Subject review

Research Trends in European Forest Fuel Supply Chains: a Review of the Last Ten Years (2007–2017) – Part One: Harvesting and Storage

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Abstract

Forest fuel is a renewable source with the potential to substitute fossil fuels in several application fields, such as reducing greenhouse gas emissions and supporting rural areas by fostering income and jobs. Contribution margins in fuelwood supply are small and ensuring supply chain efficiency plays a crucial role in delivering high quality products at competitive costs. This paper provides a review of research trends related to this issue in the field of harvesting and storing fuelwood and the impact of recent technology during the last decade.

Whereas the basic suitability of supply chains and machines was research's main priority 20 years ago, the focus shifted to improving the efficiency of machines appropriate for harvesting fuelwood during recent years. Significant increase of productivity could be achieved by introducing fuelwood harvesting heads for processing whole trees to bunches convenient for forwarding (»multi-tree handling«), and adapted working techniques (»boom-corridor thinning«) were developed. Development of compaction measures for bulky raw materials, like logging residues, applied during or before processing and forwarding, culminated in dedicated machines (»bundle-harvester«). Improving the final product quality by appropriate storage practices was emphasised. The phrase »moisture content management« voiced the urgent need for prompt monitoring of fuelwood drying behaviour, which was answered by research in the form of meteorological data based drying models. Among the treatments applied before and during storage, covering has evolved as the most suitable measure. Furthermore, research advocated for greater attention to dry matter losses during storage and the development of basic energy density.

Keywords: fuelwood, supply chains, biomass, research trends, harvesting, storage, multiple-tree handling, meteorological drying models

1. Introduction

Energy from biomass is considered a major contributor to current international climate change mitigation and energy security. By 2030, the European Union (EU) is aiming to produce 27% of its primary energy from renewable sources (COM/2014/015). Forest biomass is a key renewable energy source with the potential to meet these long-term renewable energy targets. However, the potential is not exploited due to low efficiency and high costs in the supply chain, resulting in low or even negative contribution margins (Ghaffariyan et al. 2017). For this reason, efficiency improvement and cost reduction remain top priority topics of research in this field.

Recently, several overviews of research on technologies and procedures suitable for increasing the efficiency in harvesting and storage of fuelwood have been compiled. While Stampfer and Kanzian (2006) outlined the challenges and opportunities prevalent in mountainous regions, Routa et al. (2013) investigated the driving forces behind current technical solutions of forest energy procurement systems in Finland and Sweden, ending with some perspectives on possible future developments. Lately, Ghaffariyan et al. (2017) provided an extensive overview of best practice examples of state-of-the art forest biomass harvesting technologies and supply chains used in North America, Europe and the Southern Hemisphere. Focusing on the harvesting process, Bergström and Di Fulvio (2014a) estimated the effect of future harvesting and handling technologies on the cost and energy efficiency of supply chains for young, dense thinnings.

Nevertheless, there is no paper available which comprehensively covers relevant and promising research trends in the field of forest fuel supply chains, also due to an apparent conflict between subject extent and limitations in manuscript length. As part one of a series of two, this paper aims to cover the first two steps in the forest fuel supply chain, namely harvesting and storage, while the second will cover the steps comminution and transport.

In detail, the objective of this paper is to provide an overview of research papers in forest biomass supply in Europe considering the years 2007 to 2017, covering the »harvesting« and »storage« steps in the forest fuel supply chain and to analyse the impact of the presented technologies and work methods on the biomass supply chain, especially in terms of economy. The papers will be classified according to key supply processes and further into research trends. Finally, future research needs will be identified to fuel both industrial and academic development.

2. Material and Methods

In order to access and collect the papers relevant to this review, an extensive online literature search was conducted. »Scopus«, »Web of Science« and »Google Scholar« are the most used search engines. A combination of the key words »harvesting«, »extracting«, »storage«, »fuelwood«, »energy wood« and »supply chain« was applied so that at least one word from each of the search terms (logical OR operator) or multiple terms should appear (logical AND operator) either in the title or the abstract of the paper. As the focus of this paper is the development of harvesting and storage in Europe during the last decade, except for some highly relevant papers from other continents, only highly relevant studies executed or demonstrated in Europe were included in the analysis.

The search resulted in a gross list of 99 papers, of which 32 were not relevant for the focus of this paper, leaving 67 papers for the review. These papers were classified by and summarized on supply process level (»harvesting« and »storage«). These were further split into seven research trend groups, each containing novel knowledge on a certain subject gained during the last decade.

3. Results

3.1 Harvesting

Throughout the last 25 years, the research on mechanized harvesting of fuelwood underwent continuous change, steadily triggered by improvements of existing and development of new technology. Trying to figure out the most promising ones, Bergström and Di Fulvio (2014a) report that, out of a gross list of 14, five systems were considered likely to improve harvesting of fuelwood from young dense thinnings. Consequently, this section deals with these findings as well as other relevant subjects of research in this field during the period under study.

3.2 Multi-tree handling

Accumulating harvesting heads or »fuelwood harvesting heads« enable felling of more than one tree per cycle and collecting these by means of accumulating arms, a feature consequently termed »multi-tree handling«. Equipped with feeding rollers and delimbing knives, these heads process and buck tree bundles to length. Cutting elements include disk saws, saw bars and shear blades, latter available in elliptical, guillotine or scissor configuration. Guillotine cutting devices are advantageous in young stands, as, due to the absence of bar and chain, small trees cannot slip between them (Erber et al. 2016a).

Spinelli et al. (2007) tested two models of Timberjack feller-buncher heads, capable of accumulating up to six trees. Productivity depended mostly on tree mass and ranged from four to eight green tonnes per effective hour of work in thinnings. However, the cutting quality of shear heads was not satisfying in the coppice treatments in Italy and France. For a forwarder equipped with a feller-buncher head (Moipu 400E), Rottensteiner et al. (2008) found that tree volume and forwarding distance significantly influenced system productivity. Ovaskainen et al. (2008) came to a similar conclusion, adding harvesting intensity to their explanation. Unexpectedly, a ceiling to the positive effect of accumulation in terms of time required per tree was discovered at above ten trees per cycle. Belbo (2010) points out that utilisation of the theoretical accumulation capacity is limited by hampered manoeuvrability of a bunch of trees and poor visibility in dense, young stands, an issue not relevant in clear cutting operations (Jylhä and Bergström 2016).

The introduction of feed rollers and delimbing knives in fuelwood harvesting heads enables integrated harvesting of delimbed, cut-to-length bundles of fuelwood and pulpwood. Laitila and Väätäinen (2013) investigated harvesting with a Naarva EF28 fuelwood head mounted on an excavator-based harvester. It showed that the efficient use of the multi-tree handling-capability by the operator could increase the productivity to a level similar to harvesting machinery dedicated to forestry. The same head, mounted on a conventional harvester, was studied while harvesting hornbeam undergrowth from below a mature stand of broadleaves and conifers (Erber et al. 2016a). Extensive employment of (>70% of the cycles) multi-tree handling resulted in 27% longer harvesting cycles than in single tree harvesting. However, the volume extracted per cycle increased by 33%, which hence caused the overall productivity to rise by 5% compared to single tree harvesting, resulting in a cost decrease of 2.6 € per m^3. The average time per tree decreased by 59% compared to single tree handling. Hardwood conditions noticeably reduced (15%) the head's maximum felling diameter. Laitila et al. (2016) point out that crooked and forked trees present a serious obstacle to multi-tree handling in combination with delimbing and bucking. Delimbing can further be a drawback regarding removal per hectare. However, it can be beneficial and cost-efficient in stands where whole tree harvesting is precluded due to nutrient loss or other ecological reasons (Laitila et al. 2010). Petty and Kärhä (2014) state that heads with multi-tree handling, delimbing and bucking capability are only cost-efficient in early thinnings with an average diameter at breast height (DBH) below 15 cm. Di Fulvio et al. (2011) showed that additional harvest of fuelwood results in 200% more volume compared to pulpwood-only harvesting in this DBH range and that it is crucial in receiving a net income.

In thinning operations, plenty time-consuming, non-linear movements are required during felling and bunching. If »boom-corridor thinning«, a variant where trees between strip roads are harvested in 1 m wide corridors with a length corresponding to the reach of the crane, higher productivity can be achieved. Compared to conventional thinning from below, Bergström et al. (2010) observed that boom-corridor thinning brought a significant productivity increase (16%), while the time consumption for crane movement between trees decreased by 17%. In a simulation performed by Sängstuvall et al. (2012), selective multiple-tree handling increased productivity by 20% to 46% compared to single tree handling, and boom-corridor thinning resulted in a further 41% increase compared to selective multiple-tree handling. Triggered by these results, Bergström et al. (2012) decided to investigate a novel harvesting head, which could fell multiple trees of up to 8 cm DBH in a row while moving the crane at a speed 1.3 m s^{-1}.

Forwarding is significantly improved by multi-tree handling, as the harvested volume is concentrated in a smaller number of locations, consequently increasing grapple loads and speeding up forwarding (Erber et al. 2016a, Laitila et al. 2016). However, the concentration effect declines with increasing forwarding distance, because the share of loading time decreases in the total time consumption (Laitila et al. 2007). Schweier et al. (2015) reported substantially better load presentation and, therefore, drastically enhanced forwarding after multi-tree handling, while the costs did not differ from motor-manual harvesting in coppice harvesting.

3.3 Compressing and bundling

The concept of bundling small, whole trees, logging residues and pulpwood, was developed to enhance forwarding and transport economics. During the last ten years, substantial progress has been made in this field.

Jylhä and Laitila (2007) published the first study on a bundle-harvester (Fixteri). A rotating, semi-automatically operating bundling unit, mounted on the rear end of a harwarder base machine, was combined with an accumulating felling head. Uniformly sized bundles, 2.6 m long, 0.5 m^3 (pulpwood) and 0.3 m^3 (fuelwood) large bundles were formed with a productivity of 2.8–3.7 m^3 per effective hour of work. If technical issues, namely the underpowered base machine and inefficient felling and feeding units were solved, this machine would have potential, especially in small-diameter (7–10 cm) stands (Kärhä et al. 2011). However, to achieve cost-efficiency, the productivity would have to rise to 4.6 m^3 and 8.7 m^3 per effective hour depending on the tree diameter (7–13 cm). An improved version (Fixteri II) displayed a productivity increase of 38% to 77%, which was primarily attributed to a new accumulating felling head, which enabled smooth feeding of the bundling unit. Multiple-tree handling (2.9 trees per grapple during more than 80% of the crane cycles) was more efficient compared to the previous machine (1.3 trees per grapple during 19% of the cycles), increasing the volume fed into the bundling unit per cycle. Improved hydraulic capacity led to an increased share of total effective working time covered by simultaneous work elements (26% to 36%) (Nuutinen et al. (2011). The Fixteri FX15a, the third version of the Fixteri had a productivity range from 9.7 m^3 (average tree volume of 0.027 m^3) to 13.8 m^3 (average tree volume of 0.084 m^3) per productive machine hour. Multiple-tree handling was improved again (2.1 to 4.3 trees per cycle). However, utilization of the bundling capacity remained low (11% to 57%), and the felling unit was accordingly considered to remain the system bottleneck (Nuutinen and Björheden (2016).

Laitila et al. (2013) found that conventional terrain bundling of logging residues is the most cost-competitive option for forwarding distances greater than 200 m, while forwarding with successive bundling at the roadside is only beneficial for short forwarding distances (<100 m) and for a removal of >50 m^3 per ha. Spinelli et al. (2012) concluded that under mountainous conditions operational efficiency of a truck-mounted bundler could only be achieved if either productivity increased by 30% or capital cost could be decreased by one third. The authors concluded that a forwarder-mounted unit would have been more efficient, as the truck-mounted bundlers operation area was limited to the roadside and entailed frequent relocation.

Manzone (2016) presented a small, prototype bundler for woody forestry and agriculture residues, especially suitable for small businesses and individual farmers. Up to 30 bundles of 18 kg to 20 kg could be produced per hour. At least under Italian pricing schemes, cost-efficient operation is possible.

Bergström et al. (2010) presented two different concepts for compressing fuelwood loads. The first concept involved breaking and flattening branches and removing foliage and fine branches from tree bunches during processing by a dedicated unit mounted on the boom-tip of a conventional harvester. Bulk density and net energy density of fresh, small Scots pine trees increased by 40% and 80% (5 cm to 8 cm DBH) and by 160% (12 cm to 15 cm DBH), while the bundle diameter decreased by 26% and 40%, respectively. However, these effects could not be observed for trees stored for as long as 10 months, and mass loss during compressing was similar to that of stored trees. The second concept involved a device for hydraulically compressing the trees on the load-bed of a forwarder by moving the stakes from the outward to the inward position. Through compression, the bulk density of birch whole trees decreased by more than 30% and a significant increase in utilized load capacity share was achieved (75% vs. 55% to 60%). A prototype head (MAMA), equipped with a feed-roller system and capable of compression-processing of whole tree bunches was compared to a conventional Bracke C16 felling head in early fuelwood thinnings by Bergström and di Fulvio (2014b). Its use increased bunch bulk density by 47% to 70%. Compression-processing related mass loss (12% to 14%) was equalized by significantly increased forwarding productivity (12%).

3.4 Storage

Fuelwood storage and drying of fuelwood have been important research subjects for at least half a century, and comprehensive knowledge has been gathered during this period. Nevertheless, research on this topic is carried out unrelentingly, nowadays focusing also on the downstream effects of fuelwood drying, such as transport economics. Consequentially, this section deals with novel knowledge in this field during the period under study.

3.4.1 Storage season and duration

It is common knowledge that spring and summer are the periods most suitable for drying of fuelwood. Contrary, autumn and winter exhibit significantly reduced drying rates or even rewetting. Badal et al. (2015) confirmed that the particularly suitable drying regime in spring results in lower moisture content of fuelwood at the time of chipping compared to material stored during other periods. Klepac et al. (2008) found that the drying rate of Pinus taeda trees stored in summer was about 50% higher (0.36% per day) than in autumn and winter (0.22% and 0.23%). Brand et al. (2010) found that the optimal storage duration for fuelwood was four to six months, starting in spring. Longer storage into autumn resulted in rewetting and decrease of net calorific value. Gautam et al. (2012 and 2013) witnessed decrease of logging residues moisture content for two successive drying seasons, but not during a third.

3.4.2 Pile size and shape, position in the pile and fuelwood size

The size and shape of a fuelwood pile determine its drying surface and susceptibility to ventilation. Gautaum et al. (2012) report that, while half-sphere (»beehive pile«) shaped piles are suitable for long-term softwood storage, half-ellipsoid (»windrow pile«) shaped ones are best for short-term softwood storage and hardwood storage in general. This effect is attributed to the greater surface to volume ratio of the windrow piles and decreased resistance to airflow due to their limited width. The more pronounced branching of hardwoods leads to less compaction and more void space, which further improves drying. Ichihara et al. (2010) report that Japanese cedar logs dried similarly regardless of piling in either triangle or quadrilateral shape. Pile size was the determining factor for the drying performance of Loblolly pine whole trees. Those stored for 70 days in skidder-sized bundles dried significantly better (final moisture content of 23.8% to 29.2%) than trees in a large pile (28.6% to 48.9%) (Klepac et al. 2014). Fuelwood stored in piles displays a decreasing moisture content gradient from the inside to the outside (Erber et al. 2012, Ichihara et al. 2010, Kofman and Kent 2009a, Klepac et al. 2014, Röser et al. 2011). Röser et al. (2011) and Kofman and Kent (2009b) point out that this gradient is not likely in covered logwood piles. However, Manzone (2015) could not observe a gradient in uncovered piles under Italian conditions either. Piece size impacts fuelwood drying, as larger (thicker and/or longer) logs dry significantly slower than smaller ones (Kim and Murphy 2013, Visser et al. 2014, Elber 2007, Bown and Lassere 2015).

3.4.3 Covering, debarking, splitting, bundling and pre-drying in the stand

The effect of covering in fuelwood drying is strongly dependent on the climate of the storage area. In Nordic countries, it is regularly applied to prevent rewetting during winter and thaw. Röser et al. (2011) observed that covering was beneficial for coniferous and deciduous logwood in the wet climate of Scotland and Finland, while it had no effect under Italian conditions. Nurmi and Hillebrand (2007) quantify the effect of covering at a 3% to 6% lower moisture content after storage from winter to autumn. Most of the effect manifested during thaw. Filbakk et al. (2011a), Nurmi (2014), Röser et al. (2011) and Visser et al. (2014) consider covering summer-dried fuelwood crucial in maintaining the moisture content decrease gained until then. A positive effect of covering was witnessed for Sug logging residues (Yukio and Tomohiro 2011) and coniferous and deciduous logwood (Elber 2007). Kofman and Kent (2009a and 2009b) point out that covering is far more important when storing fuelwood in the forest.

Debarking breaks the barrier that a tree bark constitutes to evaporation of moisture. Röser et al. (2011) report a significant, positive effect, when the piles are covered. Bown and Lassere (2015) observed that debarked Eucalyptus logs dried 8% faster than those in bark. Contrarily, Nurmi and Lehtimäki (2011) could not detect this effect after partial or strip debarking by a modified single grip harvester head. Splitting of large logs significantly increases drying rates during summer, when the piles are covered (Visser et al. 2014).

While bundling is primarily carried out for logging residues and small trees to enhance manipulation, it can also have a positive effect on the drying performance through decreased susceptibility to penetration by snow and rain (Petterson and Nordfjell 2007). However, this behaviour could not be observed by Afzal et al. (2010) and Filbakk et al. (2011b).

Pre-drying in the stand is a common practice for logging residues in Nordic countries. Three weeks of pre-drying in the stand can reduce the moisture content by more than 20% (Petterson and Nordfjell 2007), an effect similarly observed by Cutshall et al. (2010). Yet, Nilsson et al. (2013 and 2015) witnessed that, at the end of summer, the moisture content differed only slightly between logging residues stored in-stand and those piled fresh at roadside. Similar results were observed by previous studies (e.g. Nurmi and Hillebrand 2001). However, the moisture content in Nurmi and Hillebrand (2001) started to developed differently after the start of autumn when the residues in the stand took up significantly more moisture than the piled ones.

3.4.4 Dry matter losses

Dry matter losses during fuelwood supply can be caused either by microbial activity (commonly fungal attacks) or spillage of material during handling and storage (Pettersson and Nordfjell 2007). Recent studies confirm that dry matter losses related to microbial activity during storage of logwood (1% and 4% per year; Erber et al. 2012, 2016b and 2017) were considerably lower than those of whole trees and logging residues (0% to 24% during storage periods between 1.2 to 20 months; Routa et al. 2015). Residues pre-dried in small heaps in the stand did not lose dry matter, while extensive dry matter losses have been observed for logging residues piled at the roadside immediately after harvesting, which is considered to result from poor ventilation and, therefore, increased biological activity in the large piles. Bundling of logging residues is considered advantageous regarding dry matter losses (Eriksson and Gustavsson 2010, Filbakk et al. 2011b). However, Petterson and Nordfjell (2007) point out that a rather large share of logging residues dry matter is lost along the fuelwood supply chain, either during bundling or by purposely not recovering logging residues probably contaminated by soil. Nilsson et al. (2015) revealed that only 50% to 60% of the logging residues at the harvesting site arrive at the energy conversion plant.

Nurmi (2014) advocates the use of volumetric energy density as the criteria for assessing the effect of drying. In his study, both Scots pine and Downy birch whole trees exhibited a reduction of moisture content. Nonetheless, due to extensive dry matter losses (8.5% to 14.1%), the volumetric energy density of Downy birch dropped considerably (3.4% to 9.6%), even though the moisture content had also plummeted by

10.3% to 15.5% simultaneously. On the contrary, the volumetric energy density of Scots pine ascended by 0.8% to 16.5% during the same period and by 4.8% to 17.6% after 17 months.

3.4.5 Meteorological data based drying models

Increased storage levels and thus higher capital and financial costs are a consequence of keeping fuelwood piles in storage too long to ensure that they are sufficiently dry, thus exposing them to increased dry matter losses (Acuna et al. 2012, Sosa et al. 2015). To ensure economic efficiency of fuelwood supply, forest managers must apply systems for tracking the drying performance of their piles (Gautam et al. 2012). Yet, keeping track of pile moisture content by physical sampling at intervals is time consuming, costly and error-prone. Modelling the development of the moisture content of piles is considerably more economical and reliable than »educated guesses« (Erber et al. 2016b). Appropriate meteorological data based models have been developed recently and are considered a valuable tool for resource allocation in fuelwood supply (Routa et al. 2016).

There are models for differing combinations of species, material type and treatment (e.g. covering and splitting). Most are dedicated to logwood (Bown and Lassere 2015, Erber et al. 2012 and 2014, 2016b and 2017, Kim and Murphy 2013, Murphy et al. 2012, Raitila et al. 2015, Visser et al. 2014), while whole tree (Filbakk et al. 2011a) and logging residue (Routa et al. 2016, Filbakk et al. (2011b) are less frequent. Treatments include covering (Murphy et al. 2012, Raitila et al. 2015, Filbakk et al. 2011a) and splitting (Visser et al. 2014).

The joint target variable is either the alteration of moisture content during a defined period or, in reverse, the period required to reach a defined moisture content. Explaining variables are highly diverse. However, meteorological variables are commonly included. Some models (Erber et al. 2014, Kim and Murphy 2013, Murphy et al. 2012, Raitila et al. 2015, Routa et al. 2016) employ a combination of cumulative precipitation and cumulative evapotranspiration (ET_0), a parameter derived according to the FAO Penman-Monteith method. Most models estimate on a daily basis (Bown and Lassere 2015, Erber et al. 2012, 2014 and 2016b, Filbakk et al. 2011a and 2011b, Raitila et al. 2015, Routa et al. 2016). Some models (Visser et al. 2014, Kim and Murphy 2013, Murphy et al. 2012) opted for a weekly basis or a 10-day estimation period. Erber et al. (2017) concluded that the modelling period, apart from the 10-minute basis, does not affect the modelling accuracy to a large degree.

All models comply with the ±5% limit for the target accuracy, which is suggested by Erber et al. (2014) and Routa et al. (2016) and derived from discussions with fuelwood suppliers. Erber et al. (2012 and 2014) could show that exceeding a model valid range resulted in an utter overestimation of the drying performance. Nevertheless, validation against data from field studies is crucial to assess model accuracy (Routa et al. 2016).

Several approaches for scientifically monitoring a fuelwood pile drying performance are available. The »classic« approach is sampling by chainsaw (Filbakk et al. 2011a and 2011b) or weighing single stems or parts of the pile in intervals (Bown and Lassere 2015, Kim and Murphy 2013, Raitila et al. 2015, Visser et al. 2014). Yet, each variant is either associated with extensive workload or frequent disturbance of the experimental design. A more sophisticated approach, termed »continuous weighing approach« avoids these drawbacks (Murphy et al. 2012, Erber et al. 2012, 2014, 2016b and 2017, Raitila et al. 2015, Routa et al. 2016). Its basic principle is to track the drying performance of a fuelwood pile through the alteration of its weight. For this reason, the pile is put onto a metal frame, reminiscent of racks on logwood trucks, which rests on load cells. By cumulating weight alterations and starting from the physically sampled initial moisture content, the actual moisture content can be estimated. Along with the weight data, meteorological data, necessary for modelling, is recorded (Erber et al. 2012, 2014, 2016 and 2017, Murphy et al. 2012, Routa et al. 2015 and 2016b). Nevertheless, this method does have drawbacks of its own, as extensive dry matter losses and snow cover can jeopardize the estimation.

4. Discussion and Conclusion

Increasing the efficiency of fuelwood supply is a topic of research as old as fuelwood supply itself. Naturally, the focus and trends have undergone changes over time, interacting with emerging technologies and milestones in improvement.

As Stampfer and Kanzian (2006) identified, small tree dimensions are the challenging factor in fuelwood harvesting. A decade later, the challenge remains the same. There is still plenty of room for improvement, even though significant improvement has been made. Accumulating harvesting heads (multi-tree handling) and dedicated working techniques (boom-corridor thinning) significantly enhance fuelwood harvesting and the most sophisticated heads are equipped with feed rollers and delimbing knives, which enables the production of delimbed, cut-to-length bundles of fuelwood, convenient for forwarding. The suitability of these heads is perfectly illustrated by Belbo (2010), who could show that the degree of accumulation increases with decreasing tree size. However, the utilization of the theoretical accumulation capacity is limited by hampered manoeuvrability of a head full of trees and limited visibility in dense stands. What is more, the operator's skills remain the deciding factor for the productivity of generally highly sophisticated and costly procurement machinery. For this reason, special attention shall be paid to usability when developing new technological solutions (Routa et al. 2013). Multi-tree handling capacity and dedicated harvesting techniques increased the productivity of harvesting by 2% to 17%, depending on the study conditions, in comparison to a single-tree handling. However, as stated by Laitila et al. (2007), it is the forwarding productivity that benefits most (+9% to 17%) from multi-tree handling.

Bundling logging residues and small trees with dedicated machines has been considered as a feasible option to increase the load density for transportation and to increase productivity when chipping for more than a decade (Johansson et al. 2006, Kärhä and Vartiamäki 2006, Ranta and Rinne 2006, Cuchet et al. 2004). However, the effects of bundling have not been found to be as significant as expected. Bundling itself proved to work well. However, the preceding processes remain the bottlenecks in bundle-harvesting. Even though improvements have been achieved, they severely hamper cost-efficient operation. However, bundle-harvesting is still considered a feasible option for small-diameter wood (Nuutinen et al. 2016) in Nordic countries. On the contrary, in mountainous regions, bundling has been ruled out as a feasible option due to space limitations on the forest roads.

Fuelwood storage and drying have been the subject of research for a long time, as indicated by early publications, as the one of Byram (1940). During the last decade, the mechanisms of storage and drying have been investigated in detail and several treatments to facilitate fuelwood drying have been tested. Covering is feasible, but the extent of its effect depends on the climatic conditions at the storage location. Meteorological data based drying models are a recent research trend, although there has already been work on this topic as early as in the eighties (Stokes et al. 1987 and 1993). However, modern ICT has opened a whole new dimension for these models. Integrated into fuelwood procurement systems, models enable day-to-day monitoring of fuelwood pile drying performance and present a major step in improving forest fuel quality and logistics management. However, more research is required to better understand degradation processes during drying.

In fuelwood harvesting, semi-automated and remotely controlled harvesting machines, also equipped with devices for enhancing vision in dense young stands, can be considered trends for the far future. In the short term, developments will certainly focus on incremental improvements of existing technology (combined harvesting of saw logs, pulpwood and fuelwood), ergonomic innovations and widespread introduction of innovative working techniques (boom-corridor thinning). Linked to the operation of winch-supported fully mechanized harvesting systems in the transition area to cable yarding-only terrain, fuelwood harvesting heads working range will expand, too.

The future of bundling is less certain. With the insolvency of Fixteri Oy, the main proponent and driver of bundling has disappeared. However, as the bundling unit has never been the system bottleneck, a revival of this technology could be fuelled by more productive harvesting heads. In terms of handling and transport economics, bundling can still be considered a feasible option. Contrarily, fuelwood harvesting heads capable of compressing have to be considered a pioneering technology, both in terms of compaction and avoidance of excessive nutrient removal.

In fuelwood storage, research can be expected to focus on improving existing and developing new, more sophisticated drying models, which are capable of addressing degradation effects more accurately. As these models are fuelled by modern ICT and readily available high-resolution meteorological data, they will be introduced in forestry with less reluctance. Moisture content management is not limited to fuelwood. Sawmills show increasing interest in meteorological models for scheduling the point of transport and sawing. However, the latest calls in research indicate a shift of focus from energetic towards material use, a circumstance that researchers in this field will surely have to consider. Either way, moisture content management will be a topic in the future, regardless of the exact purpose.

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