Subject review

Drivers of Advances in Mechanized Timber Harvesting – a Selective Review of Technological Innovation

Ola Lindroos, Pedro La Hera, Carola Häggström

Abstract

Timber harvesting operations vary greatly around the world, as do the adaptations of technology to the complex, locally variable conditions. Similarly, technological innovations occur as a response to a large number of different situations. This review examines the three main drivers considered to generate substantial technological change in mechanized timber harvesting: 1) availability of new technology, 2) demand for new products and 3) introduction of new regulations. The main focus is on Nordic cut-to-length harvesting using a harvester and forwarder, partly due to its advanced level of technology and partly due to the authors' backgrounds. Examining new technology, progress towards increased automation is highlighted with examples of entry-level products that provide computer-assisted motion control and semi-automation. Examples of unmanned machines and other high-level automation are also presented. Innovations in the field of bioenergy harvesting are presented as examples of advances addressing the demand for new products. Thus, illustrations span from harvesting of tree parts other than stemwood, to how such harvesting and transportation can be integrated into the traditional stemwood harvest. The impact of new regulations on technological innovation is demonstrated with advances aimed at reducing soil damage. Examples range from technical solutions for reducing soil pressure, to walking, flying and even climbing machines. Some predictions are given as to when certain advances can be expected to become reality. However, even though the main drivers are likely to change timber harvesting with new products and new rules, they will probably do so through a continued adaptation of technology to local needs.

Keywords: mechanization, automation, technological change, harvester, forwarder, CTL, logging

1. Introduction

Timber harvesting operations vary greatly around the world. Current practices adapt to complex, locally variable conditions in, for example, geo-physical conditions (terrain), management regimes, tree properties, climate, ownership structure, industrial infrastructures, labor availability and capacity, and societal rules for acceptable practices. As most harvesting operations are mechanized to some extent, we had three choices to cover the proposed scope for this invited paper: 1) attempting to cover all developments for all kinds of harvesting operations, 2) to focus only on a limited set of harvesting operations, or 3) to find a way to cover the scope in a generalized manner. The first two alternatives would, however, easily end up as a list of current technological advances and related predictions, such as those found in, for example, Hellström et al. (2009) and Vanclay (2011), and have a rather local or limited scope (e.g. Warkotsch 1990, Gellerstedt and Dahlin 1999, Guimer 1999, Harstela 1999). Lists of technological advances are naturally interesting, but become rapidly obsolete. Therefore, it was considered more relevant to address the mechanisms behind the progress of changes in the technology used for timber harvesting. However, that is obviously a great challenge, particularly in the limited space of an article format. The aim of the following paper is to highlight the driving forces that result in development of logging operations. A simplified framework for technological innovation is used to highlight the major general driving forces, for which examples of various interesting technical advances are presented. It should, however, be noted that examples have been selected based on their relation to the innovation drivers, and not on the authors' opinions of their potential (good or bad) viability.

2. Background

2.1 Definitions and limitations

In this paper, the focus will be on the technological part of timber harvesting. Technology is a well-used, but ill-defined, term in the sense that it also encompasses the know-how and tools to solve a practical task (e.g. Berry and Taggart 1994). Technological innovation spans across various research fields. Therefore, there is a variety of definitions, approaches and conceptual models depending on different viewpoints (e.g. Porter 1985, Garcia and Calantone 2002, Crossan and Apaydin 2009). Within this paper, we merely skim the surface of this wealth of research on technological innovation, and are aware of the simplifications that come with such an approach. Moreover, we will mainly focus on the technological part of timber harvesting development. Other work has examined labor, environmental and organizational aspects as important areas for improvement and development of mechanized forestry work (Silversides and Sundberg 1988, Heinimann 2007, Vancay 2011, Häggström and Lindroos 2016).

For the sake of clarity, we will use a simplified framework to highlight drivers for technological innovation. Nevertheless, there may be several drivers that independently or interactively result in a given innovation (Trott 2008). However, we have no intention to provide a full classification of drivers. Moreover, we will focus on timber harvesting in general, without addressing drivers for a given innovation.

We are aware that this kind of work will always be biased by the perceptions, values and expectations of the authors. Thus, there will be a significant focus on the Nordic CTL harvesting system with a harvester and forwarder, partly due to the fact that the authors are based in Sweden. However, the topic was deliberately chosen, since the Nordic CTL system is the most technologically advanced in the world, and thereby provides many good examples for future progress.

It should be noted that we will mainly use the term »mechanization« for technological innovations in timber harvesting operations.

2.2 Timber harvesting

At a high level, logging operations are part of a production system in which raw material is converted

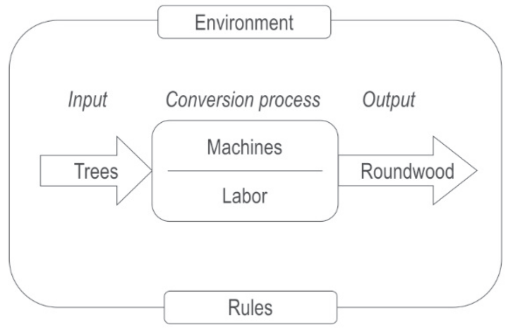

Fig. 1 Simplistic conceptual model of the production system of timber harvesting, with a conversion process designed and adapted to the local physical environment and rules

into products. Machines and labor are used for the production work, which is carried out whilst being affected by the local environment and complying with defined rules (Fig. 1). Appropriate labor standards have to be met, and the production system has to be profitable, on a macro scale (forest industry) as well as on a micro scale (individual firm). In other words, forest operations should be carried out in a way that is bio-physically effective, economically efficient, individually compatible, environmentally sound and institutionally acceptable (Heinimann 2007). This is common to other production systems, such as agriculture, mining and various kinds of factory-based manufacture. However, forest harvesting is different because, for instance, the work is done outdoors, in rough terrains and in remote areas.

Tree harvesting can be divided into five distinct work elements:

- ⇒ i – accessing/reaching the tree
- ⇒ ii – felling the tree
- ⇒ iii – debranching the tree
- ⇒ iv – cross-cutting the stem/tree
- ⇒ v – transporting the stem/log/tree to a roadside landing.

All five elements have to be carried out to enable delivery of roundwood logs to industry, but in what order and where they are carried out differ greatly. In fact, order and location determines what harvesting method is used. For instance, in cut-to length (CTL) harvesting, elements i – iv are carried out in the forest with the trees being felled, debranched and bucked into saw-logs and pulpwood lengths according to industry demands and quality features, before off-road transportation to the roadside. In full tree harvesting, tree felling is often followed by transportation to the roadside. The equipment used for harvesting defines the harvesting system. Various harvesting systems can be used to carry out a given harvesting method. The harvesting method CTL, for instance, can be achieved using a manual harvesting system (hand tools and animals), as well as using a fully mechanized harvesting system consisting of a harvester and forwarder (»Nordic CTL«).

Although there are many technical and transactional processes required to enable a full harvesting operation (see e.g. Heinimann 2007), our scope will be limited to tree conversion and off-road transportation.

2.3 Mechanization and automation

Mechanization here implies the use of machinery to replace human or animal labor. In order to understand the future of mechanized timber harvesting, it is necessary to understand the work involved, the mechanization process, and the drivers for mechanizing the work.

The mechanization process has a long history in forestry. From the 20th century, timber harvesting has progressed from being entirely manual and animal-powered to being fully mechanized and partly automated (Silversides 1997). This progress has been described as having six phases, from hand tools to feedback-controlled machines (Silversides 1997). However, with recent progress in automation technology, as observed in the fields of robotics, artificial intelligence and control systems, there are reasons to consider additional phases. In engineering, the degree to which a given task is automated is known as the Level of Automation (LOA). LOA serves to explain the ability of an algorithm to carry out a given automatic function, and how much human involvement there is in the process. Although the definition of LOA varies slightly, it is quite similar in most fields involving automation technology, such as robotics, artificial intelligence, and automatic control. Currently, there is a summary of five levels to educate the wider community about the step-wise progression of automation. A comprehensive definition of these levels is presented in IEEE (2000). For the sake of simplicity, we have provided an overview of LOA definitions in Table 1, together with examples related to a field familiar to most people: the automotive industry.

According to the LOA specifications, a chain-saw operator in combination with a farm tractor would be a harvesting system with an automation level of 0. In contrast, a harvester-forwarder combination would have an automation level of 2, if relying on automated functions such as automatic bucking and computer-assisted crane control.

The LOA enables comparisons of the state-of-the-art of automation in different industries. From the examples in Table 1, it can also be seen that automation level 3 is the highest level of automation currently available in modern engineering. Industries using equipment with an automation level of 3 include the automotive, robotics, and aerospace industries, where systems equipped with advanced artificial intelligence and embedded hardware are able to compete against human skills. While these autonomous systems are good under certain conditions (conditional automation), they are not good at everything, especially tasks such as learning, making maps, easily identifying objects, or other basic human abilities needed to accomplish more advanced operations. Recent developments in the areas of automation involve efforts to improve technology to an automation level above 3, but such developments will take years to reach maturity. Examples of research problems include learning from demonstrations, understanding spoken lan-

Table 1 Definitions and examples of Levels of Automation (LOA)

Level	Description	Human involvement	Example
0	Operator only	A human operator carries out all tasks	–
1	Operator assistance	Basic simplified control functions	A human operator carries out all tasks, but receives computer support simplifying some actions. Some examples include automatic transmission, cruise control, or anti-sliding control
2	Partial automation	Function-specific automation	Vehicles performing automatic self-parking, or automatic braking to avoid collisions
3	Conditional automation	Limited self-driving automation	A vehicle trained to drive in a city, but under constant supervision of a person. The ability to reason outside a given set of conditions is limited
4	High automation	Fully automated for a defined use	A vehicle trained to drive on its own, and not requiring supervision from a person, but will request help when a situation not covered in its database arises
5	Driverless	Fully automated for all situations	A vehicle driving on its own, not requiring any supervision, as it is able to make its own decisions and learn from its surroundings

guage, wireless network communication, and quickly identifying objects in images. Experts believe that an automation level of 4 will be achieved no earlier than the year 2025. Level 5, however, takes us into the more distant future, where autonomous systems may work by themselves in all situations, without any human supervision.

To describe it in words without using LOA nomenclature, a forestry machine must be capable of advanced localization and decision-making to achieve higher levels of automation. For instance, it should be capable of understanding where it is located, and the status and location of its parts. It should also understand the surrounding environment, and how the work objects (trees/stems/logs) are placed within it, their qualitative features, etc. Consequently, it should possess the computing ability to decide how to carry out the work, whether it is harvesting or transporting logs. In other words, an intelligent machine has to possess all the basic human operator abilities through sensing and computing. Before reaching full automation, semi-automated solutions and increased decision support can be expected first (Westerberg 2014, Hellström et al. 2009).

2.4 Technology innovation

Technology innovation in forestry has been described as following paradigm shifts (Heinimann 2007) and discontinuous evolution (Samset 1966), analogous to Schumpeter's (1942) process of »creative destruction«. This can be understood in the context of harvesting operations, locally or over larger areas, progressing and maturing in alternating leaps of evolution. It can also be seen as adaptations to various stimuli that force current operations to become new types of operations. Irrespective of which perspective is taken, it can be concluded that there would be no progress without some kind of driver for change. It is also understood that technological change is inevitable (Schumpeter 1942, Porter 1985), so it is just a matter of when and what drivers cause the change. Even though mechanization is applied within individual firms, in this paper the drivers are mainly addressed generally and at a forest industry level.

Technology innovations in general are also referred to as technology change, technology shift and technology development (e.g. Porter 1985, Tongur and Engwall 2014). In its most simplistic form, the process of technology innovation can be conceptualized as a linear process in which either a novel device or method is offered to the market (technology push) or market needs trigger innovations (market pull). Drivers for the innovation process can be either internal (e.g. available knowledge) or external (market opportunities or imposed regulations) (Crossan and Apaydin 2010). Hence, technology push corresponds well to the internal driver, whereas market pull corresponds to the two external drivers. Naturally, innovation processes are far more complex than described here (Trott 2008, Crossan and Apaydin 2010), but the simple approach is useful for structuring current technological advances. Thus, for the categorization purpose of this selective review, the following main drivers of harvesting mechanization will be used:

⇒ availability of new technology (*new technology*)
⇒ new needs of forest-based products (*new products*)
⇒ need for changes in current operations (*new rules*).

Below, we briefly describe the aspects (»triggers«) of the production system that are considered to trigger innovation processes, as shown in Fig. 1. It is understood that it will not be possible to provide a complete list of all possible triggers here, or their interactions with the main drivers. Thus, also the categorization should be seen as a simplification, for the sake of clarity.

Production costs, labor and technology can be seen mainly as triggers of the main driver of new technology (i.e. to improve current operations), whereas product value applies to the market's need for new products (i.e. to change operations to (also) produce new products). Last but not least, rules, labor and, to some extent, environment are triggers of the need for new operations (i.e. need to make the same products in a different way).

2.4.1 Production costs and product value

The need to decrease costs and/or increase product value is an essential driver of mechanization (e.g. Porter 1985). However, this economic aspect is funded in the economic system of constant growth, with expectations of steadily increasing production costs (e.g. salaries) but without a corresponding increase in product prices. Hence, the economic drivers of mechanization would be less obvious without the growth-based economy. Competitiveness might then be achieved in other ways. However, since there is no apparent viable alternative to a growth-based economy, economic performance can be expected to continue to be a highly influential driver of timber harvesting mechanization.

The value of the products determines the acceptable production costs. Thus, with high-value timber, expensive harvesting systems such as heli-logging are feasible, whereas stands with low-value trees may not even be possible to harvest profitably. Cheaper is naturally better, but high-value products enable larger profit margins and thereby other options for harvesting. Thus, the harvesting of certain products might be dependent on product price, and/or enabled through advances that decrease harvesting costs. Bioenergy harvesting is an example of that, with a profitability that is highly dependent on energy prices.

In financial value creation, there are two distinct results, depending on the factors limiting the production (Sundberg and Silversides 1988). With unlimited forest resources, forest operations are limited by other shortages, for example a shortage of labor, capital or markets. Then the focus is to maximize the profit per production unit (e.g. per machine), and so only harvest the high-value trees, leaving the low-value ones. There is room to expand operations, and development of new machine systems might enable the harvesting of unused forest resource. Historically, various production shortages have vanished, and eventually the forest resource has become the limiting factor. Western Europe is an example of this kind of transition (Sundberg and Silversides 1988). With limited forest resources, the operation revolves around maximizing the profit per area of forest. Measures to increase forest production are implemented, and as much forest as possible is harvested, using all profitable types of trees. With a limited amount to harvest, this implies that harvesting turns into a more-or-less steady state, with a limited opportunity to expand harvesting operations.

2.4.2 Labor

Protection of workers from harsh environments is an important trigger in the mechanization process. Labor-triggered mechanization involves the improvement of the work environment for health, safety and comfort reasons, but can also be economically-motivated since it expands the possible conditions that allow work (Häggström and Lindroos 2016). Thus, heated cabins and artificial light enable operations to take place in cold and dark conditions. Moreover, work from within a machine cab is safer than motor-manual felling with only a helmet for protection from falling trees. Indeed, mechanization has been shown to substantially improve work safety in logging operations (Axelsson 1998).

While operators in general, and expert operators in particular, are becoming difficult to recruit (Bernasconi and Schroff 2011, Baker and Greene 2008), a shortage of qualified labor highlights the need for usable, user-friendly machines in the future (Häggström and Lindroos 2016), both to enable a larger part of the available workforce to operate machines and to shorten the lengthy time needed to become proficient in the operation of, for instance, harvesters (Purfürst 2010). More productive machines, as well as some automation initiatives, are also a means to address the labor shortage, since they can enable a single operator to harvest larger quantities.

It is traditionally understood that machines enable operators to work faster, longer and with more strength. However, there are areas where the operator's abilities limit the operations. To operate a harvester or a forwarder efficiently involves considerable cognitive work (Häggström et al. 2015), and often over very long work shifts. One example is the complex coordination required to seamlessly issue joystick commands resulting in motions of the crane and vehicle. Precise control of the many crane links and the harvester head usually requires a series of expertly coordinated movements that can prove tiring over time. Hence, computer-based assistance could improve performance and reduce operator strain.

Legislation of labor health and safety is also an important trigger for technological innovations, with vibration and noise reduction laws being typical examples (Andersson 1988).

2.4.3 Technology

Technological advances in society present an abundance of possible applications for forestry. However, with limited numbers of machines sold annually (compared to agricultural and construction machines, for example), forest machine manufacturing is a tough business with scarce resources available for product development. Ironically, for a given size of harvest, even fewer new machines will be needed the more productive they are. Nevertheless, there is no shortage of technological advancements within forestry and related fields. With an active forestry industry, the question is not only whether things could be done differently but whether a change would be beneficial regarding costs and other important aspects. In fact, most technological innovations do not result in a change in operations (c.f. Porter 1985).

Put simply, there are two ways to cope with the challenges of low production numbers of forest machines: To produce highly specialized, advanced and very expensive machines (e.g. harvester and forwarder), or general, basic and rather cheap machines (cf. Gellerstedt and Dahlin 1999). Both are able to do the job, but might differ in usefulness, labor competence, safety, product quality and cost-efficiency under various conditions. To some extent, the choice might be the result of differences in the machine capabilities to handle the specific trees and the industrial requirements (e.g. CTL versus full tree). Furthermore, the choice is also likely to be substantially influenced by whether the machine production is a limiting factor or not.

Some of the challenges in forest operations correspond to military and space research and development, in terms of developing robust machines capable of navigating rough terrain. However, military and space-oriented research and development receives substantially higher investments. Thus, forest mechanization is more likely to benefit from military and space innovations than the other way round.

2.4.4 Environment

Development is largely triggered by the challenging environment machines have to cope with during work. If the forest operations are carried out in an intense, agricultural-like fashion, the demands are somewhat similar to agricultural machines, in terms of the potential to alter the area of operation. On the other hand, in »close-to-nature« forestry, forestry machines should ideally manage to operate in rough environments without changing the environment to needs and without damaging that environment. Thus, technical development aims to construct machines capable of navigating rough, soft and steep terrain, while simultaneously being able to handle the trees they are processing (Billingsley et al. 2008). This requires very robust and, possibly, very advanced machines (cf. 2.4.3). Climate change might change local environmental conditions, which might trigger technological innovation. However, given the multitude of existing machine systems adapted to various local conditions, it might also only trigger a change to other existing technology.

2.4.5 Rules

Rules define the framework that dictates how forest operations are permitted to be carried out, and derive from laws, regulations and certification schemes as well as informal rules resulting from areas such as landowner objectives and social values. Such rules vary geographically and over time. Radical changes of rules could force forestry to either adapt, or to shut down.

Thus, machines must be able to cope with the given operating conditions, and also avoid unacceptable effects on the workforce and the environment. Labor health and safety rules have been important triggers for technological innovations in mechanized harvesting (Andersson 1988). With a continuing focus on environmental concerns (Ollikainen 2014), environmental rules are gaining in importance as a trigger for technology innovation, with the aim of better meeting the rules on avoidance of environmental damage caused by mechanized harvesting. Minimizing the damage to soil is probably the most common requirement (Cambi et al. 2015). This is challenging even when leaving the machines out of the picture, since the weight of the harvested trees alone is several hundred tonnes per hectare. To transport such loads on natural soil without causing damage is naturally challenging, encouraging small (i.e. light) loads and careful driving. Economic considerations, on the other hand, call for large loads and high speeds. However, the same considerations also imply the avoidance of soil damage, since driving on soft ground reduces speed and increases fuel consumption. Additionally, a machine that becomes stuck in the mud results in both severe time losses and possible machine damage.

3. Current technological innovations

As demonstrated by the many »triggers« listed above, together with those not mentioned, it is naturally difficult to single out one that will be the main source of future developments. This is especially true since there is such variability in forest operations worldwide, with variation in expectation of future developments. However, based on current trends, it is considered that the three specified main drivers, either individually or in combination, are currently responsible for producing significant advances in timber harvesting. Below, we present examples of various technical progress that can be seen as responses to the main drivers.

3.1 New technology – automation

The use of the term *new* technology is debatable when applied to automation, since the interest in automated forest operations developed soon after the first mechanization. Examples of this interest are, for instance, the IUFRO Div. 3 symposium on »Forest Harvesting Mechanization and Automation« in 1974 (Silversides 1974), and a Swedish workshop on »Automation and Remote Controlling of Forest Machinery« in 1983 (Uusijärvi 1985). More than a decade later, ideas to produce fully automated, but supervised, logging systems were described (Hallonborg 1997). More recent publications have summarized the state-of-the art and the possible ways ahead (e.g. Hellström et al. 2009, Parker et al. 2016). Indeed, over time there have been plenty of innovative projects that have attempted to automate forest operations. So far, however, few have successfully reached the market.

3.1.1 From automation level 0 to level 2

Among the forest machines being operated conventionally, Nordic harvesters are the most advanced ones. Nevertheless, a harvester still requires almost complete operator input. For instance, the operator has to control the many crane links and the harvester head precisely using a series of expertly coordinated movements. Computer-assistance is available for bucking, in the form of an automated decision support system that suggests value-maximizing log lengths and assortments. Nonetheless, mechanized harvesting, even with a harvester, can be considered to be at an automation level of 0. However, there are efforts to introduce LOA 1, mainly by providing computer-assistance for motion control. Over recent years, several entry-level products with automation level 1 technology have appeared on the market, such as:

⇒ **Cranes equipped with motion sensors**, providing entry-level products that use improved motion control software (Cranab 2015)

⇒ **Basic boom-tip control**, where the operator receives computer support to carry out expertly coordinated end-effector movements with less effort (John Deere 2013)

⇒ **Reduced crane vibrations**, making the operation of the crane more comfortable (John Deere 2013, La Hera and Ortiz Morales 2015)

⇒ **Active suspension**, improving the ride quality over uneven terrain (Ponsse 2017)

⇒ **Hydraulic valves equipped with digital electronics**, providing entry-level products that use improved software for dynamic motion control of the machine (Mathworks 2016, Danfoss 2015).

Among the examples listed above, the concept of boom-tip control has long-been anticipated. Finally, in 2013, John Deere became the first forestry machine manufacturer to produce smooth and intelligent boom control (SBC&IBC) systems for forwarders. By now, John Deere IBC system has expanded towards harvesters as well. At the same time, Cranab released their »Cranab Intelligent System« (CIS), a system comprising of sensors integrated in the cranes. Simultaneously, different producers of hydraulic valves have released products involving sensors and computers, resulting in a technology known as »intelligent valve«. This combination of sensors in cranes and intelligent hydraulics provides sufficient technology for more machine manufacturers to develop their own automated crane functions. All these examples are entry-level solutions, opening the door to automation. Various concepts for automated crane functions have been tested and/or implemented in test beds (Ortiz Morales 2015, Hansson and Servin 2010). For instance, the number of different boom tip-control algorithms that can be implemented on a machine is huge, because these algorithms respond to selectable optimization options such as minimum kinetic energy control, minimum potential energy control, failure recovery, strength optimization and fuel consumption (La Hera 2011, Westerberg 2014, Ortiz Morales 2015).

The five examples listed above show how current developments are starting to consider the hardware requirements and initial software needed for automation. However, transitioning towards this technology will not be easy, because developing software and redesigning all hydraulics and embedded electronics for forestry machines will be challenging, particularly when trying to make a profit in this process. Therefore, entering the world of automation level 1 will be a difficult step, and we expect that it will take the forest industry at least 15 years to complete it. In those years, however, improvements can be expected in control performance, particularly precision boom movements using motion sensors and operator-assistance software. Creating smarter machine movement will rely on libraries containing specific automated functions, many of which have been demonstrated by scientists over the past few years (Ortiz Morales et al. 2014, La Hera and Ortiz Morales 2015). However, the operator will still be an essential part in the correct use of these features, and many difficult movements will still be carried out manually.

At the later stages, operators are expected to take advantage of advanced computer vision systems in this emerging human-machine partnership. This is likely to enable new ways of controlling the machine, with the operator choosing from actions suggested by the computer (Fig. 2). Consequently, expertly coordinated automatic movements will harvest and collect trees, dramatically increasing productivity and reducing operator fatigue. At this point, the industry will have reached automation level 2. The operator will coordinate the tasks of the machines and, by then, technology will enable the possibility of operating machines with many cranes, because cranes will be able to operate autonomously for short periods (Figs. 3 and 4)

Fig. 2 Augmented reality will be used in future machines, presenting the possibility to select trees by, for instance, pointing to their location (Photo courtesy of Luu et al. 2016)

Fig. 3 Technology will enable a single operator to control many cranes simultaneously, because cranes will operate autonomously for short periods (Photo courtesy of Mellberg 2013)

(Ersson et al. 2013). Nonetheless, most planning tasks will be carried out by people, who will also carry out tasks manually in very difficult situations. For both of these cases, the user interfaces will become simpler, because many unnecessary buttons and joysticks will be replaced by software algorithms. On the other hand, an interface for controlling several cranes will also add complexity.

3.1.2 Automation level 3 and beyond

From automation level 2, it will be possible to rethink fundamentally how machines are designed. This might enable further increases in work and fuel efficiency. Surpassing automation level 3 will produce machines that do not necessarily need to be manned (Fig. 4). Thus, designing smaller and lighter machines will become possible. Having machines without an on-board operator will remove the need for comfortable, ergonomic cabs. Therefore, machines will be cheaper to manufacture, and most of the costs will come from the hardware, software, number of cranes, and power source. Machines of this kind will have better movement capabilities, better power sources, and use dynamic motion control, all of which will contribute to the overall energy efficiency. Later still, machines may begin to have bio-inspired designs (Fig. 5), because designs of this kind could improve the efficiency of off-road navigation and reduce soil damage (Winkler et al. 2015).

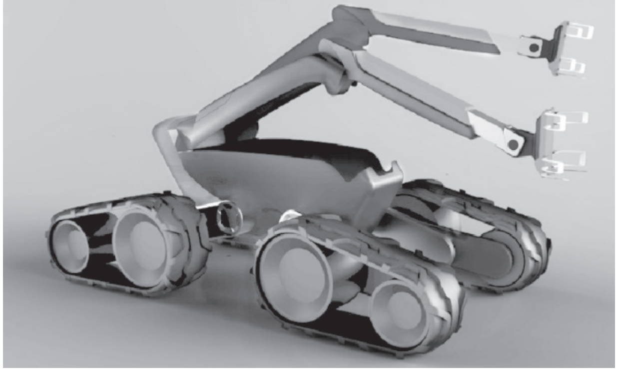

Fig. 4 Having machines without people will remove the need for comfortable, ergonomic cabs; Automation might also enable several cranes to operate on the same machine (Photo courtesy of Leijon 2016)

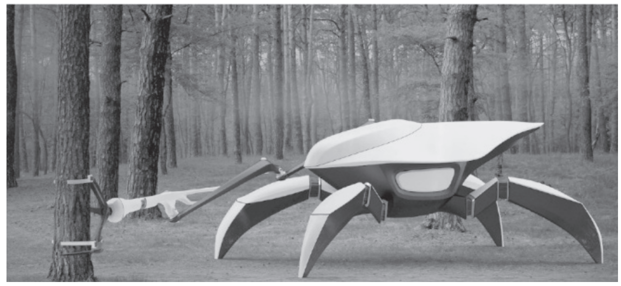

Fig. 5 Automated machines might eventually begin to have bio-inspired designs, to improve the efficiency of off-road navigation and reduce soil damage (Photo courtesy of Ludwign 2016)

This technological progress will enable a re-structuring of timber harvesting operations, because it will present the opportunity to run forest operations with practically no people in the forests. In essence, these technological advances will enable the complete automation of the forest operation. Operators will initially be located in a command center nearby the machines, but eventually they will be moved far away, close to cities. Hence, progress is expected to follow developments in, for instance, the mining industry, and in harbor and airport management.

Past and current forest machine developments have indeed considered many of the scenarios mentioned above. For instance, machines without cabs have been described (Bergqvist et al. 2006, Konrad 2017), machines with efficient (hybrid electric) power sources have been designed (Elforest 2017), and initial ideas for bio-inspired designs were presented two decades ago (Billingsly et al. 2008).

3.1.3 Challenges

The challenges presented in achieving automation levels 0 to 2 relate to integration of sensor technology and development of control systems, to control machine movements efficiently. The research into teleoperated forestry vehicles (Milne et al. 2013, Westerberg and Shiriaev 2013, Bergkvist et al. 2006) and unmanned self-navigating vehicles (Ringdahl et al. 2011, Hellström et al. 2009, Vestlund and Hellström 2006) have highlighted the challenges in making sensors perceive and understand the structure of »natural« forest land. Moreover, development is needed to enable automatic detection of qualitative features of the trees and logs. Such capability will be required to enable automated decisions on which tree to harvest, as well as to enable automated value-optimized bucking.

Automated machines must be proven safe to humans and animals residing near the operating site. Thus, safety issues might delay implementation. On the other hand, automation can also be prompted by operator safety, as exemplified by the use of tele-operated ground-based machines on steep terrain (Milne et al. 2013). Increased automation might also influence an operator's capacity to interact with automated operations. With increasing automation, operators receive less on-the-job training in manual procedures, thus reducing their knowledge and, specifically, their skilled expertise. Insufficient operator knowledge and ability to override the automation, when necessary, could lead to significant effects on both safety and productivity (Amalberti and Deblon 1992).

Other problems to be solved before successfully implementing teleoperation are the problems of information presentation and visibility. For instance, the viewing angle and abstraction level have been shown to affect operator performance (Westerberg and Shiriaev 2013). When introducing two cranes, they will be positioned in new ways that might restrict the operator's line of view. If not carefully designed, this may result in musculoskeletal injury and accidents if the operator has to alter their position to see properly (Eger et al. 2010, Thomas et al. 1994, Hansson 1990). Moreover, it may have a negative effect on operator performance (Häggström and Lindroos 2016).

3.2 New products – bioenergy harvesting

When an operation is expected to produce new products, it may be influenced by the adaptations required to produce the new product. The products from timber harvesting are traditionally roundwood of various lengths, with the production system being able to meet the industrial need for specific dimensions and quality features. However, operations might have to change to meet the requirements of new industries that may be interested in chemical content and not the dimension or structure of the wood (Ollikainen 2014). It is still too early to predict how such new products might influence silviculture and harvesting. Therefore, the focus will be on another »new« product – to use forest biomass for energy. Burning wood is not new but, nevertheless, it has received renewed attention recently (Björheden 2006, Hakkila 2006). The drive to replace fossil fuels introduced a desire to use increased amounts of forest resources for energy. However, the forest industry had no unused surplus to redirect apart from residuals from conventional forest products, which were already being substantially used in energy production. Thus, the focus turned to the use of hitherto unused parts and types of trees, to avoid competition between traditional products (that naturally could be burnt) and bioenergy assortments (Helmisaari et al. 2014). Even though this new feedstock was introduced in response to the oil crises during the 1970s and the expected fiber shortage, it never became part of the product range that conventional mechanized harvesting was adapted for (Björheden 2006). The recently renewed interest in forest-based bioenergy has resulted in substantial recent research. In fact, this bioenergy-oriented effort has most likely formed the majority of forest engineering research in the new millennium, and has contributed to maintaining, or even increasing, the number of people active in forest engineering research.

Some examples of areas investigated are machines and methods for harvesting of stumps (e.g. Spinnelli et al. 2005, Lindroos et al. 2010a, Berg et al. 2012), branches and tops (also known as logging residues or slash) (Wolf et al. 2014) and small trees (Jundén et al. 2013, Bergström and Di Fulvio 2014, Hanzelka et al. 2016). Interest has also increased in biomass production from the border between agricultural land and forestry, in the form of short-rotation woody crops for energy purposes. How such plantations should be harvested has sparked interest in both new use of traditional forest and agricultural machines, as well as the development of new machines (Spinelli et al. 2012b, Ehlert and Pecenka 2013).

The bulkiness of the material, relative to roundwood, is a challenge especially for transportation, since it gives low payloads. Since payment is given per energy unit in the material, and energy content is related to (dry) mass, low payloads are related to low profit per transport round. This has been addressed by various means that have tried to increase payload, mainly by various attempts to densify the material (e.g. Lindroos et al. 2010b, Bergström et al. 2010, Wolfsmayr and Rauch 2014, Wästerlund and Öhlund 2014, Nuutinen and Björheden 2016, Manzone 2016).

In addition to harvesting technologies, it should be mentioned that interest has also been shown in how to process the material into sizes and qualities suitable for combustion (e.g. Spinelli et al. 2012a, Eriksson et al. 2013, Anerud et al. 2016, Nuutinen et al. 2016) as well as in new analytical methods, aiming to find, define and measure the new products (Routa et al. 2015, Fridh et al. 2014, 2017).

An important aspect of research is to integrate the products i.e. how to combine the harvesting of roundwood and bio-energy assortments (e.g. Berg et al. 2014, Joelsson et al. 2016).

Besides operational aspects, the effects of bioenergy harvesting on site productivity, ecology and climate change have been subject to a good deal of research (e.g. Magnusson 2016, Bouget et al. 2012, Achat et al. 2015, Egnell et al. 2015).

The dependency on energy price and availability of industry residues have resulted in a current downturn in the harvesting of forest biomass in the Nordic countries. Nevertheless, we expect that energy-related and other new products will result in a substantial change in current timber harvesting within the next 10 to 20 years.

3.3 New rules – avoidance of soil damage

Although rules differ substantially geographically, the general trends indicate a continuous increase in environmental consideration necessary during timber harvesting, and especially with regards to the avoidance of soil damage.

Over time, there has been plenty of development aimed at minimizing and, ultimately, avoiding negative impact on soil. However, financial as well as practical restrictions have limited the success for most development projects with this as their main driver. The approaches applied can be split into at least three separate groups: those trying to minimize driving by improved planning, reinforcing the soil and altering the machine usage. The first two are covered only briefly here, whereas the latter is addressed in more depth.

3.3.1 Improved planning

Soil damage is likely to be reduced if the operator could be guided into making better choices of where to drive, and how often. Decision support systems, such as the development of LOA 1, may play an important role in this process. Algorithms to extract the best (driest) route are under development (Mohtashami et al. 2012, Flisberg et al. 2007), but this is a complex problem if trying to produce an optimum route for the full operation of, for example, forwarding a stand while simultaneously considering both environmental and economic aspects. However, progress in remote sensing as well as sensor technology is rapidly advancing the frontier of inputs to such planning systems (Lideskog et al. 2015, Ågren et al. 2014, Pohjankukka et al. 2016).

3.3.2 Reinforcing the soil

Soil damage from machine traffic can be reduced by applying various materials to the soil surface (Cambi et al. 2015). Most commonly, the logging residues from CTL harvesting (branches and tops) are collected onto the strip-road, and the created »brush-mat« increases the carrying capacity of the soil. The thicker the layer, the better the capacity, but with an energy-based demand for logging residues, there is a trade-off between usage for energy and soil damage avoidance. Other materials and structures have also been tested as soil reinforcement. However, they have to be transported to the site, laid out, and possibly also removed. Thus, if found successful in preventing soil damage, they have often been found to be too costly to use, and particularly in comparison to the use of logging residues.

3.3.3 Alternations of machines and mode of transport

Machines can be modified in several ways to reduce soil damage, and the various aspects of such damage. One approach is to reduce the pressure of the machine on the soil (Cambi et al. 2015). The bearing capacity varies between soil types, as well as within soil types over time (due to variables such as weather conditions). However, the less pressure applied on soils, the less damage is caused. Since the pressure is the result of the mass distribution on the area in contact with the soil, both those aspects can be altered to achieve pressure reduction. Increased area for wheeled machines can be achieved by, for instance, the use of additional wheels (Ala-Ilomäki 2011) or bogie tracks (Edlund et al. 2013a, 2013b). Tracked machines are another option, and they also tend to be more suitable for working on steep terrain (Visser and Stampfer 2015).

Lower mass can be achieved by the use of small machines. However, small machines and the normally related small loads, result in more journeys for a given volume of product. Thus, there is a trade-off between the load carried on a single journey of the vehicle, and the total load of all journeys required to move all the products harvested (Cambi et al. 2015, Solgi et al. 2016).

The mass of a machine can also be reduced by the use of lightweight materials, to achieve a good relationship between the machine's laden weight and its load capacity (i.e. a high load index). However, recent developments have produced machines with lower load indexes than before. On the other hand, the heavier, more robust machines are also more durable (Nordfjell et al. 2010). To equip the main machine with a trailer (Lindroos and Wästerlund 2014, Manzone 2015) is an option for increasing the load index and reducing the soil impact.

Another approach is to address the ground-based mode of transport. Here we can distinguish between new ground-based solutions, and those not ground-based. Among the ground-based solutions, there are

Fig. 6 The Portalharvester, with its two tripod legs and sliding cab (Photo courtesy of Christian Knobloch)

some walking machines designed for timber harvesting, such as the PlusTech Ltd. (now John Deere Ltd.) harvester of the 1990s (Billingsly et al. 2008) and the recent Portalharvester (Fig. 6) (Anon. 2013, Erler 2013). The benefits of walking machines, compared to wheeled and tracked machines, include the improved negotiation of certain obstacles and terrains, although such machines have limitations in terms of complexity, fuel consumption, etc. (Billingsly et al. 2008). The benefit from a soil damage perspective is that only soil compression points are created and not continuous tracks. Thus, avoidance of tracks prevents the risk of blocking off roots and water from certain areas by walls of compacted soil.

Aerial logging is another option, with several conventional systems available, such as cable yarding (Lindroos and Cavalli 2016) and heli-logging (Bigsby and Ling 2013). Balloons were suggested until the 1970s (Peters 1973), whereas the recent advances in unmanned aerial vehicles (UAVs) suggest usage in forestry for various monitoring purposes (Torresan 2016). However, given the large loads needed to be carried when harvesting or extracting trees, current UAV technology is unlikely to be used for such purposes, at least in the near future.

Tree-based transportation is a solution that lies between ground and aerial transportation. Indeed, the tree-to-tree moving robot developed in New Zealand was inspired by how monkeys move (Parker et al. 2016). As with aerial systems, it would avoid soil damage and would not be influenced by how rough or steep the terrain is. However, as with UAVs, the work that can be carried out by climbing machines is probably limited in relation to harvesting purposes. To develop a tree-to-tree moving machine capable of tree felling might be feasible. However, the weight of logs that could be carried while climbing is probably limited.

4. Discussion

As can be clearly seen by this limited selection of ongoing development related to mechanized harvesting, there is no shortage of innovation. There is also a great variation in innovation focus, which is to be expected since current timber harvesting practices are a complex mixture of adaptation to complex, locally variable conditions. Future development will be influenced by the necessity for local adaptation, and there is no »perfect solution« in sight (besides some very futuristic scenarios as described below). Thus, in this paper, we have not tried to cover the full range of timber harvesting scenarios. Instead, we have attempted to provide an understanding of the drivers of development. We have chosen a rather simplistic approach, and focused on what we perceive are the main drivers that will lead to substantial change in the conversion process (Fig. 1). Naturally, the innovation process is far more complex (see, for instance, Crossan and Apaydin 2010) and, depending on the point of view, there are other ways to categorize the involved drivers. For instance, Guimier (1999) chose to define another set of drivers, some of which are what we have called triggers. We have also chosen to have a very narrow scope, with the focus on machine development, even though we acknowledge the complex network-like structure required to run modern harvesting operations efficiently (e.g. Heinimann 2007). Simple models facilitate understanding of complex systems, but require that the simplifications are duly handled when attempting to turn the understanding into action. The limitations of the study allows for clarity at the expense of coverage. Nevertheless, the chosen scope can be considered useful for highlighting how innovation is the result of various drivers, among which some are responses to external needs to adapt current operations, whereas others originate from the internal requirement to improve operations constantly.

Following this line, new technology constantly emerges, and can be perceived as being pushed into the timber harvesting operations that already work (more or less) as desired. Possible advances might be intriguingly fascinating, but do not necessarily originate from a well-defined need that requires substantial change. UAV development is one such current example: the technology exists and now it is being investigated for possible forestry usage (Torresan 2016). Another example is the recent concern over increasingly stagnating productivity in Nordic harvesting operations that has triggered a new development focus. However, it is easy to desire increased productivity and profit, but virtually impossible to achieve it without a well-defined idea about a method of doing so.

With a general, but ill-defined, need for efficiency improvements, it is easy to wait impatiently for rapid advances. However, there is no need for a risky search for change if the actual need is small. Thus, it is important to analyze thoroughly whether or not innovations will render actual and important improvements (e.g. Lindroos et al. 2015). What problems are solved, and what might be created? Otherwise, innovative technical solutions lacking operational viability might be supported (c.f. Lindroos 2012, Ringdahl et al. 2012) at the expense of more relevant development projects, and might even become burdens for the entrepreneurs that start using them.

New technology will slowly but surely change current timber harvesting operations. Until we see substantial advances in automation, however, there will be a limited effect on the conversion process (Fig. 1). The process will be the same, but with different machines and slightly differently structured operations. However, with unmanned machines, there will be a substantial change, of a magnitude similar to when powered tools and machines were brought into the process. However, automation will advance slowly in forestry due to the challenges specified above and, also, because it is a response to the general need for improvement of ongoing, functional operations.

As emphasized above, slowly decreasing profit margins have not proven to be a reliable driver for substantial and fast changes to current operations. In contrast, this and other »small« drivers are likely to result in slow change. That is not to say that such development is bad in any way, but it might fail to meet expectations.

With a well-defined problem, as with new products and new rules, the needs for change are more obvious. The old operations should be adapted to accommodate new conditions, to provide the new desired products to make more profit and to meet new rules or close the business down. The challenge is then to find the most appropriate changes.

Energy wood has (again) complemented the product mix of pulpwood and sawn wood, and has thereby substantially contributed to recent efforts in technical development. Other, less conventional, products can be expected in the form of new usage of trees, and in alternative/complementary products such as biochemicals (Ollikainen, 2014). In fact, the CTL system might not prove to be the most efficient one when the number of products starts to increase, due to the logistic challenges of handling numerous (and possibly differing sizes of) products (cf. Harstela 1999). Instead, it might prove more efficient to extract trees to a central point (terminal or log yard), where the various products are created, collected and distributed. If it is relevant to collect small and rather unusual materials, it is likely to be done efficiently at sizeable facilities. It is reasonable to suppose that CTL might not be efficient in such a supply system, but that will depend on the price relationship between traditional and new products, as well as on how well the extraction of new products will fit the current CTL system. As an example of how new products might influence operations, it is noted that in the Nordics, where logging residues are used for energy, the tops and branches have to be collected separately from the logs (i.e. an adaption). With full tree harvesting on the other hand, both logs and logging residues end up by road-side even if just aiming for the logs.

A completely new product may be in the form of eco-system services, in the sense that future forestry is likely to have the responsibility of creating, balancing and maintaining various kinds of such services. The concept is far from operationalized, but it is likely that there will be a trade-off between various eco-system services. It is also likely that new business models will be developed, in order to form eco-system services into a product that is paid for when being produced (or charged for when being consumed). Thus, this might require forest operations to produce other eco-system services rather than supplying forest biomaterials. The fact that timber harvesting commonly integrates restoration and creation of social and ecological forest environments (e.g. Gustafsson et al. 2012) is an indication of how this might proceed.

Irrespective of the size of jumps in technological advances, those expected over the next few decades will most likely be seen as fine tuning of current timber harvesting operations. However, to stretch this future-oriented prose a little, two truly drastic advancements that would alter operations substantially will be mentioned. To defy gravity and to be able to teleport would alter the laws of physics that currently define and limit timber harvesting operations.

If machines, trees and logs could be handled without the effect of gravity (i.e. to have them fly in new ways), substantial advances in transportation-related work could be expected. Most of such advances are described in the section about avoiding soil damage. The even more tantalizing step would be the possibility of teleportation. With that, trees could be disintegrated in the forest, teleported to a desired location and materialized into a desired shape. Thus, trees would be the raw material, and the teleportation would be the transportation and possibly also the conversion process. Teleportation would naturally be a paradigm shifter for mankind, in so many more aspects than enabling new timber harvesting operations.

Teleportation is not likely to happen for many decades or even centuries, but there have been some intriguing advances, although on a scale substantially smaller than timber (Pirandola et al. 2015).

As with all studies that aim to predict the future, this study has some strengths and many weaknesses. We can only present our best educated guesses and speculations, from our limited viewpoint. However, although we are aware that there might be a multitude of other ways of viewing the here-and-now and the possible future, we have tried to provide a somewhat general view of the advances in already highly mechanized operations. We have great hopes for the advances over the coming decades. Moreover, we are curious to see what changes will arrive and what will be their driving forces – and how far from our predictions they will be.

5. References

Achat, D.L., Deleuze, C., Landmann, G., Pousse, N., Ranger, J., Augusto, L., 2015: Quantifying consequences of removing harvesting residues on forest soils and tree growth– A meta-analysis. Forest Ecology and Management 348: 124–141.

Ågren, A.M., Lidberg, W., Strömgren, M., Ogilvie, J., Arp, P.A., 2014: Evaluating digital terrain indices for soil wetness mapping – a Swedish case study. Hydrology and Earth System Sciences 18(9): 3623–3634.

Ala-Ilomäki, J., Högnäs, T., Lamminen, S., Sirén, M., 2011: Equipping a conventional wheeled forwarder for peatland operations. International Journal of Forest Engineering 22(1): 7–13.

Amalberti, R., Deblon, F., 1992: Cognitive Modeling of Fighter Aircraft Process-Control – a Step Towards an Intelligent on-Board Assistance System. International Journal of Man-Machine Studies 36(5): 639–671.

Anerud, E., von Hofsten, H., Eliasson, L., 2016: An alternative supply system for stump biomass – coarse grinding combined with sieving of the produced hog fuel. International Journal of Forest Engineering 27(3): 109–114.

Anon., 2013: Vollmechanisiertes Fällen und Aufarbeiten mit Portalharvester; Rücken mit Flachlandseilkran (Fully mechanized harvesting with the portalharvester, transporting with flat-land cable crane). AFZ-DerWald 18/2013: 50–59.

Axelsson, S.-Å., 1998: The mechanization of logging operations in Sweden and its effect on occupational safety and health. International Journal of Forest Engineering 9(2): 25–31.

Baker, S.A., Greene, D.W., 2008: Changes in Georgia's Logging Workforce, 1987–2007. Southern Journal of Applied Forestry 32(2): 60–68.

Berg, S., Bergström, D., Athanassiadis, D., Nordfjell, T., 2012: Torque required to twist and cut loose Scots pine stumps. Scandinavian Journal of Forest Research 27(8): 724–733.

Berg, S., Bergström, D., Nordfjell, T., 2014: Simulating conventional and integrated stump-and round-wood harvesting systems: a comparison of productivity and costs. International Journal of Forest Engineering 25(2): 138–155.

Bergkvist, I., Nordén, B., Lundström, H., 2006. Besten med två virkeskurirer – studier av prestation och bränsleförbrukning (The Beast with two shuttles – studies of performance and fuel consumption). Arbetsrapport; no. 616, Skogforsk. Uppsala, Sweden. (In Swedish)

Bergström, D., Nordfjell, T., Bergsten, U., 2010: Compression processing and load compression of young Scots pine and birch trees in thinnings for bioenergy. International Journal of Forest Engineering 21(1): 31–39.

Bergström, D., Di Fulvio, F., 2014: Evaluation of a novel prototype harvester head in early fuel-wood thinnings. International Journal of Forest Engineering 25(2): 156–170.

Bernasconi, A., Schroff, U., 2011: Professions and Training in Forestry. Results of an Inquiry in Europe and northern America. Bern: Federal Office for the Environment. Retrieved from www.umwelt-schweiz.ch/ud-1052-e

Berry, M.M., Taggart, J.H., 1994: Managing technology and innovation: a review. R&D Management 24(4): 341–353.

Bigsby, H., Ling, P., 2013: Long-term productivity of helicopter logging in Sarawak. International Journal of Forest Engineering 24(1): 24–30.

Billingsley, J., Visala, A., Dunn, M., 2008: Robotics in agriculture and forestry. In: Springer handbook of robotics, Springer Berlin Heidelberg, 1065–1077 p.

Björheden, R., 2006: Drivers behind the development of forest energy in Sweden. Biomass and Bioenergy 30(4): 289–295.

Bouget, C., Lassauce, A., Jonsell, M., 2012: Effects of fuelwood harvesting on biodiversity – a review focused on the situation in Europe. Canadian Journal of Forest Research 42(8): 1421–1432.

Cambi, M., Certini, G., Neri, F., Marchi, E., 2015: The impact of heavy traffic on forest soils: a review. Forest Ecology and Management 338: 124–138.

Cranab, 2015: Forwarder cranes with world leading technology. www.cranab.se/site_specific/.../05/cran_fc_2015-eng-lr.pdf. Retrieved 2017-01-24.

Crossan, M.M., Apaydin, M., 2010: A multi-dimensional framework of organizational innovation: A systematic review of the literature. Journal of management studies 47(6): 1154–1191.

Danfoss, 2015: Robust and efficient in harsh environments. http://www.danfoss.com/technicalarticles/cf/robust-and-efficient-in-harsh-environments/?ref=17179879857#/ Retrieved 2017-01-24.

Konrad, 2017: Ground Carriage PULLY. Retrieved from http://www.forsttechnik.at/en/products/ground-carriage-pully.html. Retrieved 2017-01-24.

Edlund, J., Keramati, E., Servin, M., 2013a: A long-tracked bogie design for forestry machines on soft and rough terrain. Journal of terramechanics 50(2): 73–83.

Edlund, J., Bergsten, U., Arvidsson, H., 2013b: A forest machine bogie with a bearing capacity dependent contact area: acceleration and angular orientation when passing obstacles and drawbar pull force and free rolling resistance on firm ground. Silva Fennica 47(3): article id 1017.

Ehlert, D., Pecenka, R., 2013: Harvesters for short rotation coppice: current status and new solutions. International Journal of Forest Engineering 24(3): 170–182.

Eger, T., Godwin, A.A., Henry, D.J., Grenier, S.G., Callaghan, J., Demerchant, A., 2010: Biomechanics and evaluating the workplace. Why vehicle design matters: exploring the link between line-of-sight, driving posture and risk factors for injury. Work 35(1): 27–37.

Egnell, G., Jurevics, A., Peichl, M., 2015: Negative effects of stem and stump harvest and deep soil cultivation on the soil carbon and nitrogen pools are mitigated by enhanced tree growth. Forest Ecology and Management 338: 57–67.

Elforest, 2017: Elforest Technology, About us. http://elforest.se/eng/home-2.html. Retrieved 2017-01-24.

Eriksson, G., Bergström, D., Nordfjell, T., 2013: The state of the art in woody biomass comminution and sorting in Northern Europe. International Journal of Forest Engineering 24(3): 194–215.

Erler., J., 2013: Portalharvester und Flachlandseilkran (Portalharvester and Flat-land cable crane). Forst & Technik 9: 18–21.

Ersson, B.T., Jundén, L., Bergsten, U., Servin, M., 2013: Simulated productivity of one-and two-armed tree planting machines. Silva Fennica 47(2): article id 958.

Flisberg, P., Forsberg, M., Rönnqvist, M., 2007: Optimization based planning tools for routing of forwarders at harvest areas. Canadian Journal of Forest Research 37(11): 2153–2163.

Fridh, L., Volpé, S., Eliasson, L., 2014: An accurate and fast method for moisture content determination. International Journal of Forest Engineering 25(3): 222–228.

Fridh, L., Volpé, S., Eliasson, L., 2017: A NIR machine for moisture content measurements of forest biomass in frozen and unfrozen conditions. International Journal of Forest Engineering 28(1): 42–46.

Garcia, R., Calantone, R., 2002: A critical look at technological innovation typology and innovativeness terminology: a literature review. Journal of product innovation management 19(2): 110–132.

Gellerstedt, S., Dahlin, B., 1999: Cut-to-length: The next decade. Journal of Forest Engineering 10(2): 17–24.

Guimier, D.Y., 1999: Canadian forestry operations in the next century. Journal of Forest Engineering 10(1): 7–12.

Gustafsson, L., Baker, S.C., Bauhus, J., Beese, W.J., Brodie, A., Kouki, J., Lindenmayer, D.B., Lõhmus, A., Martínez Pastur, G., Messier, C., Neyland, M., Palik, B., Sverdrup-Thygeson, A., Volney, W.J.A., Wayne, A., Franklin, J.F., 2012: Retention forestry to maintain multifunctional forests: a world perspective. BioScience 62(7): 633–645.

Hakkila, P., 2006: Factors driving the development of forest energy in Finland. Biomass and Bioenergy 30(4): 281–288.

Hallonborg, U., 1997: Ingen man på maskinen – en förarlös vision (No man in the machine – a driverless vision). Arbetsrapport; no. 399, Skogforsk. Uppsala, Sweden. (In Swedish).

Hansson, A., Servin, M., 2010: Semi-autonomous shared control of large-scale manipulator arms. Control Engineering Practice 18(9): 1069–1076.

Hanzelka, N.C., Bolding, M.C., Sullivan, J., Barrett, S.M., 2016: Productivity and costs of utilizing small-diameter stems in a biomass-only harvest. International Journal of Forest Engineering 27(1): 43–52.

Harstela, P., 1999: The future of timber harvesting in Finland. Journal of Forest Engineering 10(2): 33–36.

Hellström, T., Lärkeryd, P., Nordfjell, T., Ringdahl, O., 2009: Autonomous Forest Vehicles: Historic, envisioned, and state-of-the-art. International Journal of Forest Engineering 20(1): 31–38.

Helmisaari, H.S., Kaarakka, L., Olsson, B.A., 2014: Increased utilization of different tree parts for energy purposes in the Nordic countries. Scandinavian Journal of Forest Research 29(4): 312–322.

Heinimann, H.R., 2007: Forest operations engineering and management – the ways behind and ahead of a scientific discipline. Croatian journal of forest engineering 28(1): 107–121.

Häggström, C., Englund, M., Lindroos, O., 2015: Examining the gaze behaviors of harvester operators: an eye-tracking study. International Journal of Forest Engineering 26(2): 96–113.

Häggström, C., Lindroos, O., 2016: Human, technology, organization and environment – a human factors perspective on performance in forest harvesting. International Journal of Forest Engineering 27(2): 67–78.

IEEE, 2000: A Model for Types and Levels of Human Interaction with Automation. IEEE transactions on systems, man, and cybernetics: A publication of the IEEE Systems, Man, and Cybernetics Society. New York, NY: Institute of Electrical and Electronics Engineers 30(3).

Joelsson, J., Di Fulvio, F., De La Fuente, T., Bergström, D., Athanassiadis, D., 2016: Integrated supply of stemwood and residual biomass to forest-based biorefineries. International Journal of Forest Engineering 27(2): 115–138.

John Deere, 2013: Smooth Boom Control / Intelligent Boom Control. http://www.deere.com/en_US/docs/forestry/SBC_IBC_FastFact_FNL.pdf Retrieved 2017-01-24.

Jundén, L., Bergström, D., Servin, M., Bergsten, U., 2013: Simulation of boom-corridor thinning using a double-crane system and different levels of automation. International Journal of Forest Engineering 24(1): 16–23.

La Hera, P., 2011: Underactuated Mechanical Systems: Contributions to trajectory planning, analysis, and control. Doctoral dissertation thesis. Umeå University, Sweden.

La Hera, P., Ortiz Morales, D., 2015: Model-based development of control systems for forestry cranes. Journal of Control Science and Engineering: 15 p., article ID 256951.

Leijon, M., 2016: Forestry machines in 2050. Umeå Institute of design. Umeå University. Sweden.

Lideskog, H., Karlberg, M., Bergsten, U., 2015: Development of a Research Vehicle Platform to Improve Productivity and Value-extraction in Forestry. Procedia CIRP 38: 68–73.

Lindroos, O., 2012: Evaluation of technical and organizational approaches for directly loading logs in mechanized CTL harvesting. Forest Science 58(4): 326–341.

Lindroos, O., Wästerlund, I., 2014: Theoretical Potentials of Forwarder Trailers with and without Axle Load Restrictions. Croatian Journal of Forest Engineering 35(2): 211–219.

Lindroos, O., Cavalli, R., 2016: Cable yarding productivity models: a systematic review over the period 2000–2011. International Journal of Forest Engineering 27(2): 79–94.

Lindroos, O., Henningsson, M., Athanassiadis, D., Nordfjell, T., 2010a: Forces required to vertically uproot tree stumps. Silva Fennica 44(4): 681–694.

Lindroos, O., Pettersson, M., Johansson, P., Nordfjell, T., 2010b: Productivity of a prototype truck-mounted logging residue bundler and a road-side bundling system. Silva Fennica 44(3): 547–559.

Lindroos, O., Ringdahl, O., La Hera, P., Hohnloser, P., Hellström, T., 2015: Estimating the position of the harvester head – a key step towards the precision forestry of the future? Croatian Journal of Forest Engineering 36(2): 147–164.

Luu, T., Sabir, E., Sundelin, L., 2016: Forestry in 2020. Operating the Harvester Crane. Umeå Institute of design. Umeå University. Sweden.

Ludwign, 2016: Forestry in 2050. Autonomous Harvester. Umeå Institute of design. Umeå University. Sweden.

Magnusson, T.P., 2016: Long-term effects of stump harvest on mercury and general chemistry in discharge water. Scandinavian Journal of Forest Research 32(3): 230–238.

Manzone, M., 2015: Performance of an electronic control system for hydraulically driven forestry tandem trailers. Biosystems Engineering 130: 106–110.

Manzone, M., 2016: A bundler prototype for forestry and agricultural residue management for energy production. International Journal of Forest Engineering 27(2): 103–108.

Mathworks, 2016: INCOVA Designs Intelligent Valve-Control System for a 20-Ton Excavator. https://www.mathworks.com/company/user_stories/incova-designs-intelligent-valve-control-system-for-a-20-ton-excavator.html Retrieved 2017-01-24.

Mellberg, A., 2013: Extension–Operator Environment for Forest Harvesters. Master thesis. School of Engineering, Jönköping, Sweden.

Milne, B., Chen, X., Hann, C., Parker, R., 2013: Robotisation of forestry harvesting in New Zealand – An overview. In 2013 10th IEEE International Conference on Control and Automation (ICCA): 1609–1614.

Mohtashami, S., Bergkvist, I., Löfgren, B., Berg, S., 2012: A GIS approach to analyzing off-road transportation: a case study in Sweden. Croatian Journal of Forest Engineering 33(2): 275–284.

Nordfjell, T., Björheden, R., Thor, M., Wästerlund, I., 2010: Changes in technical performance, mechanical availability and prices of machines used in forest operations in Sweden from 1985 to 2010. Scandinavian Journal of Forest Research 25(4): 382–389.

Nuutinen, Y., Petty, A., Bergström, D., Rytkönen, M., Di Fulvio, F., Tiihonen, I., Lauren, A., Dahlin, B., 2016: Quality and productivity in comminution of small-diameter tree bundles. International Journal of Forest Engineering 27(3): 179–187.

Nuutinen, Y., Björheden, R., 2016: Productivity and work processes of small-tree bundler Fixteri FX15a in energy wood harvesting from early pine dominated thinnings. International Journal of Forest Engineering 27(1): 29–42.

Ollikainen, M., 2014: Forestry in bioeconomy – smart green growth for the humankind. Scandinavian Journal of Forest Research 29(4): 360–366.

Ortiz Morales, D., 2015: Virtual Holonomic Constraints: from academic to industrial applications. Doctoral dissertation thesis. Umeå University, Sweden.

Ortiz Morales, D., Westerberg, S., La Hera, P.X., Mettin, U., Freidovich, L., Shiriaev, A.S., 2014: Increasing the Level of Automation in the Forestry Logging Process with Crane Trajectory Planning and Control. Journal of Field Robotics 31(3): 343–363.

Parker, R., Karen, B., Clinton, P.W., 2016: Robotics in forestry. New Zealand Journal of Forestry 60(4): 8–14.

Peters, P.A., 1973: Advanced Logging System-II: Balloon Logging: A Look at Current Operating Systems. Journal of Forestry 71(9): 577–579.

Pirandola, S., Eisert, J., Weedbrook, C., Furusawa, A., Braunstein, S.L., 2015: Advances in quantum teleportation. Nature photonics 9(10): 641–652.

Pohjankukka, J., Riihimäki, H., Nevalainen, P., Pahikkala, T., Ala-Ilomäki, J., Hyvönen, E., Varjo, J., Heikkonen, J., 2016: Predictability of boreal forest soil bearing capacity by machine learning. Journal of Terramechanics 68: 1–8.

Porter, M.E., 1985: Technology and competitive advantage. Journal of business strategy 5(3): 60–78.

Ponsse, 2017: Ponsse Active Frame. http://www.ponsse.com/se/produkter/skotare/activeframe. Retrieved 2017-01-24.

Purfürst, T., 2010: Learning curves of harvester operators. Croatian Journal of Forest Engineering 31(2): 89–97.

Ringdahl, O., Lindroos, O., Hellström, T., Bergström, D., Athanassiadis, D., Nordfjell, T., 2011: Path tracking in forest terrain by an autonomous forwarder. Scandinavian Journal of Forest Research 26(4): 350–359.

Ringdahl, O., Hellström, T., Lindroos, O., 2012: Potentials of possible machine systems for directly loading logs in cut-to-length harvesting. Canadian Journal of Forest Research 42(5): 970–985.

Routa, J., Kolström, M., Ruotsalainen, J., Sikanen, L., 2015: Precision measurement of forest harvesting residue moisture change and dry matter losses by constant weight monitoring. International Journal of Forest Engineering 26(1): 71–83.

Samset, I., 1966: Loven om den sprangvise vikling (The law of discontinuous evolution). Norsk Skogbruk 12: 737–741. (In Norwegian)

Schumpeter, J., 1942: Capitalism, socialism and democracy. Harper and Brothers. New York.

Silversides, C.R. (ed.), 1974: Proceedings of the IUFRO Division 3 symposium »Forest harvesting mechanization and automation. Proceedings«. 25 Sept – 5 October, Ottawa, Thunder Bay and Sault Ste. Marie, Canada. Canadian Forestry Service, Dept. of the Environment. Ottawa, Ontario, Canada.

Silversides, C.R., Sundberg, U., 1988: Operational Efficiency in Forestry. Volume 1: Analysis. Dordrecht, The Netherlands: Kluwer Academic Publishers.

Silversides, C.R., 1997: Broadaxe to flying shear: the mechanization of forest harvesting east of the Rockies. Transformation Series no. 6, National Museum of Science and Technology. Ottawa, Canada.

Solgi, A., Naghdi, R., Labelle, E.R., Tsioras, P.A., Nikooy, M., 2016: Effect of varying machine ground pressure and traffic frequency on the physical properties of clay loam soils located in mountainous forests. International Journal of Forest Engineering 27(3): 161–168.

Spinelli, R., Nati, C., Magagnotti, N., 2005: Harvesting and transport of root biomass from fast-growing poplar plantations. Silva Fennica 39(4): 539–548.

Spinelli, R., Cavallo, E., Facello, A., 2012a: A new comminution device for high-quality chip production. Fuel processing technology 99: 69–74.

Spinelli, R., Schweier, J., De Francesco, F., 2012b: Harvesting techniques for non-industrial biomass plantations. Biosystems engineering 113(4): 319–324.

Trott, P., 2008: Innovation management and new product development. 4th ed. Pearson Education Ltd, Harlow, England.

Torresan, C., Berton, A., Carotenuto, F., Di Gennaro, S.F., Gioli, B., Matese, A., Miglietta, F., Vagnoli, C., Zaldei, A., Wallace, L., 2016: Forestry applications of UAVs in Europe: a review. International Journal of Remote Sensing 38(8–10): 2427–2447.

Uusijärvi, R., 1985: Automation and remote controlling of forest machinery. Report from NSR workshop in Sweden, April 1983. Wood Technology Report No. 70, Swedish Institute for Wood Technology Research. Stockholm, Sweden. (In Swedish with English summary).

Vanclay, J.K., 2011: Future harvest: what might forest harvesting entail 25 years hence? Scandinavian Journal of Forest Research 26(2): 183–186.

Warkotsch, P.W., 1990: Timber Harvesting in South Africa – Past, Present, Future. South African Forestry Journal 153(1): 55–63.

Westerberg, S., 2014: Semi-automating forestry machines: motion planning, system integration, and human-machine interaction. Doctoral dissertation thesis. Umeå University, Sweden.

Westerberg, S., Shiriaev, A., 2013: Virtual environment-based teleoperation of forestry machines: Designing future interaction methods. Journal of Human-Robot Interaction 2(3) :84–110.

Vestlund, K., Hellström, T., 2006: Requirements and system design for a robot performing selective cleaning in young forest stands. Journal of terramechanics 43(4): 505–525.

Winkler, A.W., Mastalli, C., Havoutis, I., Focchi, M., Caldwell, D.G., Semini, C., 2015: Planning and execution of dynamic whole-body locomotion for a hydraulic quadruped on challenging terrain. In: 2015 IEEE International Conference on Robotics and Automation (ICRA), 5148–5154.

Visser, R., Stampfer, K., 2015: Expanding ground-based harvesting onto steep terrain: a review. Croatian Journal of Forest Engineering 36(2): 321–331.

Wolf, D.P., Meek, P., Jones, T.A., Cormier, D., Caspersen, J.P., 2014: Forest harvest residue recovery in semi-mechanized hardwood selection operations. International Journal of Forest Engineering 25(3): 229–237.

Wolfsmayr, U.J., Rauch, P., 2014: The primary forest fuel supply chain: a literature review. Biomass and Bioenergy 60: 203–221.

Wästerlund, I., Öhlund, A., 2014: Productivity Study of WoodPac Bundling of Logging Residues and Small Stems. Croatian Journal of Forest Engineering 35(2): 139–151.

Received: January 24, 2017
Accepted: June 9, 2017

Authors' addresses:

Prof. Ola Lindroos, PhD. *
e-mail: ola.lindroos@slu.se
Pedro La Hera, PhD.
e-mail: xavier.lahera@slu.se
Carola Häggström, PhD.
e-mail: carola.haggstrom@slu.se
Department of Forest Biomaterials and Technology
Swedish University of Agricultural Sciences
SE-901 83 Umeå
SWEDEN

* Corresponding author