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The Evolution and Expansion of Cut-to-Length Harvesting Systems Beyond Scandinavia: Challenges and Opportunities in Central and Southern Europe and North America

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Abstract

Purpose of Review We evaluated the development of mechanized cut-to-length (CTL) harvesting systems outside of the Nordic countries in areas with great potential but limited adoption. We explored the Nordic countries for context, then focused on Central/Southern Europe and North America as two examples. Within North America, we highlighted the US South as an area of potential growth for CTL systems, despite this region currently being dominated by full-tree harvesting. We reviewed the past, present, and future uses and applications of the mechanized CTL system, examining its capabilities, limitations, successes, failures, and opportunities.

Recent Findings GIS-based applications for CTL machines continue to advance, utilizing new data and technologies for harvest planning and machine trafficking to avoid wet or sensitive areas. Communication between machines related to pile assortment and location continues to improve, streamlining CTL team efficiency. The introduction of machine-mounted terrestrial LiDAR for tree selection during thinning is promising and may accelerate the development of autonomous capabilities. Unfortunately, the widescale adoption of these technologies is limited beyond the Nordic countries, where significant market and logistical challenges remain.

Summary Mechanized CTL harvesting technologies and capabilities have advanced significantly since their inception in the 1970s, with current machines representing the highest levels of mechanization, safety, ergonomics, technology, and site impact mitigation. However, several limitations impede the system's widescale adoption such as 1) the lack of effective operator training, 2) market constraints limiting the justification for value recovery benefits in small-diameter harvests, 3) lack of industry adoption of CTL-sized wood in markets dominated by tree-length stems, and 4) challenges related to productivity and cost when compared to full-tree systems.

Keywords Harvesting technology · Supply chain challenges · Mechanization · Innovation · Harvester · Forwarder

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Introduction

The mechanized cut-to-length (CTL) forest harvesting system was developed in the Nordic countries in the 1970 s and has since evolved into a two-machine system consisting of a harvester and a forwarder. The harvester and forwarder form a team in which the harvester fells, delimbs, bucks and sorts stems at the stump while the forwarder transports processed stems to landings for offloading onto cold decks or loading onto log trailers [1]. Over the past 50 years, equipment manufacturers have consistently updated and improved CTL machine designs to enhance their capabilities, efficiency, and ergonomics while reducing environmental impacts. These advancements, through field trials, research, and development, positioned the system so that even by 1999, nearly 100% of the logging in the Scandinavian region was conducted using the CTL method [2].

Use of the CTL system has expanded to different regions of the world, including Europe and both North and South America, eastern Canada and the United States (US), particularly the Lake States region and the northeastern states. However, CTL has failed to gain further prominence outside of Scandinavia for numerous reasons, in part due to significant investments in supply chains dominated by full-tree harvesting systems with corresponding transportation and unloading infrastructure, such as in the US South. CTL systems are complex and expensive, require trained operators, and frequent, specialized maintenance [3]. However, they can operate very efficiently, utilize computer-aided bucking at the stump, forward effectively on both wet ground and moderately steep slopes, optimize travel routes, minimize soil disturbance, and require relatively small landings. Full mechanization has also improved the ergonomics, health, and overall safety of logging equipment operators.

However, market logistics, navigating cultural norms, difficulty finding and/or developing experienced operators, and the per machine high capital investment have limited widespread adoption of CTL beyond the Nordic countries. Therefore, this review aims to explore the progression of the CTL system beyond the Nordic countries, highlighting patterns of adoption in areas with seemingly great potential but limited adoption. We reviewed the past, present, and future uses and applications of the CTL system focusing on capabilities, limitations, successes, failures, and opportunities. We began with the Nordic countries for context, then focused on central/southern Europe and North America as two examples. The US South, dominated by full-tree harvesting systems, is highlighted as an area of potential growth.

The Development, Evolution, and Opportunities for CTL Systems in the Nordic Countries

Cut-to-length harvesting has a long tradition in both Swedish and Finnish forestry, and the driving forces have been both markets and where the wood has been used. In the late nineteenth century, Lovén [4] wrote about sawlogs from the same cut being destined to different sawmills, while smaller dimensions were being sold for charcoal or firewood if there was a local market. However, logs could be longer than today and even comprise the full sawtimber length of the tree in some areas. Finland had a similar market situation in which logs produced from the same cut were destined for different mills and buyers [5].

The technical aspects of mechanization of logging operations in Fenno-Scandia have been well described [6, 7]. In the 1950 s, extraction by horse to waterways, railways and to smaller customers started to be replaced by forestry-equipped farm and crawler tractors. At the same time, the network of forest roads was expanded, enabling trucks to become an increasingly important solution for long-distance transportation. In many areas, forest roads reduced extraction distances from the forest to the landing. In the 1960 s, purpose-built forest tractors, forwarders and skidders were introduced for the extraction work [8], and late in the decade, the first feller-bunchers, delimbers, bucking machines and processors were introduced [6].

As a result of mechanization, the use of full-tree and tree-length methods increased in Sweden, and in 1970, about 10% of the harvested wood was harvested with these methods [9]. Although they worked well on large sites on state and company lands, these methods were less suited for harvesting on non-industrial private forest land. On the latter, average harvested volume per site was about 700 to 1000 m^3 standing volume [9]. Low harvest volumes and restricted landing space often led to low utilization of the machines in the full- or tree-length system. Delimbing, manual or mechanized, was most often performed in the harvest area due to restricted landing space, while bucking and sorting were conducted either on the landing or at a terminal. Due to low machine utilization and more difficult operational planning, the SCA company, which had harvested 31% of their annual cut with full-tree systems in 1971, phased them out during the 1970 s in favor of mechanized CTL systems. Early mechanized CTL systems utilized the same types of feller-bunchers as in a full-tree system but added a processor for delimbing and bucking and replaced the skidder with a forwarder [6]. Thus, it was still necessary to move three machines to each harvesting site. That changed to two when the first double-grip harvesters were introduced in the 1970s. In 1979, fully mechanized harvesting accounted for 64% of the volume obtained from final felling operations in Sweden, but only 13% of the volume obtained from thinnings. This changed with the introduction of the single-grip harvester in 1984, and in 1993, 91% of the thinning operations and 96% of the final felling operations were fully mechanized [10]. The mechanization of felling and processing increased productivity and reduced cost, while also leading to a significant decrease in work-related accidents and fatalities among forest workers [11].

To enable economic comparisons between harvesting systems and to provide service providers and buyers with base data for contract negotiations, large productivity studies were conducted in both final felling and thinning operations [12–15]. As the continuous improvement of work methods and machine performance made earlier productivity standards obsolete, new larger studies were conducted [16–20]. Studies also evaluated different thinning work methods [21–24], harvesters [25], and the quality effects of mechanized thinning [26–28].

The use of harvesters and forwarders is not confined to just thinning and final felling operations, and studies were made to evaluate their performance (both productivity and work quality) in shelterwood establishment [29] and removal [30, 31], patch cutting and single tree selection [32–36]. Single-grip harvesters soon proved that they could be used for most felling operations prescribed by management plans [37]. Furthermore, use of harvester and forwarders reduced both harvesting costs and improved safety in salvage logging of wind damaged stands [38]. In the mid-1990s, the single-grip harvester was considered the more versatile and profitable choice by machine owners, and the double-grip harvesters were discontinued.

As many harvesting sites in Finland and Sweden are small and the cost of machine relocations between sites can be high, a single machine that both harvests and extracts the logs to the landing may make sense [39, 40]. In the late 1990 s and early 2000 s, the first studies of such machine prototypes (harwarders) were made both in thinning and final felling [39, 41, 42]. The general conclusion was that the harwarder was an expensive machine for extraction, and the reduced relocation costs were not large enough to make it an alternative for larger sites or sites with long extraction distances. Development has continued and theoretical analyses show that these machines have an economic potential to replace the current system with harvesters and forwarders on a large share of the annual sites harvested [43]. However, the harwarder has never become popular among contractors, and currently no major machine manufacturer has a serial production of harwarders.

A factor widely debated during the 1970 s and early 1980 s was whether full-tree systems enabled a higher value recovery than the CTL system [44, 45]. In the end, these gains could not motivate the increasing production costs but led to an intense R&D effort, to both enable optimal and correct bucking as well as minimize wood damage by the processors and harvesters. It was soon realized that machine operators needed assistance to reach acceptable bucking results, which led to the first bucking computers being introduced in harvesters [46]. To enable the forest companies and forest owner associations to provide computers in their own as well as contracted machines with up-to-date log prices, it was realized that harvester data needed to be standardised. In 1988, the first StanForD forest machine data communication standard was presented, which was superseded by the StanForD2010 standard in 2011 [47]. While the first bucking computers strove to maximize value given log prices in a pricelist, soon systems to buck the logs according to sawmill demand were introduced [46, 48].

The bucking computers and data communication standards not only allow forest organizations to send bucking instructions to the machine but also enable machines to send data on harvested logs back to the system by the client. That has had a large impact on both supply chain efficiency from forest to mill and transportation planning [49, 50]. Furthermore, that has also influenced the evaluation of the machine system itself. It is no longer just an issue of evaluating productivity and costs for harvesters and forwarders, but the effects on product values and logistic costs all the way to the mills need to be included in the evaluation.

As there were computers and as it was easy to fit GPS-receivers in the machines, GIS systems were introduced in the machines [51]. That enabled the transfer of site maps with boundaries of the cut and positions of planned landings and main machine trails to the machines. That, in turn, enabled the introduction of additional decision support systems in the machines and led to increased research on systems to help the operators plan their work and monitor their progress, e.g.:

- Planning of trails and wood storage on landings to minimize forwarding distance reducing fuel consumption and emissions [52].
- Use of GIS support (soil type maps, depth to water (DTW) and other moisture maps, hydrology maps, and terrain models) to avoid damage to soils and streams [53–57].
- Use of harvester data to follow up harvesting intensity in thinning [58].
- Transfer of assortment data and wood pile positions from the harvester to the forwarder [59].
- Use of LiDAR-aided tree selection to improve thinning efficiency, quality, and prescription accuracy [60].

- Document treated areas, thinning results, as well as areas left or treated differently due to environmental reasons or cultural heritage [61].

Currently, manufacturers introduce automation of other work tasks than bucking, e.g. boom movements [62–64]. Technical research focuses on further automation as well as remote control (i.e., teleoperation) of forest machines leading to increased autonomy of the machines [65, 66]. However, to enable remote operations further research is needed to improve decision support systems, and in the case of autonomous machines refine them into decision systems.

The History of Use and Opportunities for CTL in Central and Southern Europe

Compared to traditional motor-manual techniques, mechanized CTL harvesting offers the benefits of multiplying operator productivity [67] and drastically enhancing operator comfort and safety [68]. Those benefits did not escape forestry entrepreneurs outside the Nordic regions, who also faced increasing production costs and labor shortages. However, the acquisition of the new technology required a significant capital investment, often beyond the capacity of those companies that operated within the bounds of an agrarian rather than an industrial economy [69]. Private forests were often small-scale and could not offer a large enough harvest volume to the new industrial machines. In contrast, public forests were often managed by large state companies, which had the necessary volumes to support mechanization but pursued primary social objectives and were more interested in maximizing employment in depressed rural areas than achieving higher production and financial efficiency. Once those companies were liquidated between the early 1990 s and the early 2000 s, the situation did not improve much, since their assets were dispersed among a myriad small owners (restitution process) and logging contractors (outsourcing to contractors). The introduction of mechanized CTL was further delayed by the constraints of close-to-nature forestry and of tree species with challenging form and architecture. Heavy branching represented a significant hurdle, especially when dealing with hardwood-dominated stands [70]. Completely different was the case of fast-growing tree farms, which had become a strategic objective of the European economy in the post-war years, in response to the depletion of the European wood reserves and the dwindling imports that followed the decolonization process. Those plantations would be managed for the industry and presented very favorable characteristics to the introduction of the new technology: gentle terrain, regular spacing, single tree species.

Industrial Plantations

The best examples of this group are the maritime pine (*Pinus* spp.) plantations of southwestern France, the poplar plantations of northern Italy and the eucalypt (*Eucalyptus* spp.) plantations of Portugal and Spain – all of which cater to large wood industries, such as pulp mills, particleboard factories and veneer plants. The introduction of CTL technology to the French plantations was relatively simple, given the slender shape and light branching of maritime pine. In fact, the French endeavoured to develop their own CTL equipment, with the goal of producing light and compact models that could tackle early thinning operations more efficiently than the larger Nordic machines. The French Sogedep brand [71] is a legacy of that work, originally conducted in the 1980 s [72]. By the early 2000 s, the management of those plantations was fully mechanized and was entrusted to a large machine fleet that included most commercial brands, especially Nordic. Mechanizing the harvesting of Iberian eucalyptus was more difficult, due to the need for debarking the logs at the time of felling, since the bark bond strength rapidly increases with decreasing moisture content [73]. Furthermore, in-stand debarking avoids the accumulation of bark residue at the field edge or at the processing plant and effectively responds to the lack of capable log debarking facilities at the receiving plants, which was often the case in Portugal and Spain [74]. The Nordic machine manufacturers responded by modifying the feeding rollers of their harvester heads with the application of angled steel cleats designed to break up the bark and rip it off the eucalypt stems. Just like in France, a few local manufacturers eventually developed and commercialized their own local CTL solutions [75, 76], which are appreciated by local entrepreneurs, although the Nordic product remains prevalent.

The Italian poplar (*Populus nigra* M.) plantations are another interesting case: they represent 1% of the national forest surface and 50% of the national timber production at one time, offering a stunning example of production efficiency. These plantations also present very favorable conditions for mechanization, and especially easy access and industrial management. Italian poplar trees are grown for valuable veneer wood, and therefore, value recovery is a key factor to plantation success. Owners are especially concerned with stem breakage, surface damage and suboptimal grading [77]. For that reason, they employ professional graders who mark the cutting points on pre-felled stems to guide optimal bucking. That has resulted in rather convoluted harvesting schemes, whereby the harvester first fells, delimbs and aligns the trees in orderly rows, then crosscuts them into logs only after the professional grader has inspected all stems and marked the cutting points [78]. Given the relative difficulty of cutting exactly on the crosscut mark, that operation is often delegated to grapple saws equipped with an adjustable saw on sliding guides [79].

Conventional Forests

With few exceptions, European forestry has always been managed for multiple benefits, which acknowledges the crucial role of forests in supporting a dense rural population. The emphasis on specific functions keeps changing with time and place, but no forest business can focus on exclusive timber production without any significant concerns for soil protection, water quality and recreation [80]. In recent times, recreation, biodiversity and conservation have become the dominant goals of forest management, leading to close-to-nature silviculture and continuous cover forestry. Foresters have replaced clearcuts with selection cuts and shelterwood operations, favoring repeated light harvests over heavier maturity cuts [81]. The presence of multi-cohorts with varying tree size distributions and species mix offers increased stability and higher yields as compared to mono-specific even-aged stands [82, 83]. Those benefits are contrasted by lower work efficiency, which results from the dense residual stand and the unfavorable tree size distribution (i.e., many trees are too small for cost-effective harvesting or too large for the capacity of the machine [84]). Furthermore, many forest owners have been hesitant to introduce heavy machines to their property, as they fear severe site impact. On the other hand, the growing labor shortage has forced forest entrepreneurs to mechanize, despite the difficulties they eventually faced. Hence, the introduction of mechanized CTL technology to central and southern European silviculture has been quite slow until nature intervened. The conclusive affirmation of mechanized CTL technology is demonstrably associated with extreme events capable of forcing the issue. Germany came first, with storms Vivian and Wiebke, which hit the Country in 1990 and threw over 100 million m^3 [85]. Ten years later, it was the turn of France, with storms Martin and Lothar, that blew to the ground over 200 million m^3 across most of central Europe [86]. Then, in 2018, storm Vaia swept across northern and eastern Italy, causing massive forest damage [87]. Every time, forest owners faced the problem of dealing with harvest volumes that were 4 to 7 times larger than the planned annual cut and had to be salvaged as soon as possible under extremely dangerous work conditions. Full mechanization was no longer an option: it was the only viable solution, and since the traditional harvesting method was CTL in all cases (e.g., Germany, France, and Italy), that meant a rapid shift to mechanized CTL technology. In all cases, large machine fleets were assembled from all over Europe, and once the decision was made, there was no turning back.

The Fleets

While full-tree harvesting is also applied, mechanized CTL is dominant in central and southern Europe, representing 65%, 55%, 60% and again 60% of the annual harvest in Germany, France, Italy and Spain, respectively [88]. Obviously, fleet size is proportional to the annual harvest, and it is largest in Germany and France, with 1400 and 800 harvesters, respectively [89, 90]. The corresponding numbers of forwarders would be 2200 and 1400. In Italy, those numbers are estimated to be approximately 250 harvesters and 300 forwarders, which reflects the much smaller annual harvest, estimated at 15 million m^3, vs. 72 million m^3 in Germany and 50 million m^3 in France [91]. As a reference, the combined fleets of the Czech Republic, Poland, Romania and Slovakia include approximately 1100 harvesters and 1800 forwarders, with an annual harvest volume of 80 million m^3 [92, 93]. The same source also indicates that the fleets of the Baltic countries (Estonia, Latvia and Lithuania) count 600 harvesters and 1300 forwarders, with an annual harvest volume of 33 million m^3.

Extant Issues

Harvesters, processors, and forwarders have become widespread across Europe, far beyond the borders of the Nordic countries where they were first conceived and built. Today, their use is no longer limited to gentle slopes (gradient < 25%) and softwood forests, as demonstrated by the growing popularity of winch-assisted solutions [94] and the effective deployment in French [95], German [96] and Italian [97] hardwood stands. Even where motor-manual harvesting is made competitive by cheap labor, there is a general interest in mechanization because of anticipated future labor shortages. Mechanized CTL technology has shown remarkable flexibility and is being constantly adapted to the new emerging scenarios. At present, much work is being devoted to salvaging beetle damage through the adaptation of eucalypt debarking heads to softwood operations [98, 99].

The management of site impacts is another crucial issue that has not been solved. The quest for maximum efficiency is pushing the market towards increasingly large and heavy machines [8], which is not going to alleviate the problem. Most German forestry administrations and several sustainable forestry certification schemes require in-stand traffic be constrained to permanent designated tracks, with ever-widening spacing. Those new rules make it impossible for conventional forest machines to reach all trees needed to be cut however long the boom (and heavy the carrier) one tries to develop [100]. Once the solution of ghost-trails [100, 101] was also rejected, the only alternative was to cut distant trees with a chainsaw and then drag them to the designated trail with a light tractor – eventually a specialized miniskidder [102]. Unfortunately, that process denies full mechanization and comes at the cost of decreased worksite safety, which remains the ethical imperative. Researchers are working on new solutions to minimize site impacts, which include the introduction of traction winches [103, 104], an increase in the number of axles, or the development of completely new locomotion concepts [105]. Another challenge is the adaptation of CTL technology to the requirements of close-to-nature forestry, which is based on selection cuts, increased stand variability, and extended rotations [106]. Each of those requirements brings about specific challenges for machines that were originally designed for operating within relatively limited tree size and form specifications. However, CTL technology is remarkably adaptable, and it can successfully operate under different conditions than originally intended: in fact, its adaptability to close-to-nature forestry has already been demonstrated over 20 years ago [107]. As the concept of close-to-nature forestry evolves, so will the technology tasked with its practical implementation: the important thing is that the adaptation capacity of CTL technology is matched by an equivalent adaptability of forestry practices, avoiding an imbalanced hierarchical relationship.

Mechanized CTL technology is just a tool, and like all tools, it is only as good as the arm that wields it. Operator selection and training are a main priority. A number of French and German training centres offer structured courses to harvester and forwarder operators, within specialized facilities equipped with state-of-the-art simulators and a test-drive fleet. That is not the case for Italy, where a massive training effort is focused on chainsaws rather than mechanized harvesting equipment [108]. Such an approach may mitigate current problems, but it will not solve them, nor will it prepare the next generation of loggers for their high-tech jobs. Currently, most CTL equipment operators rely on the brief ad-hoc training received by the machine dealers when the machine was sold. That is insufficient to make full use of the many opportunities offered by modern equipment. Furthermore, silviculture is seldom included in the training program offered by manufacturers, while that should become an integral component of operator training, especially if one wants to use the machines in close-to-nature silviculture operations and eventually delegate individual tree selection to their drivers [109].

The History of Use and Opportunities for CTL in North America with a Focus on the US South

CTL Adoption in North America

Globally, CTL, full-tree (synonymous with whole-tree in North America), and tree-length and non-mechanized systems account for approximately equal shares of global harvest volume [8]. CTL adoption varies substantially within North America (Fig. 1). Differences in adoption rates can be attributed to forest characteristics, market dynamics, and cultural factors. In eastern Canada, the CTL system harvests an estimated 75% of annual harvest volume, whereas CTL accounts for less than 10% of harvest volume in western Canada [88]. CTL usage has been increasing in the US

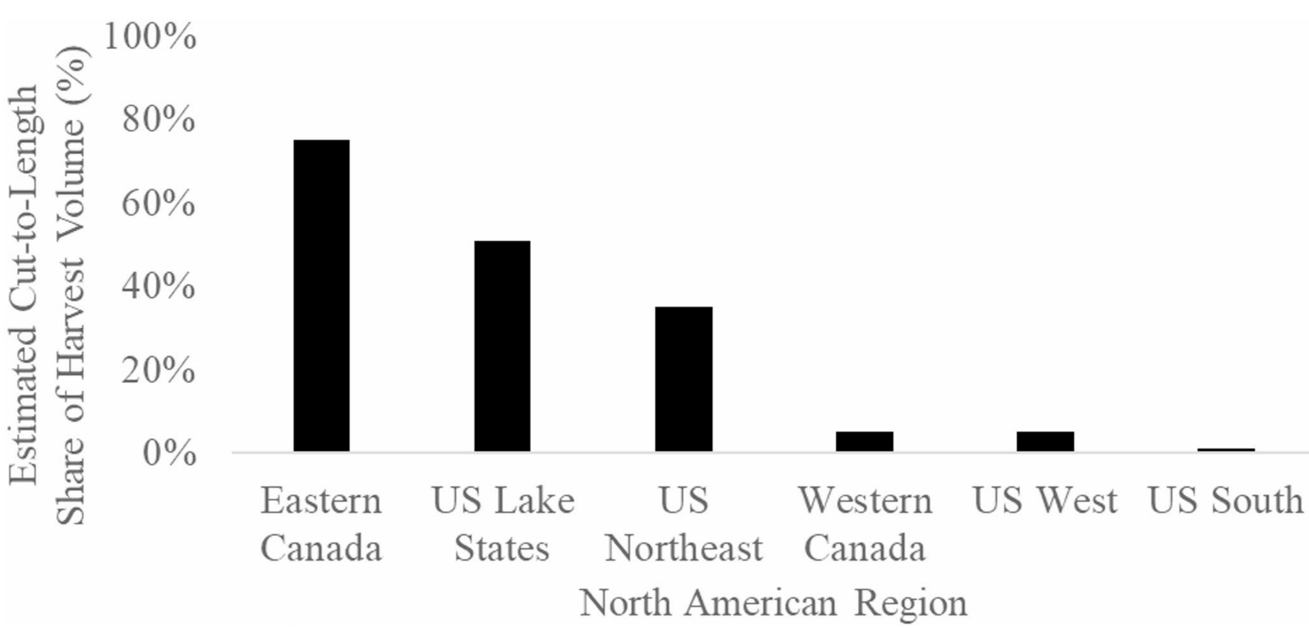

Fig. 1 Estimated share (%) of annual timber harvest volume cut with CTL systems in North America [88, 110, 111, 113–115]

Northeast and Lake States, accounting for more than 70% of annual harvest volume in the US Lake State of Wisconsin [110] and has reached nearly 40% in the northeastern state of Maine [111]. In contrast, CTL accounts for < 5% of annual harvest volume in the US South based on recent studies in Virginia, Georgia, Florida, North Carolina, and South Carolina [112–114].

The Wood Supply Chain and the History of Cut-to-Length Adoption in the US South

The US South produces 60% of the timber harvested in the US and its forest industry accounts for 4% of the total US manufacturing gross domestic product [116], has a $250 billion USD economic impact, and accounts for 2% of all jobs in the region. Georgia's forest industry alone contributes an economic benefit of over $42 billion USD [117]. The US South's wood supply chain faces significant challenges with an aging workforce, rising costs, safety concerns, transportation obstacles, and lack of innovation [118, 119]. Notably, the region lags in the adoption of data-driven decision-making and technology use [120]. Furthermore, it stands as one of the few regions globally that relies almost exclusively on full-tree harvesting systems [121–123]. In full-tree systems of the US South, processing decisions are most often based on ocular estimates of tree and log dimensions and operator experience. In contrast, CTL systems execute all processing tasks at the stump, through the use of a harvester equipped with precise diameter and length measuring technology, allowing for computerized, optimized bucking to market specifications [124]. These attractive capabilities, combined with a suitable timber resource and diverse markets, make the US South an area of potential growth for mechanized CTL systems.

During the 1980 s and 1990 s, logging mechanization and productivity advanced significantly in the US South. In 1979, the bobtail truck was still being utilized by 75% of all wood producers [125, 126]. This initial system relied on small teams conducting manual felling, delimbing, bucking, piling, and loading onto trucks [127, 128]. The bobtail system was long-lived, accounting for 21% of all pulpwood producers in 1987 [129]. However, the system was gradually replaced by full-tree operations beginning in the 1970 s with the introduction of cable skidders [130]. The manual felling and cable skidding system was short-lived due to the rise of mechanized felling using hydraulic shears and later the development of wheeled feller-bunchers with disc-saws [131]. During the same period, many loggers transitioned from the cable skidder to the more productive grapple skidder. This combination resulted in the creation of the feller-buncher and grapple skidder system utilized today. In this system, trees are severed at the stump, skidded to the landing, and most often delimbed and sorted by a trailer-mounted knuckleboom loader [130].

By 1987, the feller-buncher and grapple skidder had become the major timber harvesting system in the region [131]. In a 1997 study of Georgia loggers, 90% of loggers removed tree-length products, 74% removed log-length, and only 15% harvested shortwood pulpwood [132]. Furthermore, the feller-buncher and grapple skidder system represented 88% of the total respondents in a 1997 survey. Rubber-tired grapple skidders spread quickly, consisting of 86% of skidders reported in 1997. Trailer-mounted knuckleboom loaders were employed by 90% of respondents in the same year [132], and weekly production nearly doubled between 1987 and 1992 [131]. Widescale adoption of mechanized CTL systems never materialized. At their peak, forwarders were only used by approximately 8% of all producers in 1979 [125], and their usage dropped to only 4% in 1987 [129] and had practically disappeared in Georgia by 1997 [132]. CTL systems currently account for less than 1% of all logging crews in the region [112–114].

Despite the lack of broad adoption, considerable CTL research has been conducted in the US South, often evaluating the benefits and limitations of the system compared to the predominant full-tree system. In 1982, Lanford [133] evaluated the use of a small forwarder in pine plantation thinning applications, whereas Tufts and Brinker [134, 135] evaluated the productivity of a CTL system in second thinning with larger stems. In 1995, Lanford and Stokes [136] compared post-harvest stand and site conditions following both CTL and full-tree thinning operations while McDonald and Seixas [137] evaluated the soil compaction effects of residual logging slash on forwarder trails. A side-by-side thinning productivity and cost comparison of full-tree and CTL systems found comparable results that varied based on stem length [138]. Another study evaluated the effects of tree diameter on productivity and cost of CTL systems and determined that CTL systems were consistently more expensive than other mechanized systems, especially for small diameter trees [139]. In 2002, Bolding and Lanford [140] conducted a productivity study on a CTL harvester in a mixed pine and hardwood forest working on steep slopes up to 46% in northern Georgia. As expected, slope steepness had a significant negative effect on harvester productivity; however, no significant difference was found related to species. A study evaluated the value recovery potential of CTL harvesters in Alabama and Georgia and determined that computer-aided bucking recovered 90–94% of total stem value compared to an optimal solution [141]. Finally, Bolding and Lanford [142] evaluated the use of a CTL system harvesting and utilizing small stems for biomass utilization. These studies were useful for further understanding the application of CTL systems in the US South, highlighting significant potential benefits but often concluding with challenges related to tree size, productivity, and system cost compared to full-tree alternatives.

Market Incentives and Disincentives for CTL

Timber markets in the US South generally discourage the adoption of CTL. Logging businesses in the region operate as independent contractors and are typically paid a cut-and-load rate for their services [113, 143]. These loggers earn a profit on the difference between their cut-and-load rate and the cost to harvest and load timber on a truck. Anything that increases cut-and-load costs reduces profits, which puts CTL at a competitive disadvantage because of higher equipment purchase costs [144] and lower productivity. In addition, most pulp mills in the US South were designed to accommodate long stems (>10 m), and most pay lower prices per unit volume for the shorter lengths delivered by CTL contractors. Pulpwood accounts for up to 60% of annual harvest volume in southern states such as Georgia [145, 146], and so the lower prices paid for CTL timber have an important impact on logging businesses.

North American timber markets outside the US South are generally less dependent on the pulp and paper industry and they may favor CTL products. For example, in the US state of Oregon, pulpwood accounts for less than 10% of the annual harvest [147]. In other cases, the pulp and paper industry has a history of purchasing short log lengths compatible with CTL. In the US state of Wisconsin, pulp mills purchase roundwood in 2.5-m lengths that are ideally suited to CTL [148].

In areas harvesting a large proportion of high-value products, the high value recovery characteristic of CTL [141, 149] can overcome disadvantages in cut-and-load costs. In addition, CTL systems are capable of bucking to precise lengths when properly calibrated [150, 151] and consistent log lengths will increase mill productivity and reduce the volume of low-value residuals. Transportation costs are the same under both full-tree and cut-to-length systems in the US because truck configurations and weight limits allow for comparable loading times and payloads under both systems. Therefore, when the opportunity for value recovery exists, CTL harvesting can be cost-effective when considering all costs incurred from stump to finished product, even if stump-to-roadside costs are higher for CTL.

Finally, restrictions on soil disturbance during timber harvesting favor the adoption of CTL. Because of its lower ground pressure and travel on slash mats [137], CTL may achieve more working days per year, allowing fixed costs to be spread over more working days and more tonnes of wood, which may make CTL cost-competitive with full-tree systems [152]. Extending the operating season by days or weeks can be important in the US Northeast, Lake States, and West, where soil moisture and/or fire risk restrict timber harvesting seasonally [153–155].

Opportunities for Cut-to-Length Expansion

Continued growth in the use of CTL systems is likely in North America, although it is unlikely to achieve the market share enjoyed in Scandinavia. CTL is well-established in eastern Canada, as well as the US Lake States and Northeast (Fig. 1). These areas have local expertise and familiarity, equipment dealer support, and market conditions conducive to adoption. Both the US Northeast and Lake States have significant numbers of semi-mechanized operations [110, 111, 156] that are likely to be replaced by mechanized systems in the next decade. Lack of labor availability, high insurance costs, increased attention to safety, and other factors encourage the use of mechanized systems, and CTL is likely to expand with the continued contraction of semi-mechanized operations. In the US West, the growth of cable-assist logging on steep slopes that previously required cable yarding [157, 158] also supports growth in CTL systems, as does continued emphasis on reducing the environmental impacts of timber harvesting.

While growth in CTL harvesting is likely in North America, full-tree systems will continue to play a large role. Full-tree systems retain advantages in productivity and cost that will take precedence for many loggers. Operating conditions in many areas are suitable for either system, and full-tree systems are better-suited for productively harvesting small-diameter trees versus CTL harvesters that are constrained to process only one or two stems at a time [159–161]. Continued mill preferences for long log lengths in some markets will continue to support the use of full-tree systems as well [113, 162].

Conclusions

Based on our review, the following strengths, weaknesses, opportunities, threats, and recommendations are provided related to the evolution and expansion of CTL systems beyond Scandinavia.

Strengths

The use of mechanized CTL harvesting has expanded significantly throughout the world from its origin in Scandinavia in the 1970s. In central and southern Europe, use of the system has expanded, especially with the advent of plantations, salvage logging, and winch assist systems. In North America, CTL has been most widely adopted in eastern Canada, the US Lake States, and the US Northeast. Expansion in these regions has largely been due to (1) favorable supply chains and markets that incentivize computer-aided bucking, CTL stem size, and value recovery opportunities, and (2) operating conditions that allow the system to utilize its design features such as operating on a slash mat, aiding trafficability, or minimizing landing space requirements, which represents a major advantage in mountainous operations. System strengths also include better ergonomics, health, and overall safety of logging equipment operators.

Weaknesses

Unfortunately, in central and southern Europe, silvicultural, labor, and operator training issues hinder expansion of the system's usage. The system has been studied and implemented with marginal success in the US South but has not seen widespread adoption. Regional interest in CTL has peaked and declined over several iterations since the 1970s, and research follows a similar trend with studies ranging in date from 1982 to 2005. The need for specialized operators, mill preferences for long log lengths, and elevated per unit logging costs present major challenges for CTL adoption.

Opportunities

Despite present challenges, there are opportunities to expand the use of CTL. The rapid advancement of technology and its application to forest operations problems provide motivation to revisit the capabilities and limitations of modern CTL systems [163, 164] in regions with limited adoption. Concepts such as "Forestry 4.0" [165] and "Forestry 5.0" [166] further reiterate the interest and momentum that technology advancements have provided the industry. In the US South, given the dominance of full-tree systems, the benefits of CTL systems are most often pronounced in niche applications favoring the unique capabilities of the two-machine system. Examples include stands and prescriptions with multiple product assortments where computer-aided bucking can assist operators in improving value recovery by reducing processing errors inherent in ocular estimates and avoiding processing chip-n-saw-sized logs into pulpwood or sawtimber-sized logs into chip-n-saw assortments. A second niche application is utilizing the system on harvest sites that are small, steep, sensitive, and/or wet, and therefore poorly suited to conventional full-tree systems or shovel logging systems. Finally, CTL systems have proven recently to be effective in salvage operations following hurricanes experienced in the US South, just as storm events sparked the large-scale adoption of mechanized CTL in Europe over the past decades. The harvester's ability to pick up and optimally process downed timber is a unique advantage over wheeled drive-to-tree feller-bunchers. Similarly, size reduction directly at the stump site represents a major benefit in selection cuts, which are becoming popular in many regions, as clearcutting comes under increasingly severe scrutiny.

Threats

Technological advancement must be cost-effective and balanced with operator usability and practicality. In practice, it is not uncommon to encounter machine operators who do not fully understand or utilize the capabilities of their machines, such as GIS decision support or optimal bucking, rendering powerful technology a mere added cost. Effective operator training can assist with these challenges, but unfortunately, it is not readily available in many areas. The availability of capable, motivated operators and training programs to lessen the time to proficiency is essential but scarce in many regions, especially the US South. This fact along with the dominance of full-tree systems, associated markets, and logging costs challenges pose major challenges to significant CTL adoption.

Recommendations

1. Capitalize on lessons learned and avoid prescribing the system using a "one size fits all" approach in conditions not conducive to its design capabilities;
2. Avoid using the system in "hot logging" conditions that do not provide the benefit of in-processing inventory, hinder machine utilization, and increase costs;
3. Maximize use in stand conditions and product assortments that allow utilization of computer-aided bucking and value recovery opportunities;
4. Capitalize on operator decision support technologies such as LiDAR-aided tree selection to improve efficiency and planning machine travel to avoid sensitive soils while reducing fuel consumption and emissions;
5. Utilize the system to maximize its low ground pressure and environmental protection benefits through working in challenging terrain and soil conditions not suitable for other systems, thereby extending the operating season.

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  This paper describes the technical development over a 50-year period and sales over a 42-yr period of forwarders in Sweden. Weight, ground pressure, and potential new definitions for forwarder size classes are discussed.

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Declarations

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