.7	8.3
Virgin Islands	10	81.2	11.9	6.6	0.3
Yemen	0.3	22.2	11.6	34.4	31.8
Zaire	211 196	97.4	1.4	1.0	0.1
Zambia	31 691	98.0	1.1	0.9	0.1
Zimbabwe	2415	79.3	9.9	9.3	1.5
Africa	671 203	95.1	2.5	2.0	0.4
South America	953 741	90.4	3.6	4.0	2.0
Russia	789 986	84.8	5.7	6.2	3.3
North America	813 066	82.7	6.1	7.2	4.0
Oceania	105 761	70.6	10.1	13.1	6.2
Europe	224 113	67.7	10.4	13.8	8.1
Asia	592 145	57.3	13.9	19.4	9.4
World	4 150 015	81.7	6.5	7.9	3.9

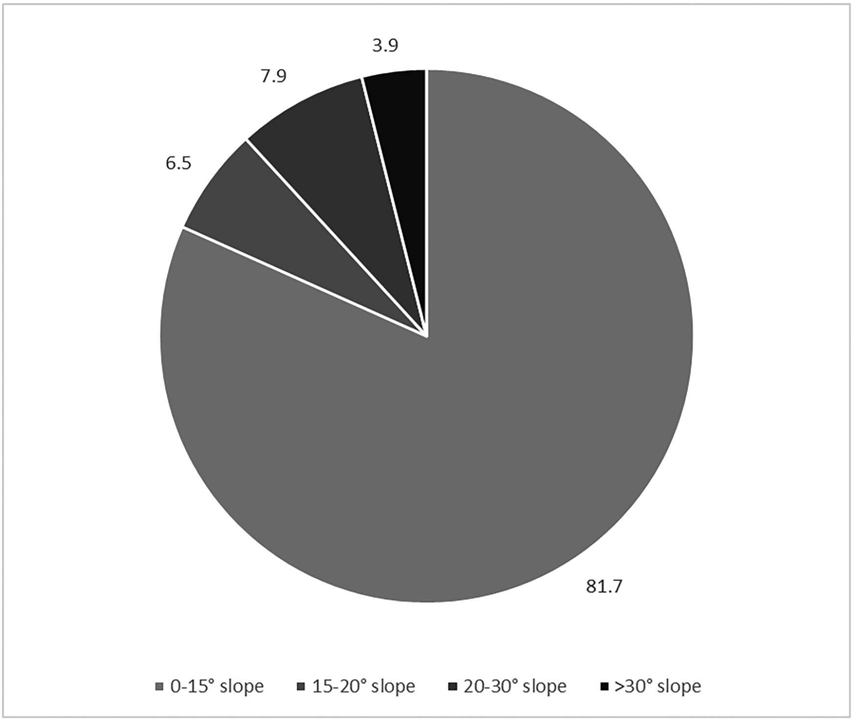

Figure 2 World's forest land distribution in the four slope classes (%).

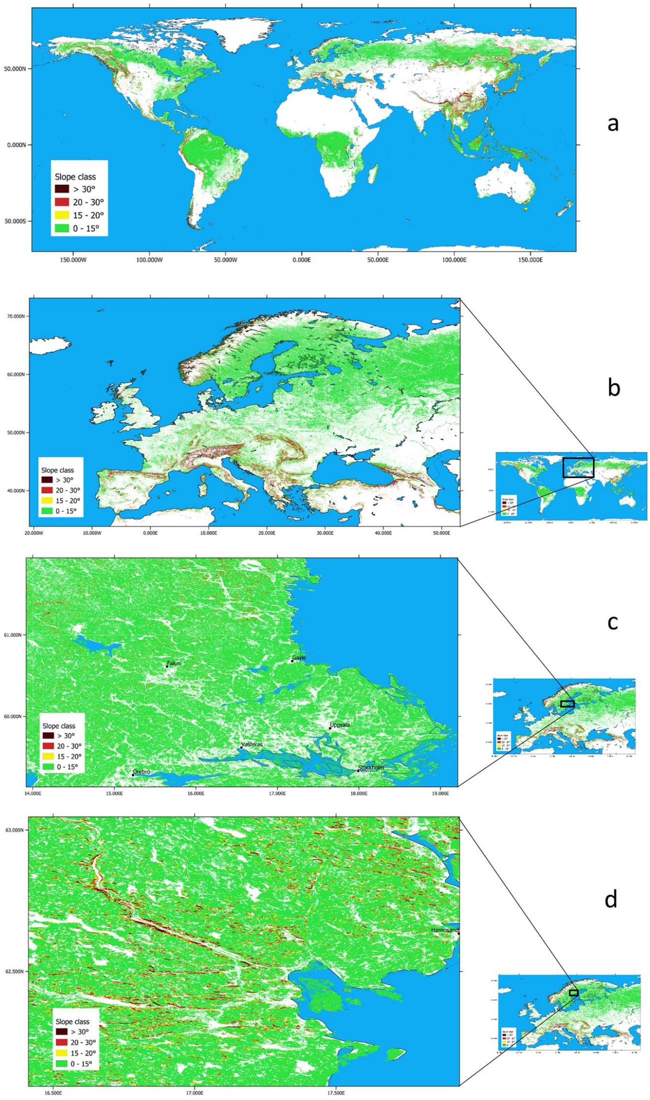

Figure 3 World map and detailed enlargements in which each forest land pixel is represented by a colour that reflects a slope class. The white areas are non-forest. From top to bottom, the following areas are shown: (a) World (except Antarctica), (b) Europe, (c) Sweden area around Stockholm and (d) Sweden 'High coast'**.**

Discussion

The main contribution of this study is to provide a global table of the share and area of forest land in four different slope classes, country by country (Table 2). The origin of this study was lack of knowledge, or at least consistent data, of slope in forest land, from a forest operations point of view. The results for Sweden in this study are similar to those presented by Von Segebaden (1975). However, the slope classes in Von Segebaden (1975) follow the Swedish Terrain Classification (Anon., 1969), whereas

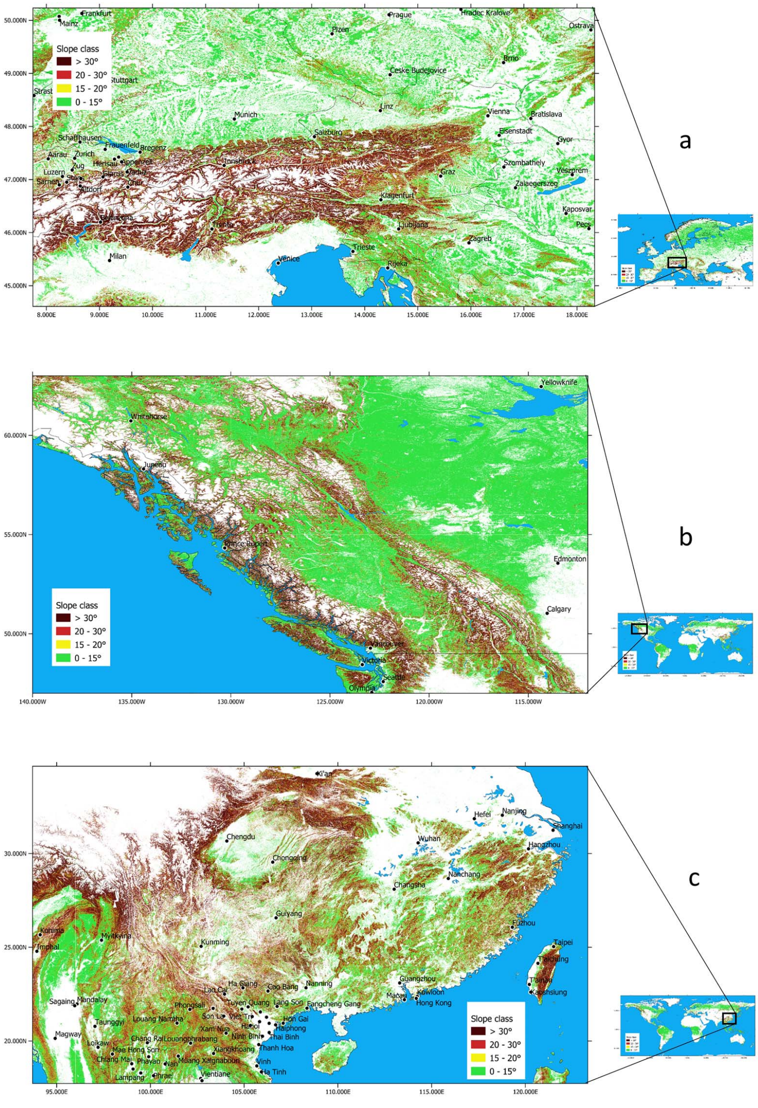

Figure 4 Detailed enlargements in which each forest land pixel is represented by a colour that reflects a slope class. The white areas are non-forest. From top to bottom, the following areas are shown: (a) Austria, (b) British Columbia, Canada and (c) south-eastern China.

in this study the classes were selected with reference to modern machinery and a worldwide application. Nevertheless, the two steepest slope classes are quite similar, 18–27° and >27° in Von Segebaden (1975) compared with 20–30° and >30° in this study. Combined, these two slope classes account for 2 per cent of the Swedish forest land in both Von Segebaden (1975) and this study. Furthermore, Von Segebaden (1975) reports that 92 per cent of the Swedish forest land has slopes of 0–11°, while this study shows 95 per cent of forest land on a slope between 0 and 15°, a quite good alignment. In Turkey, Demir (2010) states that 'Productive forests are generally found in mountainous areas which have 40–80 per cent gradient', i.e. with a slope > 22°. The

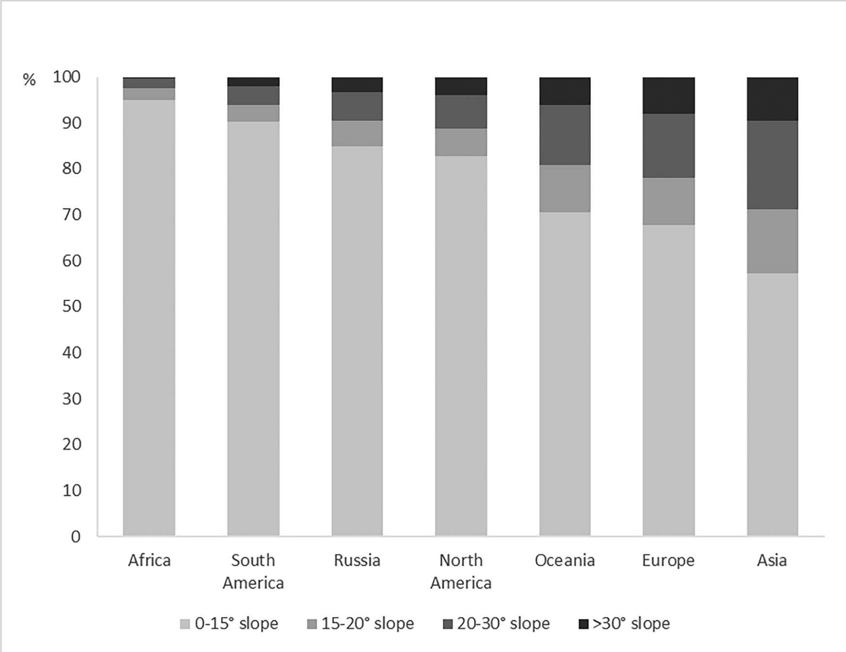

Figure 5 Forest land distribution over the four slope classes on the six continents with forestry. Russia is displayed separately and its distributions are not included in the figures for Asia or Europe.

share of forest land > 20° in Turkey according to this study is 40 per cent, one should remember though that productive forest land is only a subset of the forest targeted in this study, which means that the forests that are harvested could well be aligned with our results.

Global maps of forest cover as well as the forests timber volume, tree density and other forest characteristics have been produced for many years. The use of DEMs for various purposes is also widespread. The novelty of this study was to bring together these existing datasets to create new data. In the research field of forest operations, information pertaining to terrain slope has always been important, but, as already stated, the information has not existed in a consistent, structured and internationally comparable form before. Furthermore, the dataset attached to this study (Lundbäck *et al*., 2020) is detailed enough to facilitate analysis on smaller geographic areas than reported in Table 2, such as municipalities, see Figure 3 for a Swedish example of this.

Technical methodology implications

Forest cover data

To mask out all areas that are not forests in this study, technically any available geographic data relating to forest cover could have been used, although with different results. The distribution of forest land in the four slope classes could change with different so-called FNF masks. Potential differences depend on whether the distributions are the same in areas covered by the FNF mask and areas in reality, both regarding false positive and false negative forest pixels. For the area calculation (Table 2), on the other hand, a reasonably accurate FNF mask will directly come out as superior to a less accurate one since the official area of forest in countries is a key figure that can be found in many data sources. The benchmark for forest areas in this study was the widely known and applied Forest Resources Assessment published every 5 years by FAO, more specifically FAO (2010). Initially, an FNF mask that originated from the same TanDEM-X mission as the height data (Martone *et al*., 2018) was tested, however the misalignment with FAO data (FAO, 2010) was too large to be acceptable. The differences were almost exclusively underestimates and they seemed to be largest in boreal areas. For example, Sweden ended up with only half of its forest area compared with FAO figures, which in turn align well with figures widely accepted by foresters in the country. To provide reliable and valid data, the Hansen forest cover data were applied as the FNF mask instead of the TanDEM-X data.

The Hansen data

The definition of forest in this study is simply all trees that exceed a height of 5 m (Hansen *et al*., 2013) combined with 25 per

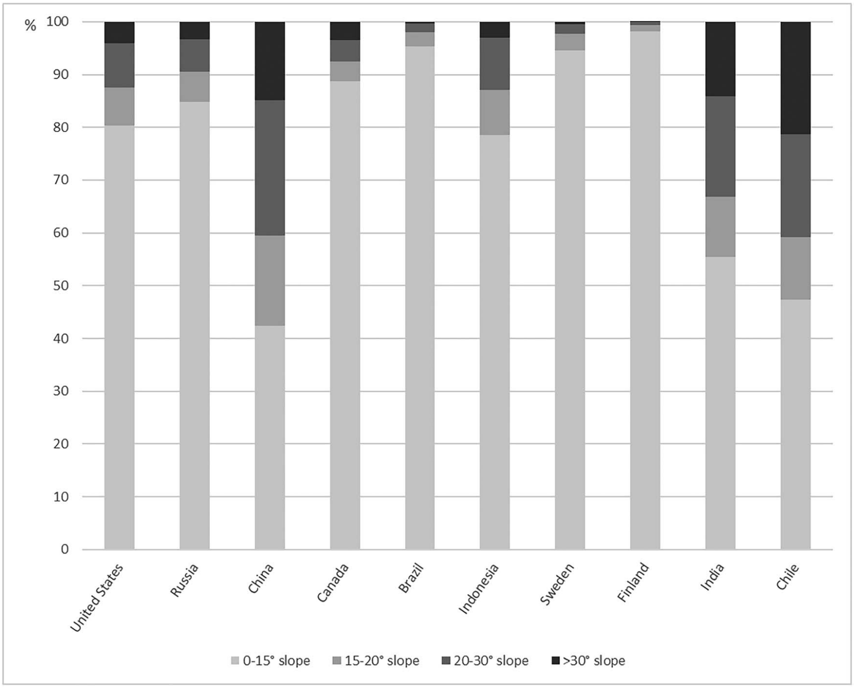

Figure 6 Forest land distribution in the four slope classes in the 10 countries that harvest 70 per cent of the world's industrial roundwood per year (US, Russia, China, Canada and Brazil together account for 50 per cent of the world's harvest). Annual harvest decreasing from left to right.

cent crown cover per 90 × 90 m pixel. The threshold of 25 per cent crown cover resulted in a total forest area of 4.15 billion ha worldwide, a figure that aligns well with FAO's corresponding figure of 4.03 billion ha (FAO, 2010). Although our results in general align quite well with FAO data, different definitions of forest can have a large impact on the results of forest area calculations in specific countries. For example, the estimated forest area in Australia deviated substantially between this study (~46 million ha) and the FAO data (~150 million ha). For the Australian country report to FAO, data from the governmental investigation *Australia's State of the Forests* were used, and this has a somewhat different definition of forests:

'An area, incorporating all living and non-living components, that is dominated by trees having usually a single stem and a mature or potentially mature stand height exceeding 2 m and with existing or potential crown cover of overstorey strata about equal to or greater than 20 per cent. This includes Australia's diverse native forests and plantations, regardless of age. It is also sufficiently broad to encompass areas of trees that are sometimes described as woodlands' (ABARES, 2018).

Differences in tree height are probably the main source of deviations. In a dry country of vast size like Australia there are large areas with trees or shrubs with a height between the thresholds of 2 and 5 m. Those trees will cause problems with the comparison, as discussed by Miller (2016). However, another important difference in definition is that this study takes a *tree cover* approach, while the definition from the Australian government report focuses on *land use*. This implies that, for example, fresh clear-cuts will not appear as forest in our data even though they will be reforested in a couple of years, and thus should not be seen as permanently deforested. Differences in definition are unavoidable in large-scale comparisons, the differences may not even be a problem depending on whether the comparisons are made between datasets or among countries within the same dataset. The implications of definitions are, however, always important to bear in mind.

Finally, it should be noted that the data for the FNF mask were gathered around the year 2000 and that the data behind the figures in FAO (2010) are probably some years more recent, depending on what data each country used for reporting to the FAO. However, we believe that this only result in minor discrepancies in forest area between the two kinds of data, compared with the issues discussed above.

Effects of aggregation of the FNF mask

When the FNF mask was aggregated from its original 30 × 30 m resolution to 90 × 90 m, some information was lost. The lower resolution was preferred for the FNF mask to match the slope data, as described earlier. To evaluate the extent to which the aggregation resulted in lost information, the forest area in each country was calculated for both resolutions. The absolute difference between those areas was calculated for each country, and for Sweden (a flat country) the difference was 0.003 per cent of the total forest area. The corresponding number for Austria (a steep country) was 0.006 per cent, and for Australia (a country where the FNF mask deviated from FAO data) 0.004 per cent. Globally, the corresponding total figure was 0.003 per cent. The global figure was calculated by adding all national absolute differences in forest area and dividing that sum of differences by the total forest area in the world. These measures of error for the aggregation may be overestimated since the difference for each country was calculated from an area defined by at least 10 per cent crown cover in each pixel in the Hansen forest cover data. Eventually, for the main analysis a threshold of 25 per cent crown cover was used, which decreased the forest areas and thus possibly also the differences.

The height and slope data

The original DEM used for calculating slopes in this study was produced using the interferometric synthetic aperture radar (InSAR) technique. In this specific case, the TanDEM-X and TerraSAR-X satellites gathered X-band radar data for generation of the DEM. Since X-band is short wave (∼3 cm), the signals will not penetrate dense crown covers in forested areas and thus result in a 'surface model' in forest areas and a 'ground model' in open areas. The bias introduced in the DEM due to this circumstance was not investigated further in this study because it was considered a minor factor for a large-scale analysis, as is the case here.

For the slope calculation, a DEM resolution of 90 × 90 m was chosen for this study as a compromise between computational load and level of detail, and also because the dataset was released freely for scientific use in that specific resolution. The basis for proceeding with that resolution was a case study on the effects on slope distributions in Sweden and Austria of using higher resolutions (20, 50 and 90 m). In the case study, country-specific forest cover masks of higher quality were applied, and national projections of the data were produced, ensuring that errors were as small as possible in parts of the analysis that did not concern the resolution. The case study revealed a pattern of increased areas of steep forests with increased resolution. For Swedish forests, which mainly grow on flat terrain, the proportion of forest land with a slope over 20° was 0.7 per cent units higher when the resolution was 20 × 20 m compared with 90 × 90 m. Since Sweden only had between 0.3 per cent (lowest resolution) and 1 per cent (highest resolution) of forest land on a slope over 20°, the change of 0.7 per cent point corresponds to a percentage of ∼230 per cent.

For Austrian forests, which mainly grow on steep terrain, the proportion of forest land over 20° increased by almost 11 per cent points for the 20 m resolution compared with 90 m, but the percentage was only ∼25 per cent. The proportion of forest land on a slope over 20° changed from 40 to 50 per cent.

Eleven per cent points is a difference worth noting, however, the transition from 20 × 20 m to 90 × 90 m resolution does not mask the main patterns of the forest land distribution in slope classes, either within countries or in comparisons between them. Steeper areas within a 90 × 90 m pixel that only appear in data with finer resolution may be small enough to be avoided by machines during harvest. Even though the slope distributions are slightly inaccurate with the bigger pixels, the result can be just as valuable as a description of accessibility from a forest operations point of view, however, more on strategic level than the detailed operational planning level. Under the presumption that the relationship between share of steep forest land in a country and the error factor is linear, with Sweden at the 'flat' end of the scale (0.7 per cent point) and Austria at the 'steep' end (11 per cent points), one could make rough calculations to correct for the error depending on resolution for a specific country. However, the correction factor needs to be critically examined and this was not tested in any way by the authors of this paper.

Further research and use

This paper comes not only with the results (Table 2), but also free to use, actual raster data containing the values of the four slope categories per pixel (Lundbäck *et al*., 2020). Thus, researchers and practitioners from all over the world can make use of it. Future research is likely to be directed towards separating the forested areas that are used as production forests from natural conservation forests. To date, there has been no global dataset of plantations that enables such a separation; however for a specific country, geographic data that distinguish these different kinds of forests often exist. As an opposite approach, global data on undisturbed forest areas have been presented by Potapov *et al*. (2008) and a combination of that kind of data with the slope data from this study could lead to new insights in the physical properties of the undisturbed versus disturbed forest areas. An interesting topic for future research would also be to compare different forest cover datasets from different years by looking at forest areas country by country.

Since the slopes are presented only for forested areas in the dataset, the impact of slope on forest inventory variables such as primary production can be assessed at a large scale. Virtually, anything connected to forests that can be quantified at the global scale can be related to slope with the help of this dataset. Analyses of the historical impact of humans on forests, e.g. land use change and control of forest fires in different countries and continents, would be of great use to better understand the present state of our planet. For example, Figure 3 reveals that Europe has a low proportion of its forests on flat terrain compared with South America and Africa. Part of the explanation could be the overall terrain of the different continents; however it could as well be a symptom of humankind's impact on nature. It is known that, historically, lots of forest land has been converted to agricultural land in Europe; it is also evident that this process is now ongoing in, for example, South America. The world has seen huge forest fires during recent years and the challenges in fighting and controlling these fires are significant. The results of this study, specifically the dataset, could be used to estimate terrain accessibility and predict fire development in strategic planning of fire-fighting activities.

Finally, the primary area of use identified by the authors is forest operations internationally. Nevertheless, the dataset, as stated above, would certainly be valuable in the fields of geology, climate research and large-scale planning of forest conservation and management.

Conclusion

Global mapping of the distribution and area of forest land belonging to certain classes of slope has not previously been available. This study reveals that 82 per cent of the worlds´ forests grow on slopes $< 15°$, the distribution of forest between slope classes varies greatly between continents, and between the dominant wood-harvesting countries. The results of this study and the actual raster dataset can be accessed and utilized freely.

Supplementary material

The following supplementary material is available at *Forestry* online: The full, global, raster data containing pixel values of the four slope classes. The raster data can be downloaded in .tiff format (Lundbäck *et al*., 2020).

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Conflict of interest statement

None declared.

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The next technological development leaps regarding harvest operations are likely to involve increased level of tele-operation and automation and the aim was to evaluate the economic potential with such forwarding (tele-extraction). The overall result showed a potential for reduced costs of 6 to 19% in Swedish cut-to-length (CTL) forwarding if tele-extraction is applied. Today, 700 Mm^3 (37%) of the worldwide industrial wood volume is harvested with mechanized CTL, and 100-150 Mm^3 out of this might be suitable for tele-extraction.

Mikael Lundbäck carried through his graduate education at the Department of Forest Biomaterials and Technology, Swedish University of Agricultural Sciences, where he also earned his Master of Science in Forestry.

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