EIP-AGRI Focus Group
Sustainable mobilisation of forest biomass

MINIPAPER 5: Harvesting and transportation technologies

Authors
Tomas Nordfjell (Coord.), Stelian Borz, Nike Krajnc, Ritva Toivonen

funded by European Commission

Index

Introduction - Motivation

This paper is about the problems related in the area of harvesting and long distance transportation technologies when focusing on an increased sustainable mobilisation of forest biomass in European Union (EU), and measures needed to overcome these problems. Overall, the annual round wood harvest in Europe is about 430-450 million m^3 solid, and still the increase in standing volume is about 400 million m^3 per year (Moffat et al. 2015). About 40% of the harvested volume is sawlogs, one third are industrial round wood (pulp), and the rest is fuel wood (Finnish statistical yearbook of forestry 2014). The structure of harvested volumes differs significantly between regions and countries, as well as the diameter and height of trees. The number of species also varies a lot. In some countries, harvests may be strongly dominated by large diameter sawlogs, while in other countries smaller diameter industrial roundwood dominates. The soil and geographical, as well as weather conditions also vary. If the mobilisation of forest biomass shall increase, it is also a need of increased harvesting operations and transportation to industries. Increased mobilisation also means that the average transportation distances will increase, since the industries in general are not located in the areas with large volumes of unutilized forest biomass. Harvesting and transportation has to be done in a way that doesn't cost too much; otherwise the forest biomass can't compete with fossil primary products on the market, and the forest owner must get a fair price for their wood to be willing to harvest. This has also to be done with as little negative environmental impact and with as little consumption of fossil fuels as possible; otherwise the mobilisation of forest biomass will not be as sustainable as wanted, and might not be accepted by forest owners and the public opinion. The harvesting technique, or techniques, has also to meet the requirements raised from different types of forest management systems (clear cutting, thinning, strip cutting, continuous tree cover etc.) and for operations on both large and small areas; otherwise it will not be possible to mobilize as much of the potential as wanted. Harvesting and transportation has to generate attractive business and work opportunities; otherwise there will be a lack of companies, contractors and personnel to make this happened. The challenge of mobilizing increasing volumes of trees includes the challenge of being able to harvest trees all-round the year, also during severe weather conditions. A problem is that the warming climate may bring about increasing vulnerability regarding insects and diseases that affect trees via wounds in roots or stems caused by harvesting.

funded by European Commission

The degree of mechanization of harvesting varies significantly, the global average being about 50% mechanized and 50% manual (Viitamäki et al. 2015). There is a clear variation in this aspect between the EU-countries: In Finland and Sweden the degree of mechanization is close to 100%, while in some countries the share of manual harvesting is still significant. Globally, the two most common systems of mechanized harvesting is TL (tree length) system, where the stems are felled and transported as such, and CTL (cut to length) system where the stems are cut to shorter logs immediately after felling. CTL is almost the only utilized harvesting system in the Nordic countries (cf. Drushka & Konttinen 1997).

The examples of differences and problems listed motivate the need of a minipaper related to harvesting and transportation technologies for sustainable mobilization of forest biomass.

Dissertation

General issues affecting the efficiency of harvesting and transportation technology
The production of wood based products is market driven, and the demand for round wood is driven from the forest products demand. Thus the demand for round wood and its harvests fluctuate according to the markets situation of forest products. This presumes ability of fast adaptation in the harvesting volumes. Forest industries must be able to sell their products at a price low enough to create a high market demand, especially if the goal is to increase the industrial wood utilization. It means that forest industries must be efficient in their production, but also that they are not able to pay more than a certain amount of money for a specific wood assortment. From a forest owner perspective, the only reason for selling wood to industries is that they get payed good enough to find it worth doing the harvest. The monetary gap between what industries can pay and what forest owners need to have must at least cover all the cost related to this wood procurement, otherwise no wood will leave the forests.

Generally speaking, the total cost for harvesting of wood, extraction to roadside and further transportation to industries can be divided into: labor costs for workers; capital costs for the machinery and equipment used; service and maintenance costs for the machinery and equipment used; energy costs (fuel) and oil for the machinery used; insurance costs and other costs of this kind that is needed. For the individual parts (harvesting, extraction and transportation to industries) all those costs can be added to a total cost per hour ongoing work. The combination of the cost per hour and the time consumption per wood volume unit defines the cost for harvesting, extraction and transportation to industries. Capital costs, energy costs and costs for spare parts are quit much the same in most parts of Europe. However, the salary costs differs more between European countries. This does not only affect the cost for operational running of machines, but also the cost for service and maintenance of the equipment.

In countries that today have a high level of mechanized harvesting operations in combination with rather high labor costs like Sweden and Finland, a rule by thumb is that 1/3 of the hourly cost for a forest machine is capital costs, 1/3 is labor costs and the remaining 1/3 is energy costs, service, maintenance and other costs. High labor costs make it economic to reduce the number of working hours, and instead invest in high capital cost technology with high productivity. High labor costs make mechanization more

funded by European Commission

profitable than if labor costs are low (cf. Nordfjell et al. 2004). In the long run, high labor costs speed up the development of mechanization and further on to automation and robotization, like it already has done in many manufacturing industries. With low labor costs, it is most often a more economical alternative to use less expensive and less productive machines than if the labor costs are high. It is important to understand that the most economic technique differs between countries with different labor cost, even if the forests and the forest terrain might be similar in those countries. Anyhow, obsolete harvesting equipment predominates in many of the East European countries. This adds to the harvesting costs with money spent in equipment repairing and maintenance and time lost to repair the equipment instead of carrying on the harvesting operations.

But, machinery can only be productive during the time as harvesting, extraction or transportation to industries actually is done. This means that it automatically costs more money to relocate high productive but expensive machinery between harvesting sites than a less productive and less expensive machine (cf. Nordfjell et al. 2004). It is also a fact that high productive machinery has to relocate many more times in a year than less productive machinery, at a constant average harvested volume per harvesting site. Because of this, the question of aggregating close by harvesting sites to reduce the number of relocations and/or making the relocations shorter is of increasing economic importance the higher level of mechanization a harvesting operation has.

Harvesting in steep terrain

The potential for increased wood harvesting in steep terrain is large. In general this depends on a less intensive harvest in the past in such stands, and the reason for this is that it is more difficult and costly to harvest in steep terrain. In real steep terrain the only possible alternative has been to use different kind of winch or sky-line systems, and this is expensive (cf. Nordfjell et al. 2004). Helicopter logging can also be done, but this is very costly (Han et al. 2004). However, new technique with a winch on forest machines that is synchronized with the wheel transmission has made it possible to use ground based machines in steeper terrain than before (Bombosch et al. 2003). The winch is anchored uphill, and the machine can drive down and up, using both its powered wheels and the power in the winch line.

Harvester capability to handle large trees

The general productivity (m^3/hour) on a harvester is higher in a stand with big trees than if the trees are small. This is a valid fact until the trees become so big that the technical limit for the harvester is reached. Large harvesters have their technical limitation at larger trees than smaller harvesters, but depending on for example road regulations (relocation between stands) and space limitations in the stand, there are practical limitations on harvester size. It is a paradox that in the north parts of Europe were the practical limitations allows the largest harvesters, the maximum size of trees are rather small. In central and south parts of Europe with much larger maximum tree sizes there are practical limitations that do not allow the largest harvesters. It is however not only the tree size that is a limiting factor for the harvester capability. Crooked trees and trees with big branches and/or forked stems are more difficult to handle than other trees, especially if they are big as well (cf. Gerasimov et al. 2012). Harvesting of hardwood forests include often a high proportion of trees that are difficult to handle with a harvester. All kind of harvesting difficulties mentioned are intensified if the terrain gives mobility and stability difficulties because of its steepness or unevenness.

Ground damages

Most of the subjects mentioned about ground damages are also relevant for the subject of vehicle mobility on soft soils. The most sever ground damages in forest terrain are caused during extraction of logs. The damages during the harvest of trees are less severs. The reason for this is that a machine for extraction is heavier (carries load) and that it also drives longer distances in the stand. Ground damages can be reduced in a number of ways. The machine design itself is one possibility with individual traction and slip control for all wheels, low pressure tires or tracks being gently to the ground as examples (cf. Edlund et al. 2012). Another possibility is some kind of reinforcement of the ground. Examples of that are logging residues on strip roads or mechanical structures that are placed on the ground at specific weak parts (cf. Eliasson & Wästerlund 2007). A third possibility is to reduce ground damages with better planning of where heavy loaded machines should drive (Mohtashami et al. 2012). Depth to water table maps is a new possibility for better machine path planning (Ågren et al. 2015).

A situation with a fixed strip road network, as in many parts of central Europe, restricts the soil damages to certain areas, but is also a hinder for development of harvesting technique. For example, if the distance is fixed to 25-30 m, this means that if a thinning shall be fully mechanized, the harvester must be able to reach trees up to 15 m away, and it requires a very big and heavy machine to be stable enough for felling trees with such a long boom reach, and the strip roads will consequently be wide. An alternative is that a smaller harvester makes strip roads at for example 16 m distance. Every second strip road can then be narrow and winding, and only meant for the harvester to drive on. The trees harvested from that strip road will be processed and piled as far away from this narrow and winding strip road as possible. The other strip roads are normal ones and designed also for the forwarder to drive on. The forwarder, that loaded is much heavier than a harvester, will then be able to reach all logs from strip roads with a distance of 32 m (16 +16). With fixed distances between strip-roads, there are limited possibilities for implementation of new innovative harvesting methods and machines.

Damages on remaining trees in a thinning or other selective harvesting operation

Thinning or other selective harvesting operations always gives some percentage of damaged trees in the remaining stand (cf. Sirén et al. 2015). Trees get damaged if hit with the machine, but more often if they are hit by the boom or the tool in the tip of the boom. The probability for such damages increases when working with a long boom reach, simply because it is difficult for the operator to see what is happening far away, and because it is more difficult to control the boom movements at long reach.

Problems caused by the injuries on the growing trees include quality problems, but also potentially infections of diseases or insects. These may cause major damages on the wood quality over time, and thus economic losses. A serious problem, especially in Norwegian spruce stands, is also root and but rot that spreads via injured roots. Thus the harvesting methods should be efficient and economic but at the same time gentle and cause as little injuries to growing trees or the soil as possible.

Energy efficiency on forest machines and trucks

Energy efficiency relates not only to economy but also to sustainability in general. Like in the development of many other vehicles, hybrid transmissions with combined combustion and electrical engines have been tried on forest machines for reducing the fuel consumption (cf. Edlund et al. 2012). This technique is however not expected to reduce the energy consumption on trucks in the same

funded by European Commission

magnitude, since the power output on a truck during use is more constant over time (cf. Svenson 2017). In addition to energy efficiency, the sustainability criteria regarding the fuels and oils in the harvesting machinery are an issue (cf. Athanassiadis 2000). Bio-oils are already in use, but the machines should be both fuel-efficient and adapted to run also on bio-diesels. In general, CTL harvesting is more fuel efficient than FT harvesting (cf. Fuente et al. 2017).

Something in common for all transportation vehicles is that the ratio between the maximum load and the kerb weight of the vehicle shall be as favorable as possible for high energy efficiency. This can be achieved with an optimized engineering design, meaning a low weight on machine that is able to carry a heavy load.

Work organization, training, safety and ergonomics at harvesting work

Wood harvesting is to a high degree performed by forest machine contractors, or by an internal harvesting organization within a large forest company or state forest company that more or less act like a contractor. Contractors are key actors in maintaining forest owner's willingness to sell wood, which has become more challenging and requires attractive service offers (Erlandsson 2016).

Some forest work is still physical hard and dangerous, and some forest work include high levels of whole body vibrations (cf. Tabell 2003). Forest work can also be stressful and include traveling long distances every day to the work place and shift work. Increased harvesting also include that more people need to work in harvesting, extraction and transportation of wood to industries (even if the level of mechanization increases). To be able to attract people to work in harvesting operations it is important to offer good working conditions that also include better possibilities to combine the forest work with family life (cf. Häggström 2015).

Another issue is that of having well-trained forest workers, able to operate efficiently and safely with very expensive equipment. This is of specific importance in some East European countries where no training programs (e.g. training on simulators) are available. Instead, the training is mostly done on-the-job, a fact that reduces the performance of operations and increases the costs and tree damage while the novice forest workers improve their skills (cf. Gerasimov et al. 2012). But also in countries were simulator training programs are common, this training could be further improved, and also include forest growth models to visualize the stand development following after a thinning operation.

One possibility for improved ergonomic and safety is to use remote operated machines (cf. Hellström et al. 2009). The operator then doesn't need to sit in a machine with a high level of whole body vibrations, or in a machine working in extremely steep terrain. However, there are other safety and working condition issues to deal with if an operator is working outdoors and close to a big machine.

On the other hand, working with modern high tech forest machinery requires special education and experience, and ability to work with several IT-software. This may be attractive but also a challenge both for educational organizations and the people working in the forest sector.

Long distance transportation infrastructure

It is about 100 times more costly to transport in terrain than on road, and if the road infrastructure is too sparse it will not be economical to transport wood to roads. Trucks will always be needed for

transportation of wood from the forest to industries, or to a terminal for reloading to train or vessels. The bearing capacity on roads is often a limiting factor. If roads can't handle trucks big enough, the wood will still not be accessible, or it will be too expensive to transport with small trucks. This is both a matter of the strength of the road and bridges, but also a matter of different weather conditions throughout the year. Sufficient space is also required at roadside to make piles of wood there. If the distances are very long, terminals are needed for reloading to train or cargo vessels.
In some parts of Europe, the harvesting operations may be concentrated in specific periods within a year as a result of law-enforced norms and meeting the natural regeneration periods. Coupled with a poor access, the trafficability of forest roads is often impaired by the concentration of large amounts of wood transportation in very short periods.

In general, the maximum allowed size and weight of loaded trucks has increased over time. At the moment loaded timber trucks can have a weight up to 76 tons in Finland, and 64 tons in Sweden. In the summer of 2017 Sweden will however increase this to 74 tons for parts of the road network. Many EU countries have restrictions on only 44 ton total weight. If the road structure can handle more heavy trucks, both transportation costs as well as emissions can decrease.

Summing up the present situation

There is no sole solution to the challenges of developing forest harvesting and transportation techniques to be more efficient and economic but at the same time sustainable. These is due to the strongly varying forests and soil structures, as well as varying forest industry structure and thus demand for wood in various parts of the EU.

However, there are some common issues to focus. Mobilization of increasing volumes of wood economically presumes increasing mechanization of wood harvesting, but different soils, sites and other conditions require different solutions. This, on its behalf, requires probably development of both silvicultural and forest management strategies as well as machinery. Anyhow, larger operation units and the overall scale of operations are probably needed for increasing efficiency and decreasing the unit costs. But decreased time and cost spent on relocation of machinery is also important since many harvesting operations will continue to be rather small. The training of forest workers and machine drivers is a necessary part of the total development vision.

Developing harvesting and transportation technologies is not only development of traditional technology and machinery as well as developed business models for contracting harvesting and transportation of wood. It also includes developing and digitalization of round wood trade and information delivery between round wood trade, forest industry operations and forest harvesting planning. Thus it is a question of developing the whole entity of the supply-chain, taking the local circumstances into consideration.

Proposals for research needs from practice and ideas for innovations

Both research needs and ideas for innovation are presented under the same headline. In the area of harvesting and transportation technologies, these issues are close linked together.

Approach for research and innovations

Techno diversity, the common key for research and innovations on sustainable systems

The term techno diversity means searching for a variety of technological solutions, which are ecologically as well as socially adapted to the local conditions and needs, since they consider economical capacities of the forest stakeholders. Analogously to the concept of biodiversity, it means to search for a technological diversity that helps to adapt to a variety of different limiting factors (economical, environmental, social and cultural). Comparisons of different harvesting systems should be done from a techno diversity point of view.

Organization, infrastructure and regulations

Business models for wood harvesting

The business models for efficient agreements and communication between forest owners, wood buyers and forest machine contractors (or the part of the big forest company having own harvesting equipment) should be further developed. This includes a combination of satisfaction for forest owners, forest machine contractors and forest industry demands on raw material for their processes of the desired quality and volume (cf. Erlandsson 2016).

Organization of forest owners and/or forest administration organizations in a way that planning tools and harvesting technique can be used not only at one forest holding at a time

This is important to be able to aggregate several nearby small harvesting operations to reduce the relocation cost for forest machines. This type of organization can be done if the forest owners get together in some kind of forest owner association (Rickenbach 2006), but also other organizational alternatives could be investigated.

The issue of standing timber sold by auctioning in some parts of EU should also be addressed, eventually by making it possible to sell packs of harvesting areas through auctioning, making this way the offer more attractive for contractors at least by reducing the relocation costs.

Combined harvesting and other forest management operations on the same site

In addition to harvesting, development of mechanization also for other tasks in forest management and silviculture may boost the degree of harvesting. At the moment, the normal procedure is that trees are harvested at one time, and other silvicultural operations are carried out later, operation by operation. At least in the case of final felling/clear-cut, one potential road for more efficient operation would be to combine harvesting and soil preparation for seedling planting at the same time. It might also be a possibility to combine this with stump harvesting at the same time (cf. Berg 2014). This is not possible or economically sensible for all sites, but might deserve attention. Another combined mechanized harvesting and management operation is utilizing biomass from dense pre-commercial thinning stands for energy

use (cf. Ligné 2004), and this has to be further developed (cf. Bergström 2009). Furthermore, the degree of mechanization of reforestation is generally seen as the next step for mechanization on forest management (cf. Ersson 2014). This would call for development of both silvicultural operations and technology, but might result in increased economic efficiency and less stress for soils and roads.

Improved long distance transportation infrastructure and road regulations
Forest roads as well as many public roads should be upgraded in many areas, and new roads built where needed. Also the rail road network should be upgraded in many areas. New terminals for wood assortments should be built for making it possible to reload to trains and cargo vessels. Terminals can also be used as a place to store for example wood energy assortments as well as to dry and comminute this material (cf. Enström et al. 2016). A terminal can then for example be a location for refining and mixing of woody biomass for new biochemical industry processes.

It is also important that the national road regulations about maximum size and weight on trucks are updated, to allow larger loads, meaning lower transportation costs and fewer numbers of driven trucks at a constant total volume transported.

Machine technique
Efficient equipment and methods for relocation of machines between stands
Even with a better organization and improved infrastructure, it will always be important to relocate high productive forest machines between harvesting sites both fast and with a low cost. Possible examples on innovations are: forest machines that are faster than today, and possible to drive on paved roads without damage them; less costly low bed trailers were forest machines can be loaded very fast, and improved logistic for trucks used to relocate forest machines.

Harvester capability to handle large trees in general and crooked hardwood trees
New technical solutions that make it possible with mechanized harvesting of real large trees as well as big and crooked hardwood trees are needed.

Harvesting technique for steep terrain
New technical solutions with further developed winches, synchronized with the transmission of the wheels on any kind of forest machine. This technique exists, but can be much more sophisticated with better control of the involved forces. Also the work methods used with such technology should be studied and improved. This kind of technique will most probably also reduce the ground damages.

Reduced forest machine caused ground damages

- Technical solutions on machines to reduce ground damages (intelligent transmission with slip control for individual wheels, big low pressure tires, tracks gently to the ground, turning without large shear forces between vehicle and ground, etc.).
- Technical reinforcement of the ground for reduced ground damages (a more optimal utilization of logging residues for ground reinforcement, purpose built “wood bridges” to move between harvesting sites and for reinforcement of week parts, etc.)

funded by European Commission

- Reduced ground damages with better planning of machine driving path (minimized total driving distance, reduced driving on the most wet and weak parts of the stand, depth to water table maps included in the planning).

Reduced energy consumption on forest machines and trucks
The energy consumption on forest machines could be reduced with more efficient hydraulic systems on the machines, with more intelligent and efficient transmission systems. This is to a high extent similar to what can be done for reduced ground damages. It is also possible to further develop forest machines with hybrid technology transmissions, which have proven to reduce fuel consumption on most type of vehicles.

A reduced kerb weight on forwarders and trucks at the same time as the load carrying capacity remains will increase the energy efficiency of the transportation work.

IT based machine functions
Several of the research needs and ideas for innovations mentioned in chapter 4.3 above include IT based functions. However, in this chapter the most IT depending research and innovation ideas are collected.

Remote controlled forest machines
New machines that are remote controlled can be developed, and used in different types of harvesting operations. The use of them in steep terrain harvesting could be a way to increase operator safety. If the machine falls down a slope, the operator doesn't. An operator will not suffer from whole body vibrations either. Remote controlled forest machines can also be a possibility to make less expensive machines without a space demanding and expensive cabin.

Automation and robotization of forest machines or forest machine functions
The ongoing development of automated functions on forest machine cranes can increase in speed and complexity (cf. Ringdahl 2011; Westerberg 2014). This will reduce the stress on the operator and decrease the learning time an operator need to reach full productivity. Automation of machine functions together with the development of remote controlled machines is important steps in the development of fully robotized machines.

Modern sensors and control technique for reduced level of damaged trees in thinning operations
Modern sensors and modern control technology can be developed to minimize the frequency that the crane on a machine hit a tree that shall remain in the stand. In that way it will be possible to use a long boom reach, and longer booms than today and still avoid collisions of the boom with trees in thinning operations.

Utilization of "Big Data" collected during harvesting
Data on logs (length, diameter, specie, and quality) collected by a harvester during work can be utilized in a much better way than today in the wood value chain for receiving industries. This data could be used as input in more optimized logistic systems than today, for delivery of the "right raw material to the right industry". Especially if new sensors on a harvester could detect wood chemical parameters, it would really be possible to select logs for specific use (cf. Eriksson et al. 2011).

Possible Big Data utilization includes also other forest data that could be collected with forest machines during work. Forest machines could be equipped with machine vision and sensors that recognize and collect small-scale data on the site where the machine operates (i.e. remaining tree species, size, quality and spatial distribution). The micro-level data from sites would help to direct the machine and to recognize e.g. trees with damages, wet spots in soil etc. This data may also be combined with other data layers, such as laser scanning information, or aerial photographs. The collected and combined data would serve to produce very accurate data for the forest management planning of the future stand treatment without extra data collection cost. Such updated input data will also improve the future knowledge about possible volumes and assortments for the next harvest in the same stands, many years from now.

Conclusions – Research needs and ideas for innovations

Knowledge gaps to be covered by research and research needs from practice

The most important knowledge gaps to be covered and research needs from practice doesn't only deal with the harvesting technique as a "stand alone subject", but the technique in relation to a number of other key issues. Areas like problems with small and scattered forest holdings, economy for forest owners and negative impact on forest soils are important to tackle, at the same time as forest contractors and workers can earn money and have good working conditions. The conclusion is then that research dealing with a combination of harvesting technique (including organization, machine technique and IT based machine functions) and forest owner issues (organization of forest owners, goals for forest owners, decision support tools for them, etc.) as well as forest contractor issues (work organization, business models etc.) are of crucial importance for future research. The term "Techno diversity" covers well the focus on relevant future research in this area. The term techno diversity means searching for a variety of technological solutions, which are ecologically as well as socially adapted to the local conditions and needs. Analogously to the concept of biodiversity, it means to search for a technological diversity that helps to adapt to a variety of different limiting factors (economical, environmental, social and cultural). Research on harvesting systems should be done from a techno diversity point of view.

Ideas for innovative projects /solutions and potential EIP operational groups

Within all subjects mentioned under research needs ideas can also be formulated for innovative projects and potential EIP operational groups.

Further research needs coming from practice, ideas for EIP AGRI operational groups and other proposals for innovation can be found at the final report of the focus group, available at the FG webpage https://ec.europa.eu/eip/agriculture/en/focus-groups/sustainable-mobilisation-forest-biomass

funded by European Commission

References

Athanassiadis, D. (2000). Resource consumption and emissions induced by logging machinery in a life cycle perspective. Acta Universitatis Agriculturae Sueciae. Silvestria 143.

Ågren, A. M., Lidberg, W., & Ring, E. (2015). Mapping temporal dynamics in a forest stream network—Implications for riparian forest management. Forests, 6(9), 2982-3001.

Berg, S. (2014). Technology and systems for stump harvesting with low ground distribution. Acta Universitatis Agriculturae Sueciae. Doctoral Thesis No. 2014:95. Faculty of Forest Sciences.

Bergström, D. (2009). Techniques and systems for boom-corridor thinning in young dense forests. Acta Universitatis Agriculturae Sueciae. Doctoral Thesis No. 2009:87. Faculty of Forest Sciences.

Bombosch, F., Sohns, D. I. F. D., Nollau, R., & Kanzler, D. I. F. H. (2003). Are forest operations on steep terrain (average of 70% slope inclination) with wheel mounted forwarders without slippage possible? Proceedings" Austro, 5-9.

Drushka, K. & Konttinen, H. (1997). Tracks in the forest. The evolution of logging machinery. Timberjack group OY. Helsinki.

Edlund, J., Bergsten, U., & Löfgren, B. (2012). Effects of two different forwarder steering and transmission drive systems on rut dimensions. Journal of Terramechanics, 49(5), 291-297.

Eliasson, L., & Wästerlund, I. (2007). Effects of slash reinforcement of strip roads on rutting and soil compaction on a moist fine-grained soil. Forest Ecology and Management, 252(1), 118-123.

Erlandsson, E. (2016). The triad perspective on business models for wood harvesting – Tailoring for service satisfaction within forest owner associations. Acta Universitatis Agriculturae Sueciae. Doctoral Thesis No. 2016:124. Faculty of Forest Sciences.

Enström, J., Grönlund, Ö., Athanassiadis, D. & Öhman, M. (2016). Invest in the right fuel terminals. In. Palmér, C-H., Eliasson, L. & Iwarsson Wide, M. (Eds.). Forest energy for a sustainable future. Composite report from the R&D programme: Efficient Forest Fuel Supply Systems 2011-2015. Skogforsk.

Eriksson, D., Geladi, P., & Ulvcrona, T. (2011). Near-infrared spectroscopy for the quantification of linseed oil uptake in Scots pine (Pinus sylvestris L.). Wood Material Science & Engineering, 6(4), 170-176.

Ersson, B-T. (2014). Concepts for mechanized tree planting in southern Sweden. Acta Universitatis Agriculturae Sueciae. Doctoral Thesis No. 2014:76. Faculty of Forest Sciences.

Finnish Statistical Yearbook of Forestry (2011 & 2014). Official statistics Finland.

Fuente, T., Athanassiadis, D., González-García, S.,Nordfjell T. 2016. Cradle-to-gate life cycle assessment of forest supply chains: Comparison of Canadian and Swedish case studies. Journal of cleaner production xxx (2016) 1-16 (in press).

Gerasimov, Y., Senkin, V., & Väätäinen, K. (2012). Productivity of single-grip harvesters in clear-cutting operations in the northern European part of Russia. European Journal of Forest Research, 131(3), 647-654.

Hallongren, H. & Rantala, J. (2010). Metsänhoitolaitteiden kansainvälinen markkinapotentiaali ja teknologian kaupallistaminen. Metla working papers 179. (The international market potential of silvicultural machinery and commercialization options. The Finnish Forest Research Institute Working Papers 179). 49 p.

Han, H. S., Lee, H. W., & Johnson, L. R. (2004). Economic feasibility of an integrated harvesting system for small-diameter trees in southwest Idaho. Forest Products Journal, 54(2), 21.

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.

Häggström, C. (2015). Human factors in mechanized cut-to-lenght forest operations. Acta Universitatis Agriculturae Sueciae. Doctoral thesis No. 2015:59. Faculty of forest sciences.

Ligné, D. (2004). New technical and alternative silvicultural approaches to pre-commercial thinning. Acta Universitatis Agriculturae Sueciae. Silvestria 331. Doctoral thesis.

Moffat, A., Oldenburger, J., Verkerk, H., Weiss, G. Wilburguer & Zingg, A. (2015). European Forests: Status, Trends and Policy Responses. In FOREST EUROPE, 2015: State of Europés Forests 2015.

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. Bacher, M. Eriksson, L. Kadlec, J. Stampfer, K. Suadicani, K. Suwala, M. & Talbot, B. Operational factors influencing the efficiency in conversion. Book chapter in: Spiecker, H. Hansen, J. Klimo, E. Skovsgaard, J. P. Sterba, H. Teuffel, K. Von (eds). (2004). Norway Spruce Conversion - Options and Consequences. European Forest Institute. Research Report No. 18. S. Brill Academic Publishers, Leiden - Boston. ISBN 90 04 13728 9.

Rickenbach, M. G., Guries, R. P., & Schmoldt, D. L. (2006). Membership matters: comparing members and non-members of NIPF owner organizations in southwest Wisconsin, USA. Forest policy and Economics, 8(1), 93-103.

Ringdahl, O. (2011). Automation in forestry – development of unmanned forwarders. Department of computing science, Umeå university. PhD thesis.

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.

Sirén, M., Hyvönen, J., & Surakka, H. (2015). Tree damage in mechanized uneven-aged selection cuttings. Croatian Journal of Forest Engineering, 36(1), 33-42.

Svenson, G. (2017). Optimized route selection for logging trucks. Acta Universitatis Agriculturae Sueciae. Doctoral Thesis No. 2017:7. Faculty of Forest Sciences.

Tabell, L. (2003). Vibration transmission in a single-grip harvester. Department of Silviculture. Report no. 55. Swedish university of agricultural sciences Licentiate dissertation.

Viitamäki, K., Laitila J., Malinen J. & Väätäinen, K. 2015. Metsäkoneiden vuotuiset käyttötunnit ja vaihtokonemarkkinoiden rakenne Euroopassa. Luonnonvara- ja biotaluden tutkimus 37/2015. (The annual operating hours of forest harvesters and tractors and the markets for useed machines in Europe. Luke bioeconomy research reprt 37/2015). 28 p.

Westerberg, S. (2014). Semi-automating forestry machines – Motion planning, system integration and human-machine interaction. Doctoral thesis. Department of applied physics and electronics/Industrial doctoral schoool. Umeå university, Sweden.

funded by European Commission