Chapter 6
Harvesting of Continuous Cover Forests

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Abstract

- Overall forest management objectives and stand properties set the requirements and possibilities for harvesting in continuous cover forestry (CCF).
- Harvester and forwarder operators play a key role in successful CCF harvesting, as both productivity and quality of work are essential factors in harvesting operations.
- Optimal stand conditions improve work productivity on selection harvesting sites; harvested stem volume correlates well with work productivity in cutting, and density of remaining trees does not significantly reduce work productivity in forwarding.
- Carefully executed group cutting and shelterwood harvesting can reduce the number of damaged remaining trees, which is beneficial for future tree generations.
- Research-based information is needed about work productivity in harvesting, damage caused by harvesting, and optimisation of strip road and forest road networks for CCF.

Keywords Harvesting · Cutting · Forwarding · Productivity · Forest operation management

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6.1 Introduction

Harvesting operations in Fennoscandia are characterised by highly productive, fully-mechanised harvester-forwarder systems using the cut-to-length (CTL) method (Uusitalo 2010). The forest machines are flexible and can be used for all current cutting directives. Apart from occasional cable yarding operations in Norway, motor-manual tree felling and processing has been replaced by the fully-mechanised CTL system in Fennoscandian commercial forestry, accounting for up to 95% of harvests in Finland, Sweden and Norway (Lundbäck et al. 2021). This has shifted the sector from labour intensive to capital intensive, where high levels of machine utilisation and throughput volumes have reduced harvesting costs and increased work safety (Axelsson 1998). A shift towards CCF will significantly affect current harvesting operations, by increasing demands on planning and operator skills (Uusitalo 2010).

Technological advances in machinery and other equipment can also facilitate more precise and efficient harvesting operations, supporting the implementation of CCF. For example, modern harvesters and forwarders equipped with satellite positioning systems (GNSS) and advanced boom controls can accurately fell and extract selected trees, while minimising damage to the remaining trees. In Fennoscandian countries, it is the responsibility of the harvester operator to select trees, which further increases the mental workload during logging operations. However, improvements in remote sensing and forest inventories are improving strategic and operative decision-making in CCF harvesting.

In Fennoscandian CCF, the harvester operator is responsible not only for selecting and harvesting individual trees but also for maintaining optimal forest health for future activities. This requires a high level of skill and precision in identifying and targeting specific trees for removal, while leaving remaining trees intact. The operator must assess the quality, size, position, and growth potential of individual trees when making selection decisions during harvesting. In Fennoscandia, the working environments can vary significantly, from peatland soils with poor bearing capacity in Finland and Sweden to steep rocky terrains in Norway. Operators must be able to adapt to various conditions when logging, so they play a key role in successful execution of CCF harvesting. Training and skills maintenance, and continuous learning, are extremely important.

There are currently several national and international ongoing research and development projects, aimed at improving efficiency of forest operations in CCF harvesting. This is achieved by improving working methods or by using decision-support tools when planning the harvesting activities.

The aim of this chapter is to provide information about planning and execution of selection, group, and shelterwood harvesting in CCF, focusing on stand-level decision-making. The chapter considers first the planning phase of the logging activities, and then key features, such as expected work productivity or harvesting damage, associated with each harvesting method.

6.2 Planning Harvesting

Once the forest owner has made the decision to apply CCF harvesting in a selected stand, operational planning begins. Harvesting planning is usually carried out by a forestry professional, representing either the forest industry, the local forest owners' association, or a forestry service provider. In the planning phase, the forest owner chooses the desired and most suitable harvesting method—selection, shelterwood, or group cutting. The method selected depends on access, stand properties, management guidelines, regulations, and the forest owner's management objectives. The expected volumes of different timber assortments influence the requirements for landing sites and logistics.

Planning of harvesting (cutting and extraction) of a stand begins with evaluating accessibility. Accessibility depends on forest road quality and network density, and stand accessibility (topography). These are affected by weather conditions, which also impact logging operations. CCF is particularly affected by accessibility of forest roads, since the frequency of harvesting operations in a single stand is assumed to be higher compared with rotation forestry (RF). For example, Finnish forestry management guidelines (e.g. Metsänhoidon suositukset Tapio 2023) state that selection harvesting in spruce stands in southern Finland should take place after approximately 10–20 years, whereas in RF, thinning can be carried out after around 30–40 years and final felling at 60–100 years, depending on forest management plans. The more frequent harvesting in CCF favours a permanent forest road network, but this is an additional cost factor due to construction and maintenance work. In individual cases where volume of timber from harvests is expected to be low over longer periods, a focus on efficient machine trails might be more relevant to keep road costs low, despite higher extraction costs associated with the longer routes. Innovative planning aids, such as depth-to-water maps (Hoffmann et al. 2022) to identify suitable and trafficable machine routes for ground-based equipment, and software tools like Seilaplan (Bont et al. 2022) for cable yarding layouts, could be used in such situations to ensure low impact and efficient timber extraction.

Throughout Fennoscandia, current planning methods for harvesting from stump to roadside storage were mainly developed for traditional RF. In CCF harvesting operations, it is crucial that strip roads are placed according to log concentration, so that the work can be carried out efficiently with minimum damage to soil and remaining growing stock. Moist peatlands with low bearing capacity should be harvested in winter when the soil is frozen, whereas stands on mineral soils with good bearing capacity can be harvested at any time of the year. Compared to selection cutting, strip cutting, which can be considered a variant of group cutting, allows greater freedom in the location of on-site forwarding routes, as well as in organising route schedules. This is particularly beneficial in peatland forests (Laitila et al. 2020).

Stand properties set the framework for the work environment, harvesting productivity, costs, and quality of silvicultural outcome. The work environment includes technical harvesting factors: (1) stand structure before cutting, (2) amount of removal (m^3/ha), (3) stem volume (m^3/stem), (4) size distribution of removed trees, and (5) terrain characteristics (soil bearing capacity, slope, terrain roughness, and potential ditch network). These technical factors influence the productivity and costs of harvesting, and affect the accessibility of stands from and to the roadside. A recent study by Manner et al. (2023) supports earlier studies showing that the stem volume of removed trees is the most significant variable affecting productivity in selection cutting (Fjeld 1994; McNeel and Rutherford 1994; Suadicani and Fjeld 2001).

Stands on steep terrain comprise challenging environments for harvesting, mainly in Norway, but also in Sweden to some extent. Harvesting operations in steep terrain are expensive due to restricted access, the high level of planning required, use of specialised work systems with adapted equipment, and commonly lower productivity rates (Ghaffariyan et al. 2010; Böhm and Kanzian 2023). Lundbäck et al. (2021) note that, globally, mechanisation level falls as terrain steepness increases, although in Fennoscandia, the level of mechanisation used in steep terrain is higher than the worldwide average. Specialised machinery and equipment designed for steep terrain is required, such as ground-based machines with traction winches and steep-slope cable yarders that improve worker safety and operational efficiency (Holzfeind et al. 2020).

Planning of harvesting in steep terrain must also include protecting forest land from erosion as much as possible. Cable yarding has low environmental impact and is suitable for application in complex alpine silvicultural systems (Spinelli et al. 2015), but is only used on a limited scale in Fennoscandia. In Norway, less than 30,000 m^3 timber is produced annually through cable yarder operations, with no indication of expansion due to unavailability of a suitable workforce (Ottaviani et al. 2011).

CCF operations are not excluded from steep terrain, but they require well-conducted and adapted mechanised operations. Suadicani and Fjeld (2001) proved that carefully-planned mechanised selective harvesting in steep terrain can be productive, especially with larger stem volumes. The suitability of traction winches for overcoming technical terrain limitations and mitigating site impacts will be of particular interest in upcoming research, and projects are ongoing in Norway. Future technical developments must determine whether fully mechanised operations can be used in terrain conditions previously only harvestable using motor-manual felling and yarder extraction. One consideration is whether harvesting operations need to be conducted in all terrain conditions in the forested landscape, or whether other management objectives should be given priority in less-accessible areas.

Forest management guidelines, successful planning of harvesting, and appropriate technologies and cutting methods all contribute to the profitability of timber production, forest recreational values, and high biodiversity levels. However, the stand structure, i.e. distribution of suitable seedlings, can vary considerably within an individual cutting area (Fig. 6.1), which is why cutting may not always follow local forest management guidelines (e.g. Metsänhoidon suositukset Tapio 2023).

Professionalism and expertise of the harvester operator are particularly important in CCF, where the work environment, work planning, feasibility of the work method, and avoidance of damage to remaining trees ultimately determine the

Fig. 6.1 The thinning treatment and its timing are crucial in the success of CCF. Left: an even-structured stand. Right: a more irregular-structured stand. Photos: Erkki Oksanen/Luke

success of harvester work. The impact of the harvester operators' skills has been identified as a major factor in work efficiency (Sirén 1998; Ryynänen and Rönkkö 2001; Väätäinen et al. 2005; Kariniemi 2006; Palander et al. 2012; Purfürst and Erler 2011; Liski et al. 2020). Differences in operator skills increase as harvesting conditions become more difficult, and work planning and skills of the harvester operator significantly affect the number of damaged seedlings. In a simulation study (Miettinen 2005), when trees away from the strip road were felled, 45% of seedlings were exposed to damage. When trees were felled on the strip road where possible, 38% of seedlings were exposed. Use of the same felling directions and strip roads requires the harvester to have sufficient power and good control over the tree during felling. According to a pilot study by Manner and Ersson (2023), forwarding productivity in selection harvesting was found to be dependent on log concentration on the strip roads, while the density of remaining trees had very little effect. These issues must be carefully considered when planning and selecting a suitable CCF harvesting method for each stand.

Especially in CCF, where logging activities are frequent, the quality of remaining trees after each harvesting is crucial for maximising the future harvesting potential. However, the amount of information available is rather limited. Generally, selection cutting is perhaps the most demanding CCF harvesting method, while for example in group cutting, the proportion of damaged remaining neighbouring trees has been observed to be small.

Silvicultural outcome refers to the structure and quality of the residual trees, and soil damage and root system breakage in strip roads after cutting and forwarding

(Surakka and Sirén (2007). Harvesting maps predicting the bearing capacity of the terrain are available for most of Finland through the Finnish Forestry Center (Peuhkurinen 2017). In Sweden (Mohtashami et al. 2022) and in Norway (Heppelmann et al. 2022) there are hydrological models that can be used for predicting the risks of track rutting when planning CCF logging operations. The controller area network (CAN) of the harvester's on-board production statistics system makes it possible to compile a map of strip roads for forwarding (Ala-Ilomäki et al. 2020). With better pre-harvesting information from remote sensing and other sources such as soil maps, harvesting activities can be planned to improve cost-efficiency and minimise damage.

6.3 Selection Cutting

In Fennoscandia, selection cutting is a method used in CCF management in forest dominated by Norway spruce (*Picea abies* (L) Karst.; Lähde et al. 1999). It is mostly the largest trees that are felled to vacate growth space for the remaining trees, and dense groups of smaller trees are thinned (Surakka and Sirén 2007; Puettmann et al. 2015; Sirén et al. 2015, Lundqvist 2017).

There are challenges in the actual practice of selection cutting. One is the constant care needed to avoid damaging standing trees, which hampers harvester crane movements (Surakka and Sirén 2007). There is also a risk of damage to smaller trees in the lower canopy layers (Fjeld and Granhus 1998; Hämäläinen 2014; Sirén et al. 2015; Nyman 2016).

Finnish management recommendations for CCF (Metsänhoidon suositukset Tapio 2023) suggest no pre-clearing of undergrowth before selection cutting. However, dense undergrowth reduces visibility, and disrupts harvester head operation. In forests harvested by selection cutting, the location and quality of log bunches are not always as good for forwarding as in traditional thinning. This slows the loading work phase in the CCF stand.

The structure of timber assortments and volume of removal in the first CCF selection cutting (the conversion of even-aged stands into continuous cover stands) is generally positive for harvesting productivity. Laamanen (2014) explored the structure of eight CCF logging sites. The basal area of the sites before cutting was approximately 19–30 m^2/ha and the volume 157–285 m^3/ha. After cutting, the basal area was 6.6–14.3 m^2/ha and the volume 46–121 m^3/ha. The harvested volume was 110–231 m^3/ha, and average stem volume of the removed trees varied between 0.251 and 0.410 m^3. It should be noted that volumes from conversion harvestings may not fully correlate with future harvesting; in a long perspective, the volumes would vary according to variables like tree species, stand structure, and site index.

Several studies on work processes (e.g. Suadicani and Fjeld 2001; Manner et al. 2023) indicate that the harvester's processing time consumption (seconds per stem) in CCF selection cutting does not vary much from that in clearcutting, given trees of similar size. However, overall harvester productivity (m^3/hour) in selection cutting may differ slightly from final felling in RF, because selection cutting removes mostly the largest stems in the stand (Fjeld 1994; Lilleberg 1998; Suadicani and Fjeld 2001; Andreassen and Øyen 2002; Hämäläinen 2014).

When harvesting costs of CCF are compared with those of RF, calculations must include all harvesting treatments over the entire rotation period. However, forest owners and forest managers are more interested in revenues (timber sales) and harvesting costs (cutting, forwarding and relocation costs) when assessing feasibility in the next management decision. Lilleberg (1998) and Imponen et al. (2003) reported that the lower productivity of cutting and forwarding increased the cost of selection thinning by about 10% compared to clearcutting. However, the experimental sites were RF spruce stands without undergrowth. In Sweden, Jonsson (2015) found that the cost of CCF harvesting over the entire rotation cycle was 28% higher and machinery fuel consumption 21% higher than in RF. In Norway, Andreassen and Øyen (2002) compared selection thinning and clearcutting in uneven-aged spruce stands, with an average stem volume of 0.6 m^3 in selection thinning and 0.3 m^3 in clearcutting. The harvesting cost of selection cutting was about 10% higher than in clearcutting.

The structure and condition of standing trees after selection cutting determine the development of the forest and the timing of the next cut, and therefore the silvicultural outcome of harvesting is crucial (Sirén et al. 2015). The most important feature for near-term timber production and harvesting opportunities is trees of height 5–15 m. Studies report that 10–20% of these trees are damaged (Fig. 6.2) in

Fig. 6.2 Breakage of tops and damage to bark are typical examples of damage caused by selection cutting. Photos: Erkki Oksanen/Luke

the first mechanised selection cutting (Fjeld and Granhus 1998; Hämäläinen 2014; Sirén et al. 2015; Nyman 2016).

In CCF, the emergence of new seedlings and survival of existing ones are crucial for the long-term stand development. According to Hagström (1994), Granhus and Fjeld (2001), Vanha-Majamaa et al. (2002), Hanssen et al. (2007), and Surakka et al. (2011a, b), the damage rate of saplings of 0.5–3.0 m was between 2 and 61% in mechanised selection cutting. Laitila and Repola (2023) found that 2–4% of remaining trees were damaged after selection cutting of two Scots pine stands. The greater the volume extracted (m^3/ha) and the closer the seedlings are to the strip road, the greater the proportion of damage. There is also a large variation in the proportion of damage (Sirén et al. 2015). Similar observations in selection harvesting were found by Metslaid et al. (2018). Generally, the highest damage rates may be expected at high harvest levels in densely-stocked stands, since these conditions leave little room for the harvester operator to ensure the felling direction is kept away from residual trees and advance regeneration (Fjeld and Granhus 1998).

Weather conditions may also affect levels of damage in the residual stand. While snow cover may offer some protection to young seedlings, severe frost makes the shoots and stems of seedlings and saplings increasingly brittle and prone to breakage (Eliasson et al. 2003). Severe frost also increases risk of breakage of the tops among the intermediate canopy layer trees. However, more important than the damage proportions is the quantity, condition, and uniform spatial distribution of the undamaged standing seedlings.

In selection cutting, it can be challenging to obtain enough logging residue to create an adequate brush mat for protecting the roots of residual trees (Fig. 6.3). Availability of brush material is determined by the amount and distribution of trees to be removed, and their size and species (Surakka et al. 2011a, b). According to Sirén et al. (2013a, b), in RMF spruce stands, 15–20 kg/m^2 spruce and pine logging residues can be generated by processing as many of the trees on the strip road as possible.

Digital operator-assistance systems will be important in the challenging working environments of selection cutting (Ylimäki et al. 2012; Väätäinen et al. 2013). Pre-information about the stand and terrain is important in selection cutting, and this can

Fig. 6.3 Uneven-structured forests after selection cutting during the previous winter. Left: peatland. Right: mineral soil. Photos: Erkki Oksanen/Luke

be obtained through laser scanning. However, detection of undergrowth shorter than 3–4 m may be poor (Hovi 2011).

6.4 Group Cutting and Shelterwood Cutting

Knowledge about mechanised group cutting is based on a small set of studies, e.g. Fjeld (1994) and Eliasson et al. (2020). The knowledge base is greater for shelterwood cutting, with studies of shelterwood establishment (Eliasson et al. 1999; Eliasson 2000), shelterwood thinning (Eliasson 2000; Hånell et al. 2000), and final overstorey removal (Glöde 1999, 2001; Glöde and Sikström 2001). Harvesting of groups or gaps has been found to be more expensive than final fellings due to reduced extraction productivity and, to some extent, lower harvester productivity. More studies are needed of group and patch cutting, not only to identify efficient work methods but also to find suitable group designs that enable efficient harvesting operations. In the establishment and thinning phases of a shelterwood, the smaller size of the harvested trees and the restrictions caused by remaining trees both contribute to lower cutting productivity than in final felling. In the final overstorey removal of a shelterwood, the trees, on average, are larger than in clearcutting and thinning but harvesting profitability is lower, due to both the low removal volume per hectare (Mäkelä 1992; Glöde 2001) and the care needed to avoid damage to the regeneration (Glöde 2001; Glöde and Sikström 2001).

Group cutting and shelterwood cutting are hampered by the need for seedlings to become established, so strip roads must be planned well and their density minimised. In stands with established regeneration, the strip roads should be located, where possible, by making use of natural and harvested groups or gaps. In shelterwood stands with a dense understorey at the sapling stage, the strip roads should be systematically opened as in traditional thinning stands; when possible, existing strip roads should be used. When trees are being felled in small groups, care should be taken to avoid damaging the trees at the edge of the group (Isomäki and Niemistö 1990; Mäkelä 1992). In shelterwood cutting, the distance between strip roads can be extended by using a chain saw towards the end of the harvester's boom reach to fell inaccessible trees, which will be processed and bunched by the harvester. However, organising the work safely can be problematic, and the harvesting cost is higher than in simple harvester work (Mäkelä 1992).

The shelterwood is usually removed all at once to minimise harvesting costs and reduce damage to growing stock and soil (Hyppönen and Niemistö 1998), although there may be variation in the number of shelterwood removals depending on tree species. In seedling stands where maximum height is 0.5 m, it is best to remove the overstorey trees in winter when a thick snow cover protects the seedlings (Maukonen 1987). In both shelterwood cutting and gap cutting, seedlings protruding from the snow surface are especially susceptible to harvesting damage during frost (Roiko-Jokela 1983), so harvesting should take place in frost-free periods. In harvester work, the accumulation of logging residues can be controlled by adjusting working technique without reducing productivity (Nurmi 1994). The emergence of new seedlings in group cutting can be promoted by leaving bare soil, and seedling damage can be reduced by not processing logging residues on them (Fig. 6.4).

In shelterwood cutting, seedlings are damaged both during felling and processing of trees, but a solution can be to cover them with logging residues or log piles. Forwarder wheels or tracks can damage seedlings close to strip roads (Maukonen 1987; Niemistö 1995; Hyppönen 1996). The amount of damage is mostly affected by the removal volume and density of seedlings, and the strip road system (Peltoniemi 1991; Sikström and Glöde 2000). Hyppönen and Niemistö (1998) investigated the impact of shelterwood harvesting on the development of a pine sapling stand. Almost one-fifth of the seedlings were damaged, with the damage mostly associated with the removed volume per hectare and the density of the strip road network. Forwarding caused 60% of the damage. More important, however, is the number of undamaged seedlings remaining, and Sikström and Glöde (2000) reported that the number remaining was satisfactory. Niemistö et al. (2012) reported that careful releasing of spruce undergrowth in a shelterwood stand decreased the productivity of cutting by 11–17% compared to clearcutting. However, after harvesting, sufficient vigorous spruces were detected. According to Tamminen (1985) and Piri (1996), root damage to the remaining undergrowth in removal of shelterwood may be a greater risk than damage to seedlings themselves. This is because root rot infecting the root system spreads over a long period of time.

Fig. 6.4 Group cutting with logging residues piled at the edge. Photo: Yrjö Nuutinen/Luke

6.5 Conclusions and Further Research Needs

The overall impact of CCF harvesting, and especially selection cutting, will depend on its contribution at regional and national levels, because a possible increasing prevalence of CCF harvesting has a significant impact on harvesting areas, logistics, costs, and technology. According to Hannerz (2017), harvesting costs would increase and harvesting removals would be significantly reduced if clearcutting were to be stopped completely.

In the future, the key research and development area will be adaptation of harvesting technology and working methods to the work environment; this need was noted by Bianchi et al. (2023). The stand structure mainly influences the harvester's work method and choice of machine type. Knowledge of the working environment is necessary (i.e. stand structure and trafficability of the terrain) to see the impact of different CCF methods on timber production and future harvesting conditions. More frequent timber harvesting, with long-distance transportation logistics, will most likely have effects on soil and groundwater levels. These effects need to be understood better to plan the operations in the most effective and least damaging way.

Further research on CCF harvesting is needed to complement existing knowledge. In Fennoscandia, a large proportion of forests with a quite regular stand structure need a preliminary conversion thinning to start creating a CCF structure. A small number of forests are already unevenly structured or already managed using CCF methods. One important aim will be to develop logging activities through improved planning and working methods to reduce damage to remaining trees and the environment. The forest management recommendations may require revision from a methodology and technology perspective. For example, according to the Finnish recommendations (Metsänhoidon suositukset Tapio 2023), uncommercial small trees should not be cleared in selection cutting. Long-term follow-up information is needed from monitored stands about, for example, whether a permanent strip-road network should be used or whether a network should be designed separately for each thinning. Previous study results vary greatly on the productivity of CCF harvester cutting.

Since CCF is relatively new in Fennoscandia, there is a need to evaluate the use of different methods. Most of the stands to be harvested using the selection cutting method are in the early transition phase from RF towards CCF, so there is an interest in completely new harvesting methods to produce an uneven-aged structure. There are many stands where the density is relatively high due to a lack of treatment when the stand was young. One possible cutting method is boom-corridor thinning (BCT), which is a single-grip harvester's working method for young dense stands. In BCT all trees from specific areas are harvested in one crane movement cycle, and adjacent areas will be untreated, producing strand structures that are more heterogeneous than those created by uniform thinning of the stand from below or above (Nuutinen et al. 2021a, b; Bergström et al. 2022; Nuutinen and Miina 2023). The boom-corridors are about 1–2 m wide and 10 m deep, and are systematically placed on both sides of the strip road.

The development of CCF harvesting requires cooperation between forestry companies and contractors, machine operators, forestry authorities, and research and teaching organisations (Engeström 1987; Nuutinen 2013). The development of CCF training for harvester operators and the transfer and processing of new research knowledge into training programmes is important. The digital devices and methods that already exist provide good opportunities for this.

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