ARBETSRAPPORT 1225-2024

Aerial drones for thinning – a desk study

Jonas Cedergren, Line Djupström, Lars Eliasson, Emelie Fredriksson, Magnus Persson, Johan Sonesson, & Petter Öhrn

Foto: AirForestry

skogforsk

Contents

skogforsk

Uppsala Science Park, 751 83 Uppsala
skogforsk@skogforsk.se
skogforsk.se

Kvalitetsgranskning (Intern peer review) har genomförts i december 2024 av
Erik Ling, programchef. Magnus Thor, Forskningschef, har granskat och
godkänt publikationen för publicering i september 2024.

Redaktör: Anna Franck, anna@annafranck.se
 ISSN 1404-305X

Foreword

This report presents the results of a desk study whose main objective was to evaluate the feasibility of an airborne system for thinning in Fennoscandian forests. The system is based on unmanned aerial vehicles, drones. The system was evaluated from technical, environmental, and silvicultural perspectives.

Authors representing different areas of expertise contributed to specific chapters. For Chapters 1-6, the individual authors are stated, but all authors contributed to the concluding remarks in Chapter 7.

This report aims to illuminate the technical, environmental, and silvicultural aspects of using drones in thinning operations. By deepening our understanding of these factors, we can contribute to shaping future strategies for sustainable forestry and technological innovation in the forestry industry.

It is important to emphasise that the study assesses the general usefulness of drones for thinning – it is not an evaluation of the AirForestry system currently under development.

The funding for this study was provided by Vinnova in the research area 'Sustainable industry' (Hållbar industri). It is part of a collaboration project between Skogforsk, AirForestry and KTH. We would like to express our gratitude to Vinnova for their support and the opportunity to conduct this study. We hope that the results will contribute to the ongoing dialogue on the use of drone technology in the forestry sector and open doors for further research and development in the field.

Readers will note that forestry-related terminology is in no short supply in the document. A glossary to help readers understand the text is provided in the Appendix.

Summary

The objective of this study, a desk study, was to evaluate the usefulness/potential of an airborne system in thinning operations in forests of Fennoscandia. The system is based on unmanned aerial vehicles ("drones"). The potential was evaluated from technical, environmental and silvicultural perspectives.

Thinning is a common silvicultural treatment in Sweden, with the first thinning typically done when a stand has a dominant height of 10-15 metres. There are different methods of thinning. Thinning from below where smaller trees are removed, uniform thinning where trees from all size classes are removed, and thinning from above where larger trees are removed. Some 300,000-350,000 ha of forest are thinned every year, and roundwood from thinnings makes up some 20-25 percent of the annual roundwood harvest.

Issues of concern in connection with thinning include:

- Thinnings tend to, from a production perspective, be done too late in the rotation, resulting in poorer diameter growth in the residual stand.
- Late first thinnings make stands more prone to wind and snow damage.
- Future stand development is too often impeded by neglect of pre-commercial thinning, making later thinning difficult.
- Spread of root rot in connection with thinning due to mechanical damage from tyres on roots and logging damage to stems in stands where stumps, the main 'entry point' for root rot, have not been treated against rot.
- Logging damage and ground damage by heavy machinery.

An obvious benefit from an aerial thinning system is that no strip roads are needed. Strip roads tend to cover around 18 percent of stands thinned, an area cleared with associated production losses. Studies indicate a production loss of 5-10 percent over 15 to 20 years. Many trees harvested in first thinning are strip road trees, suppressed and/or damaged trees, i.e. trees that must be removed. Thinning using an airborne system can be more selective, but broadleaves and large and deformed trees may pose problems due to inherent limitations of airborne systems with harvester heads.

Nurse crops, crops of trees or shrubs that foster the development of another tree species by protecting it, could be used more if an airborne system become an option. Nurse crops offer frost protection to seedlings and control of groundwater, increase growth and yield by 10 to 15 percent over a rotation, and increase seedling survival. Establishment of nurse crops, mainly used to protect seedlings from frost, and removal of these crops using normal systems is difficult and expensive. Logging damage levels and operational economics have limited the use of nurse crops. With airborne systems, damage could probably be held at acceptable levels, and the recurrent operations needed could be economically more viable. This would enable wider use of nurse crops, not only for frost protection, but also to increase production over the rotation.

Diameter distribution in drone-thinned stands will be wider than in stands thinned with normal systems, very small trees covered by crowns of other trees will not be removed, and big trees, e.g. wolf types, may be too big to be handled by an airborne system. Broadleaves and large and deformed trees may be difficult to remove, as well as small trees not visible from above. This effect can be reduced by restricting the use of airborne systems to stands with few broadleaves and large and deformed trees.

An airborne system is an interesting option for removing spruce trees from sensitive sites like protected areas, buffer zones, and cultural heritage sites.

Alternatives to the system are worth considering, for example, using grapples instead of harvester heads on drones and using harvesters working from ghost trails. Problems with large and/or deformed trees and broadleaves may be eliminated with such a system. In addition, a grapple is not as heavy as a harvester head, thereby enabling larger payloads.

Technical perspectives

Thinning with an airborne machine that fells and delimbs selected trees and subsequently transports them to the landing is a new concept, so this evaluation is based on simulation techniques. Given the assumptions made, such a system with only one drone is not likely to be economically competitive against a conventional thinning system using a harvester and forwarder. This may change if one operator can manage multiple drones simultaneously. The results can be summarised as follows:

- Drone productivity is sensitive to tree weight, with an optimum load volume being close to the maximum payload.
- Drone productivity is sensitive to transport distance, especially for loads consisting of a small tree.
- Small trees result in low productivity. It will be difficult to position the harvester head to delimb and cut small trees positioned close to larger future crop trees. This was not considered in the simulations, and will cause further reductions in productivity.
- The desired extraction rates will be difficult to reach in thinning stands with a large variation in tree sizes, especially when the average stem weight is close to the safe payloads.

Pest control perspectives

During recent decades there has been a marked increase in disturbances caused by tree-killing bark beetles in all the world's coniferous forests, leading to large losses of economic values and other ecosystem services. Following the drought event in 2018, there has been an unprecedented spruce bark beetle outbreak in southern Sweden. Drought lowers water availability, which reduces tree defences and increases tree susceptibility to spruce bark beetle attack, while higher temperatures increase flight activity and development of the beetles.

Timely removal of infested trees is considered the most effective way to reduce bark beetle populations, but this is difficult in practice. An emerging field of research is focusing on remote sensing techniques for detecting beetle-infested trees as early as possible. However, pest control efficiency is limited by availability of harvesting machinery before the new generation of beetles leave the infested trees. Properly adapted, the use of drone harvesters could contribute to pest control, probably not by preventing bark beetle outbreaks but possibly dampening the severity of future outbreaks.

Effects on stand production

We assumed that the technical nature of an airborne drone system enables reduced thinning intensities, and that forest management goals in production forests remain unchanged. This motivates increased thinning frequencies compared to the conventional harvester-forwarder system.

The Heureka analysis showed no differences in stand economics, stand production, carbon storage, or diameter growth between the two harvesting techniques, given that the forest management goals were maintained.

No inherent differences between the harvesting methods were found, since growth and stand density were approximately the same throughout the thinning phase, despite the difference in thinning intensities on individual occasions. The strip-road effect was not accounted for in the simulations, but it can be assumed to have an effect amounting to an extra 10 to 30 m^3 per hectare over a rotation. This is not a massive volume admittedly, but on par with the extra volume gained through fertilisation some ten years before final felling, an investment often considered worthwhile.

Any future evaluations should include more detailed productivity estimates of the airborne drone system and experiences from practical thinning operations.

Biodiversity aspects

Thinning with drones is anticipated to yield positive environmental outcomes, primarily because of the elimination of strip roads. This will minimise the negative effects associated with their construction during traditional logging operations, for example soil and water disturbances. Thinning with drones means that there will be no understorey removal, promoting a denser vegetation layer. Drones reduce the risk of spreading invasive plants, as they do not drive over ground and carry seed or other matter from one location to another. Depending on the drone's range, there is potential for implementing smaller nature conservation measures outside the actively thinned stand.

To fully realise potential benefits, effective tools for planning and identification of structures, such as old broadleaves, from the air are necessary. Potential uncertainties or negative effects are dependent on the specifics of the drone harvesting method. For example, there is a potential risk of environmental disturbance to wildlife species from noise and the mere presence of drones that may differ from conventional logging disturbance. Generation of logging residues (GROT) and the potential covering of vegetation remains unknown until field studies have been conducted. Lastly, the possibility for the drone to reach areas currently inaccessible to machinery can cause disturbances to sensitive species in this type of refugia.

In summary, while thinning with drones presents several positive environmental outcomes, there are uncertainties and considerations that need further investigation and careful planning to maximise benefits and minimise potential negative impacts.

A final consideration

The transition to fossil-free vehicles, for example in the form of airborne systems in the forestry sector, can reduce the sector's environmental footprint and be advantageous for the business's economy and future. The forestry sector can strengthen its market position by adopting fossil-free vehicles, which can be a differentiating factor and increase demand for forest-based products from environmentally conscious consumers and companies.

Sammanfattning

Detta är en utvärdering av ett luftburet drönarsystem för användning i gallring. Nedan sammanfattas potentiella fördelar, fördelar och begränsningar med den typ av system som studerats i denna studie.

Frånvaron av stickvägar är den mest uppenbara fördelen med gallring med luftburna system förutsatt att gallringsstyrkan inte överskrider rekommendationerna. I Sverige täcker stickvägar normalt cirka 18 procent av beståndsytan efter gallring. Tillväxtökningen i skogar utan stickvägar relativt konventionellt gallrade bestånd är i storleksordningen 5 till 10 procent högre per år under 15 till 20 år efter gallringsingreppet. Frånvaron av stickvägar har även andra fördelar, till exempel högre motståndskraft mot vind- och snöskador. Trädvalet vid stickvägsfri gallring kan i viss mån bli friare, då det tvingande uttaget i stickvägarna undviks. Detta innebär också mer frihet kring vilken gallringsform som ska användas. Avsaknaden av stickvägar har även gynnsamma effekter ur miljösynpunkt, inte minst för markekosystemet.

En annan fördel med luftburna system är att mark- och rotskadorna kan undvikas. Detta kan minska spridningen av till exempel rotröta. Det kommer dock inte att eliminera behovet av stubbehandling, och rekommendationer om lämpliga tidpunkter för gallring kommer att gälla även för luftburen verksamhet. Risken för spridning av invasiva arter kan minskas då maskinerna inte har någon markkontakt och inte kan sprida frön eller annat material från en plats till en annan.

Ett luftburet system kan skapa förutsättningar att tillämpa mer skötselintensiva metoder till exempel lågskärmar. Lågskärmar ger plantorna skydd mot frost och försumpning, och ger virkesproduktion även under föryngringsfasen. Lågskärmar antas ge en produktionsökning på 10 till 15 procent över en omloppstid. Dessutom bildar de ett blandbestånd och ökar lövandelen. Skärmträd ska utses, frihuggas och avvecklas i flera steg. Detta är komplicerat och kostsamt med dagens teknik. Idag används lågskärmar i ganska liten skala, och då mest för att skydda plantor mot frost. Den ökade virkesproduktionen kan bli ytterligare motiv att använda lågskärm.

Skyddade områden, fornlämningar och buffertzoner, där mindre granar kan behöva avlägsnas, kan vara känsliga för skogsmaskiner. Ett luftburet system kan vara ett alternativ för sådana områden. Luftburna system öppnar möjligheter för skonsamma naturvårdsåtgärder även i delar av bestånd. Ett problem i dessa områden kan vara svårigheter att identifiera mindre träd under krontaket.

Fjärranalystekniker för tidig upptäckt av barkborreangripna träd är ett område under utveckling. Att i tid avlägsna angripna träd är en effektiv åtgärd för att minska barkborrepopulationerna, men i praktiken svårt att göra. Effektiviteten i bekämpningsarbetet begränsas av tillgång till avverkningsmaskiner innan den nya generationen av skalbaggar lämnar de angripna träden. Rätt anpassad skulle användningen av luftburna system kunna bidra till bekämpning av barkborre, förmodligen inte förhindra utbrott av barkborrar, men kan bidra till att minska deras omfattning.

Trädvalet i gallring kan, som nämnts, bli friare då stickvägar undviks, men tekniska begränsningar kan förhindra avverkning av vissa typer av träd. Skördaraggregat som arbetar sig nedåt längs stammar medför problem med träd med cymös tillväxt, det vill säga många lövträd, och stora och deformerade träd. Små träd som står nära och under kronan av större träd kan vara svåra både att upptäcka och att hantera och blir kanske

lämnade. Dessa begränsningar gör att beståndsstruktur, diameterfördelning (som kommer att vara vidare) och trädslagssammansättning kommer att vara annorlunda i bestånd som gallras med luftburna system jämfört med de som gallras med konventionell teknik. Detta är inte nödvändigtvis en nackdel ur miljösynpunkt, där viktiga strukturer under trädskiktet kan ge skydd, föda eller boplats om de bevaras intakta.

Bland miljömässiga nackdelar med luftburna system kan nämnas den förväntade störningen från buller som avverkning med drönare kan generera, och också blotta närvaron av drönare. Möjligheten att nå tekniska impediment utom räckhåll med konventionell teknik kan även hota störningskänsliga arter. Luftburna system blir av säkerhetsskäl svåra att använda i tätortsnära skogar och områden som används frekvent för rekreation.

Luftburna drönarsystem motiverar lägre gallringsstyrka men högre frekvens av gallring, till skillnad mot konventionella avverkningssystem. Båda systemen kan användas för att skapa snarlika bestånd, där skillnaderna motsvarar de ovannämnda. Simuleringar av optimala gallringsprogram för de två olika systemen visade inte någon väsentlig skillnad i skogsproduktion under omloppstiden. Detta beror på att om kravet på uttag i gallring under omloppstiden är det samma så spelar inte de ovannämnda skillnaderna någon roll.

Det simulerade luftburna systemet har en gräns för hur stora träd som kan tas. Avverkning av små träd innebär, liksom för konventionella gallringssystem, låg produktivitet och därmed höga kostnader. Därför har träd med en volym under 0,025 m^3 inte tagits ut i de simulerade drönargallringarna. Uttaget av stickvägsträd medför en fördel för de konventionella avverkningssystemen, då stickvägsträden bidrar till en ökad medelstamsvolym i uttaget. Avsaknaden av stickvägar och kvarlämnandet av för stora eller för små träd medför att gallring med en luftburen drönare kommer att ge en ändrad struktur i beståndet efter gallring. Det kan också medföra att den önskade uttagsstyrkan blir svår att nå i gallringsbestånd med stor variation i trädstorlekar, särskilt om den genomsnittliga stamvikten för de träd man vill avverka ligger nära den säkra nyttolasten.

Eftersträvar man en likvärdig gallringskostnad för de två systemen ger en luftburen drönare en för låg bruttointäkt för att vara ett ekonomiskt försvarbart alternativ för gallringsentreprenören i det analyserade scenariot "normal hastighet och normal positioneringstid". Även i de snabbare scenarierna är konkurrenskraften för drönarbaserad gallring tveksam. Om en operatör kan hantera ett större antal drönare ökar möjligheten till att gallring med drönare är ett lönsamt alternativ även om att bruttointjäningen per enskild drönare är låg.

En flygande drönare behöver inte nödvändigtvis bära skördaraggregat. Den kan i stället vara utrustad med en grip och endast användas för transport till avlägg. I ett sådant system kan avverkning göras av en beståndsgående skördare eller en markbaserad drönare. En grip är inte lika tung som ett skördaraggregat, vilket gör att drönarens lastvikt kan ökas. Då avverkningen utförs av en markbaserad skördare kan man lägga virket i viktoptimerade högar för drönaren. Dessutom medför lövträd och större eller deformerade träd troligen mindre problem för en markbaserad maskin.

Luftburna gallringssystem medger att man gallrar lättare och oftare, och därigenom får god kontroll på beståndstätheten. Detta kan underlätta anpassningen till klimatförändringar och minska konkurrensrelaterade risker såsom från torka, barkborrar och mortalitet. Detta hänger dock på utveckling av metoder som resulterar i minskade rörliga och fasta kostnader och hög flexibilitet i avverkningstekniken jämfört med konventionella avverkningssystem.

Elbaserad teknikutveckling ligger i linje med målet om minskade koldioxidutsläpp och bättre luftkvalitet. En övergång till fossilfria fordon inom skogssektorn kan minska sektorns miljöavtryck samtidigt som det kan vara fördelaktigt för verksamhetens ekonomi och framtid. Skogssektorn kan stärka sin marknadsposition genom att anta fossilfria fordon, vilket kan vara en differentieringsfaktor och öka efterfrågan på skogsbaserade produkter från miljömedvetna konsumenter och företag.

1. Introduction

Thinning – a brief review

Thinning is a common silvicultural treatment in Sweden, and most stands are thinned at least once during a rotation. Thinning reduces competition for water, nutrients and sunlight (Zeide, 2001), resulting in improved growth conditions for the remaining trees, as the availability of resources, primarily water, increases (Aussenac & Granier, 1988; Bréda et al., 1995). However, in practical forestry this is at the expense of total stand volume growth. Stand density is reduced primarily to improve the growing conditions for the remaining trees, enhance forest health (Helms, 1998), avoid mortality through self-thinning, and create flexibility for the future management of the stand, but more commonly to generate an early harvest of wood and the associated revenue.

A forest stand enters the stem exclusion phase when neighbouring trees start competing for resources (nutrients, water and sunlight). The severity of competition for resources is closely related to stand density (the number and size of the trees in the stand), and in practical forestry is estimated indirectly by basal area (m^2 ha^{-1}), often in relation to site index. From a forest production perspective, it is optimal to conduct a thinning operation just before crown closure (i.e. at maximum stand density).

First thinnings are recommended when the dominant height is 12-14 m, with a thinning intensity of 20-40% of the basal area, and a second thinning at 16-20 m dominant height, with a lower thinning intensity. Thinning in stands higher than 20 metres should be avoided, as that makes them prone to wind damage (Valinger & Fridman, 2011; Valinger & Pettersson, 1996).

A thinning regime/programme is defined by time of first thinning, thinning intensity, thinning frequency, and thinning method(s). The first thinning is usually done when the stand has reached a sufficient stand density, which, based on current tending practices of young stands, is recommended when the dominant height has reached 12-14 m. Thinning intensity is defined as the proportion of harvested basal area in relation to the basal area before thinning, usually expressed as a percentage. It describes how much of the stand density was removed in a single thinning intervention. Thinning frequency is defined as the number of thinning interventions within the thinning phase and is primarily influenced by site productivity, as more productive sites reach higher stand densities faster. Tree selection based on tree size is described using the thinning ratio, i.e. the mean diameter (often weighted by basal area) of the trees harvested divided by the mean diameter of the residual stand. Thinning ratio is used to categorise thinning form.

- **Thinning from below.** Thinning ratio below 0.85. Larger trees are favoured by the removal of smaller trees. It is a thinning form often recommended for dense stands, since the low diameter to height ratio increases the susceptibility to snow and wind damage. As primarily small trees are removed, the revenue may be low, especially in early thinning, as the harvest cost per tree increases with decreasing tree size (Lageson, 1996F).
- **Uniform thinning.** A thinning quota of 0.85 to 1.0. Trees are harvested from all size classes. Average size of trees harvested is bigger than for thinning from below, somewhat improving the economics of the operation.
- **Thinning from above.** Thinning quota above 1.0. Harvest is mainly made up of trees larger than the average size. Thinning from above increases risks of wind and snow damage but generates a higher revenue than from thinning from below.

Defining the thinning regime is central to achieving the set forest management goal. Single thinning interventions cannot be evaluated without accounting for the prior and future thinning interventions as part of the thinning regime.

General thinning practices

Thinning is the most common treatment in Swedish forestry, carried out on ~300,000 ha annually, and accounting for a quarter of the annual Swedish roundwood harvest (Eliasson, 2024). Historically, larger areas were thinned annually in Sweden, and stands were thinned more frequently, with lower timber yields. Increasing harvesting costs and risks of damage to residual trees (particularly in middle aged stands of Norway spruce) has reduced the number of thinning's carried out per rotation at stand level. However, there is currently a consensus in Sweden that thinning is an important tool in forestry; if performed properly, thinning can ensure a forest resilient to wind damage, with growth concentrated in the residual trees. The aim is to produce stands with high average stem volume at final felling.

Private forest owners and forest companies differ in the way they carry out thinning, but some general practices can be discerned from the 2016 review of silvicultural practices of the largest forest companies (Bergquist et al., 2016). The review found that stands are too dense at first thinning and average stem size is small because of a lack of pre-commercial thinning. These stands are generally expensive and complicated to work in at the time of thinning. First thinning is generally conducted later than recommended and with a thinning intensity that is typically 26 to 35 percent of the volume, which may result in a lower than recommended stand density. Later thinnings are done with a lower thinning intensity, and there is an unfortunate trend for thinning to be done at stand heights that exceed the recommended maximum height of 20 m. Postponement of the first thinning to enable a higher yield is tempting, as it may mean the difference between a negative and positive net revenue.

Normal strip road width in southern Sweden is 4.2 metres, and 4.6 in the north. Strip roads are normally 21 metres apart in the south, and 26 in the north. The strip road infrastructure needs to be established at first thinning, and a common result is that 15-25% of the stand area is harvested to make room for the strip roads (Bergquist et al., 2016).

The forest may be damaged in different ways at the time of felling, which has direct and indirect effects on forest growth and ecosystem function. Spread of root rot (*Heterobasidion* spp.) in connection with thinning is a problem all over Sweden that needs to be considered in all silviculture. Reducing the spread involves stump treatment, applying a suspension of spores from *Phlebiopsis gigantea* (product name Rotstop®S gel) on every stump harvested at the time of felling. Three to seven percent of the residual trees are damaged in early thinnings in the form of stem scars, and through damage inflicted when neighbouring trees are felled, etc. Soil disturbance occurs in some 15 percent of the stands thinned. However, the extent is generally moderate, covering less than two percent of the strip road length in the stands thinned (Bergquist et al., 2016).

Financial return in silviculture is a matter of when to reap the profits from a treatment, in the short or long term, taking calamity risks into account. This is particularly true for early thinnings.

Objectives

The objective of this desk study is to evaluate the usefulness of an airborne system in thinning operations in Fennoscandian forests. The system is based on unmanned aerial vehicles ("drones"). Usefulness is evaluated from technical, environmental and silvicultural perspectives.

The study is part of the work under way at AirForestry AB to develop a drone-based system for thinning. It is important to point out that the study is an evaluation of the usefulness of drones for thinning in general, not an evaluation of the AirForestry system under development.

2. Silvicultural aspects of drones in thinning

Jonas Cedergren

Assumptions

This section is mainly focused on the silvicultural usefulness of an airborne system in thinning operations. The consequences outlined are general, mainly indicating tendencies. Individual sites differ from each other, and so will the magnitude of the respective consequences outlined here.

The discussion is based on the following assumptions on the forests in question:

- Operations are done in stands dominated by coniferous trees.
- Ground-based logging is done using the cut-to-length system.
- The logging method currently dominant for thinnings in Sweden is used, i.e. a two-machine setup consisting of a harvester and forwarder working from strip roads (Björheden et al., 2018).

Methods for thinnings in Sweden also include using small harvesters working from both strip roads and ghost trails between strip roads. The forwarder works from strip roads (Grönesjö, 2016). Harwarders, machines that both harvest trees and forward logs to landings, are only used for thinnings to a very small extent (Bergqvist et al., 2002). Motor-manual cutting and forwarding using agricultural tractors still occurs but is rare (Jonsson, 2023).

Strip roads and growth

Strip roads are normally systematically aligned. Strip road width in normal operations using standard machinery is slightly more than 4 m (Agestam, 2015; Bergquist et al., 2016). Harvester cranes can reach and process trees at a distance of slightly more than 10 m, meaning that strip road coverage in stands to be thinned is about 18 percent. Strip roads are normally aligned so that they can also be used in future thinnings. A strip road is an area cleared of trees, and areas cleared means production lost. Edge effects prevent production losses from becoming proportional to areas cleared.

Scandinavian and Central European studies indicate a production loss of 5 to 10 percent in the 15 to 20 years after thinning (Agestam, 2015). Lundmark et al. (2014) show that a stand with a volume of some 100 m^3 sub (solid under bark) thinned with no strip roads will, over 15-20 years, have gained an additional 5-10 m^3 per hectare and rotation than if it had been thinned with a method using strip roads. This roughly corresponds to an increase in carbon sequestration of 3.5-9 tonnes. These findings are largely confirmed for operations in high-productive stands of Norway spruce in southern Sweden (Eriksson et al., 1994) and for pine stands in north Sweden (Bucht, 1981). Another effect of the absence of strip roads is that stands may be more resilient against wind and snow damage. Strip roads entail thinning effects that will be avoided when an airborne system is used.

Broadleaves

A harvester head that works its way down a tree requires trees with racemose growth. This could complicate work with several types of broadleaves, trees with wide double tops, and to some extent deformed trees. Harvesting of broadleaves will remain a challenge when trees are delimbed from the top downwards.

Mandatory trees

When a strip road is opened in ground-based operations, trees are removed with less regard for quality than in ordinary thinning. Strip road trees, together with deformed and/or large trees, are sometimes called mandatory trees. High-quality trees along the edge of strip roads may be damaged by machinery. However, healthy trees near strip roads will enjoy more benign thinning effects and have higher diameter growth than those further away from the strip roads. Natural pruning of trees along strip roads is slower, making future clear bole heights lower.

Mandatory trees make up a large proportion of the trees removed in early thinnings when ground-based logging methods are used. This proportion is so big that there is not much room for variation in thinning form (Lageson, 1996). With airborne systems, (first) thinning can be more selective, and there is no need to cut strip road trees, thereby permitting a wider range of extraction rates and variations in thinning form. Large and deformed trees may still be a problem with airborne systems.

Large and deformed trees, as well as broadleaves, will have to be considered when selecting stands to be thinned by an airborne system.

The residual stand

Thinning by aerial drones is likely to have implications for the diameter distribution in the residual stand. The number of small and large trees will increase. The large-tree community may include broadleaves and conifers with deformed stems. This will have implications for growth and yield when these types of trees compete for space, water and nutrients. Operational plans for pre-commercial thinnings in stands scheduled for thinning by airborne systems may have to be adapted accordingly. Indeed, as understanding of the system improves, it may prove necessary to tailor data gathering to identify areas suitable for airborne logging systems. Retention of small trees can also potentially change species distribution in residual stands, possibly affecting later thinnings. The potential importance of the effects mentioned above have not been the subject of scientific studies, so meaningful quantifications are not feasible.

Logging damage

Logging damage may be reduced when trees are lifted to landings instead of forwarded or skidded, but operational data to help quantify this effect are based on motor-manual felling and helicopter extraction. Reduced levels of damage to boles and the absence of heavy machinery in the stand reduces susceptibility to rot to some extent (Andersson, 1980). Using drones for thinning also most likely means that damage to residual trees will be lower, reducing the risk of root rot.

Stump treatment in connection with harvesting should be considered in the work to develop the harvester unit. The mere presence of stumps poses a risk of root rot – significantly greater than the damage to roots and residual tress at normal levels. Recommendations for timing of operations will not be affected by the use of drones.

Nurse crops

A nurse crop is a crop of trees or shrubs that fosters the development of another tree species by protecting the second species during its youth from frost, insolation, or wind (Ford-Robertson, 1971). Shelterwood trees are usually birches (Föreningen Skogen, 2000). Nurse crops can be said to be an intermediate method between natural regeneration and planting, normally a combination of planted spruce and naturally regenerated birch (Grönlund & Eliasson, 2019).

Nurse crop is a regeneration method that could increase the share of broadleaves and mixed forests in the Swedish forest landscape. In a nurse crop, birch grows ahead of spruce. Protection against frost and control of groundwater are advantages with the method. Nurse crops enhance seedling survival, and increase wood production over the rotation by 10 to 15 percent (e.g. Tham, 1988; Johansson, 2014; Lundqvist, 2014). Results of studies indicate that there is some loss of Norway spruce production, but this loss is more than compensated by production of the birch shelterwood. Interest in mixed stands, especially a mix of Norway spruce and birch, has grown in Sweden in recent decades. When managing mixed stands, the different growth patterns of the different tree species must be considered. One option is to utilise the fast initial growth of the birch to act as a shelter for the Norway spruce (Jacobson, 2015). There are substantial areas suitable for nurse crops in Sweden and, should the method be used more widely, a substantial volume of wood will be made available to the forest industry.

The birch shelterwood is removed in 1 to 3 operations, making the method more intensive and costly than normal practice. Shelterwood removal also entails risks for damage to the residual stand. Nurse crop removal using ordinary methods is also a costly undertaking, especially when the crop is gradually removed (Grönlund & Eliasson, 2019), and regeneration may be damaged as shelter trees are removed. Grönlund and Eliasson (2019) recorded damage on 7 to 17 % of the remaining trees, with the harvester mainly responsible. Their study concludes that nurse crops of birch should be used mainly on sites where conventional regeneration methods have little prospect of success. The study, of course, did not include airborne systems.

In summary, the nurse crops must be regarded as an intensive silvicultural system, requiring good local knowledge about the suitability of the site, as well as a great deal of flexibility and supervision. When this system is under consideration, many questions and problems are involved, but it clearly has great potential.

With airborne systems, damage could probably be held at acceptable levels, and recurrent operations could be economically more viable. This would enable wider use of nurse crops, not only for frost protection, but also for higher production over the rotation.

Figure 2.1. Nurse crop of birch south of Värnamo in southern Sweden.

Buffer zones, cultural heritage sites, and protected areas

Dense spruce undergrowth can be a common problem in buffer zones, protected areas, and heritage sites. Low site impact may be imperative in such areas, and airborne systems could prove useful. However, for safety reasons, public access would have to be restricted when operations are in progress in the vicinity of inhabited areas or areas used for recreation.

Bioenergy

Harvesting of biomass for energy is hardly an issue in thinnings. Should that change, it is unlikely that residuals can be extracted using drones. It may be possible to remove whole trees, thereby improving use of tree parts. Quantifying, or even confirming, this effect is not currently viable.

Technical comments

When developing the harvester head, it is important that it can accommodate a harvester production data monitoring tool. This tool enables very precise and efficient follow up of operations, for example cutting rates. Combined with Lidar scanning, a harvester production data monitoring tool can extract a wealth of information on the residual stand.

Fitting the drone with a grapple instead of a harvester head could be worth considering. In such a system the drone would be working in combination with a light ground-based harvester operating from ghost trails, in the future possibly autonomous. This would make it easier to harvest broadleaves and facilitate harvesting of deformed trees. A grapple would be lighter than a harvesting head, thereby permitting heavier loads. Working with a ground-based harvester, the drone would be transporting logs rather than stems with tops.

3. An operational evaluation of drones in thinning

Lars Eliasson

Most harvesting operations in the Nordic countries involve ground-based harvesting techniques, mainly single-grip harvesters and forwarders (Lundbäck et al., 2021). A small proportion of the wood in steeper terrain is harvested using motor-manual felling and processing and extraction with cable equipment or, on rare occasions, helicopters. In countries with a large amount of steep terrain, cable and helicopter systems are used more frequently (MacDonald, 1999). Due to the high costs of these extraction methods, they are mostly used for harvesting large trees either in final felling or in selection cutting (MacDonald, 1999) and care is taken to optimise load weight per turn to avoid loss in productivity.


Figure 3.1. Harvester in thinning of pine forest.

In thinning, harvester (Figure 3.1.) and forwarder productivity is low compared to final felling, leading to high costs (Eliasson, 2022), and there are risks of damage to both soil and the residual stand. One of the major causes of low productivity, and thereby high costs, is that the trees harvested are small (Lageson, 1996; Laitila, 2012). To increase productivity in early thinning, technology and methods that enable multi-tree handling have been introduced. Operators try to minimise soil damage by avoiding sensitive areas and reinforcing strip roads with branches and tops of the harvested trees (Mohtashami, 2022). However, as long as it is necessary for the forwarder to pass along the same strip road with multiple loads there is a risk of damage. Cable or airborne systems can reduce or eliminate the risk of soil damage (Han & Kellogg, 2000), but this comes at a higher harvesting cost. In selection harvest on flat ground, harvesting costs of approximately SEK 80 per cubic metre over bark have been reported for cable logging methods (Schweier et al., 2023).

Helicopter logging has high hourly operating costs (USD 3,000-4,000) and although productivity can be high (>60 m^3 per hour) when handling large trees, costs per cubic metre are unacceptably high for Nordic conditions. Furthermore, helicopters are sensitive to tree size, load size, and horizontal and vertical distance, as well as weather conditions (Stampfer et al., 2002; Bigsby & Ling 2013). The use of aerial drones for early thinning has previously been modelled in a master’s thesis, but the results were disappointing, as the small trees harvested led to a costly extraction (Häggström & Svangärd, 2022).

The aim of this chapter is to establish what revenues a drone for early thinning could be expected to generate for the owner of the machine, given that the contractor is paid the current Swedish thinning prices per cubic metre solid under bark (m^3 sub).

Materials and methods

Thinning using an aerial drone for felling, delimbing and primary extraction of single trees was simulated using ExtendSim. The efficient work time of the drone was modelled as the sum of the times for:

- Flight from the landing to the tree
- Positioning of the harvester head, delimbing the tree, and felling
- Flight from the stump back to the landing with the felled tree
- Placing the stem in a stack on the roadside landing

The aerial drone is not assumed to cut the stem into logs. This work task is assigned either to the log truck, which can do it with a grapple saw, or to a central processing station at the receiving pulp mill. This assumption could limit the number of log products produced to two or three pulpwood assortments.

As very little data regarding the drone capacity was available at the time of the simulations, four scenarios were analysed based on the following assumptions:

- The aerial drone can safely handle stems weighing up to 150 kg.
- The unloaded drone can fly at a speed of either 6 (normal scenario) or 15 m/s (fast scenario).
- The loaded drone flies at an average speed calculated as $\left(0.95 - 0.45 \times \frac{Stem\ weight}{100}\right) \times Unloaded\ speed$
- In the normal positioning scenario, positioning the harvester head takes 15 s, including the time for identifying the tree top and getting the head in the correct position. In the rapid positioning scenario, this time is reduced to 7.5 s.
- The time for delimbing and felling the tree depends on tree volume, and is set to 3.3 s plus the time needed for a medium-sized harvester to cut and process a tree of the same size.
- The distance from landing to the 0;0 coordinate in the type stand is set to 160 m. The onward distance to the coordinates of the trees harvested is calculated using trigonometry, resulting in an average extraction distance of 186 m.
- To avoid unnecessarily low productivity, trees with a commercial volume of less than 0.025 m^3 under bark (ub) are not harvested.

This gives four scenarios:

1. Normal scenario. Flight speed (empty) 6 m/s and 15 s for positioning
2. Normal speed and rapid positioning (7.5 s)
3. Fast scenario. Flight speed (empty) 15 m/s and 15 s for positioning
4. Fast and rapid scenario. Fast speed (15 m/s) and rapid positioning (7.5 s)

As it is difficult to estimate the cost of aerial drones per effective hour and the reliability, no harvesting costs per m^3 ub were calculated. Instead, the potential gross revenue per effective hour for the drone was calculated as its productivity multiplied by the thinning cost for a conventional harvester-forwarder thinning team under the same circumstances. The thinning cost was retrieved from “Cost and revenues in Swedish forest 2021” (Eliasson, 2022) and corrected to extraction of the same extracted mean stem size as in the simulated type stands.

In the late 1960s, many 0.1-ha (25x40 m) ‘type stands’ for thinning were collected by The Royal College of Forestry (Bredberg, 1972). In these type stands, every tree was positioned, measured (for example dbh, height, volume, weight, stem weight), and classified in a seven-grade scale based on the need for removal in the thinning. Future crop trees for the final felling stands were assigned a 6 or a 7, and those with a lower rank were prioritised for thinning.

In the simulations three of these stands were thinned with the drone (Table 3.1). The extraction rate was either according to the standard instruction for thinning, “Gallringsmall” (Skogskunskap, 2016), or 35 percent of the standing volume (Table 3.2). Trees were selected for felling from trees in thinning priority classes 1 to 5, starting from class 1 until enough trees has been selected to reach the desired extraction rate. Trees too heavy for the simulated drone or too small were excluded from selection. In stand 404, it was not feasible to reach a 35 percent extraction rate due to the large variation in tree sizes in the stand.

Table 3.1. Site descriptions (from Bredberg, 1972).)

Stand	Age	Dominant height (m)	Site index	Dbh (cm)	Basal area (m^2)	Stems per ha	Standing volume (m^3/ha)	Average tree volume (m^3ub)
202	37	13.5	T18	12	21.4	1780	126	0.060
208	38	16.0	T22	14	25.0	1480	164	0.094
404	40	20.0	G26	14	27.6	1500	231	0.131

Table 3.2. Extraction rates and extracted volumes in the scenarios with extraction according to the instruction “Gallringsmall” and 35 percent of volume.

Stand	Extraction rate (% basal area)	Extracted volume (m^3 ub/ha)	Notes	35% extraction rate Extracted volume (m^3 ub/ha)
202	27	28	Average according to standard	37
208	33	45	Average according to standard	49
404	14	28	Low extraction to lower field in the standard. Thinning could have been postponed.	69 (Not possible with the drone due to the set restrictions)

Results

In the scenario with 35 percent extraction rate and a fast drone with a rapid positioning, the aerial drone reached a potential gross revenue of SEK 940 per effective work hour in stand 208 under the assumed equivalent cost per m^3 as a conventional system (Figure 3.2). When the extraction rate is according to the standard instructions, revenue is reduced somewhat, as the average tree volume is lower than in the 35 percent extraction rate case.

In the scenario combination of normal speed and normal positioning time, the gross revenue is reduced to SEK 400-500 per effective hour. The drone is sensitive to transport distance from stump to landing (Figure 3.3), and with increasing distance the potential gross revenue is reduced.

For the normal speed scenarios, the predicted gross revenue would be reduced by 20-25 percent by an additional 100 m in transport distance, an increase from 186 m to 286 m.

In the scenarios with the fast drone, an additional transport distance of 100 m would reduce predicted gross revenue by 17-23 percent, although the cost of the conventional system increases by about 2 percent. Figure 3.3 also shows large positive effects on time consumption of flying the drone with optimum load weights, 110-140 kg in the case of the simulated drone. This is in line with previous experiences of helicopter logging (Dykstra et al., 1978).

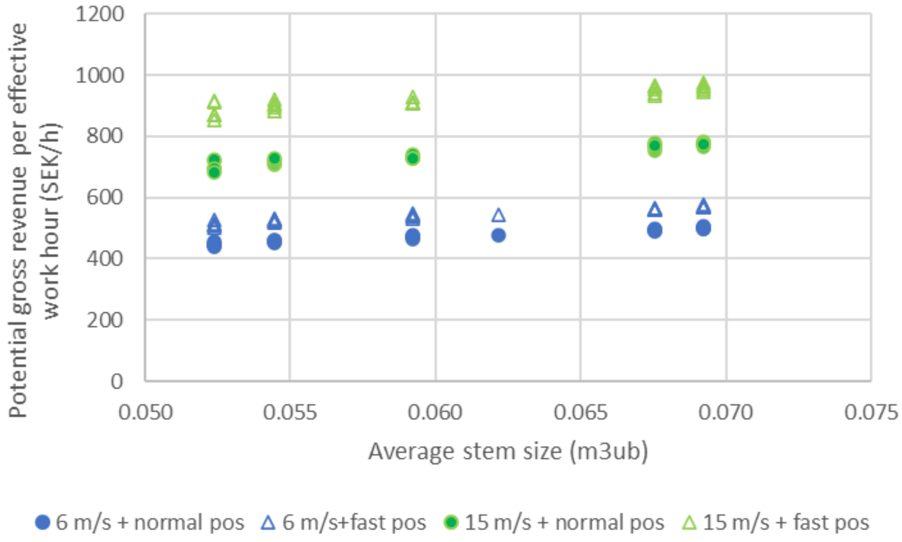
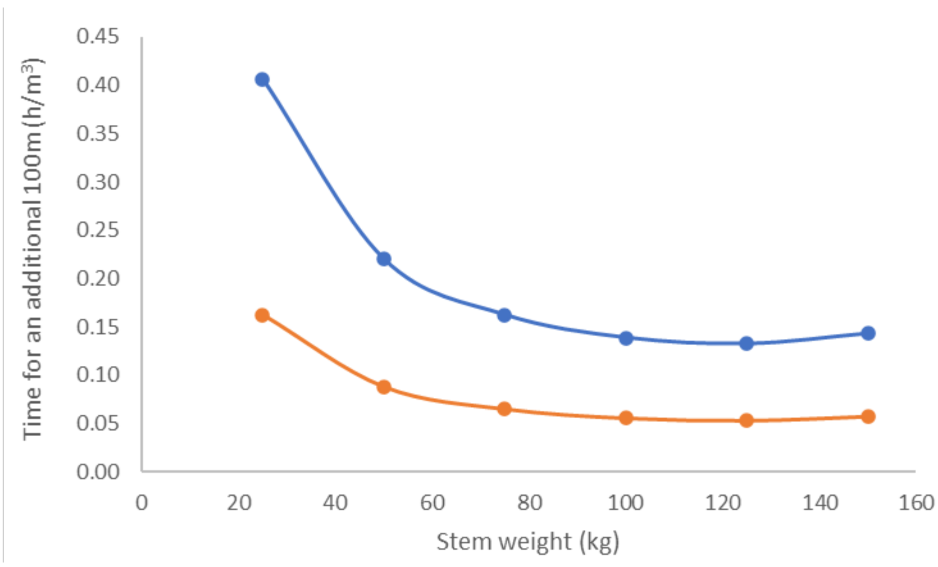


Figure 3.2. Potential gross revenue per effective work hour for the drone in three forest stands. The four scenarios are based on the set of drone capabilities described in the text.



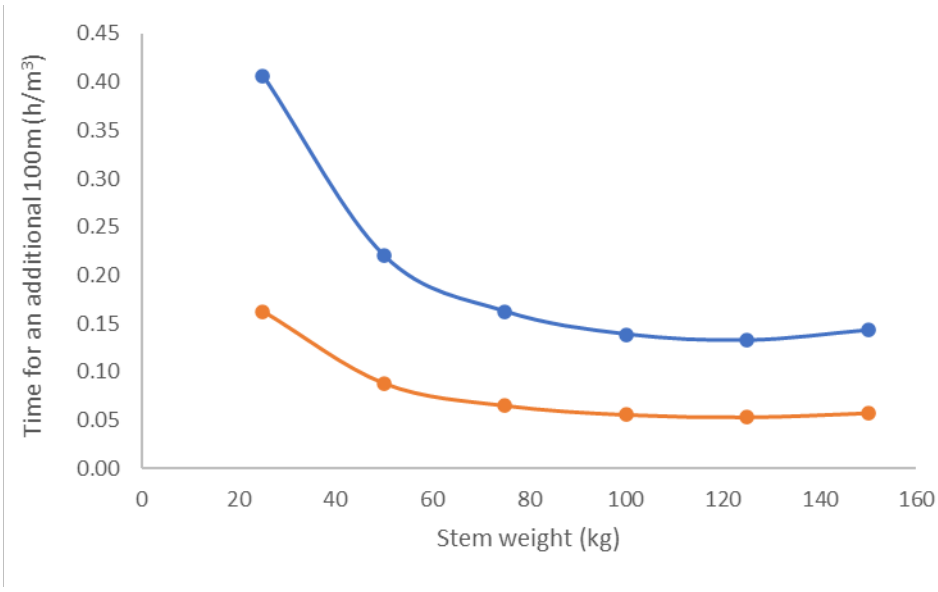


Figure 3.3. Additional flight time per 100 m increased distance between tree and landing. Blue line normal speed scenarios, orange line fast speed scenarios.

Three other conclusions can be drawn from the simulations:

- Drone productivity is sensitive to tree weight, and optimum load volume is close to maximum payload.
- Small trees give low productivity, as for most logging systems. In reality, it might be hard to position the harvester head for small trees positioned close to larger future crop trees, which will cause further reduce productivity.
- The desired extraction rates will be difficult to reach in thinning stands with a large variation in tree sizes, especially when average stem weight is close to the safe cargo weight.

The fact that there is no need for strip roads when thinning with a drone can lead to spatially more evenly distributed trees in the horizontal plane. However, as the simulated drone cannot handle large trees safely, and small trees must be left uncut because of the high cost, the consequence will be a thinned forest with a greater variety of tree sizes than after conventional thinning. The spatial heterogeneity of stands thinned with an aerial drone will likely be higher in the vertical plane and lower in the horizontal plane than stands thinned with harvester and forwarder, as shown in the example in Figure 3.4.

Figure 3.4. Stand prior to harvesting (top), residual trees after conventional thinning (bottom left) and thinning with a drone (bottom right). Harvested trees (black triangles), remaining trees (green dots), remaining due to small size (green circles), and remaining due to weight (blue dots). Thinning according to standard instruction ("Gallringsmall").

Discussion

It is important to note that the calculations are estimates of the possible gross revenue for a drone contractor based on actual thinning costs for a conventional harvester forwarder operations and modelled productivities for the thinning drone. The calculations are not based on any assumptions of operating or investment costs for the drone system. A work task, and thereby an additional cost for the drone system, not taken into account in the analysis, is the cross-cutting of stems into logs at the landing. This cost can be kept low if done by a grapple saw on the log truck, but that may reduce the value recovery for possible saw logs.

Cost efficiency of drone operations could be improved if some work tasks can be automated, allowing one operator to operate two or more drones at the same time. This will distribute the operator cost over several drones and increase the likelihood of profitability, although the gross revenue per drone is still low. The gross revenue per workplace hour will be far lower than the presented potential gross revenue per effective hour, as the time for establishment on a site, battery changes, repair and maintenance, and delay time due to bad weather has to be added to the effective work time. For a conventional system this added average time is about 10-15%, but is highly variable due to e.g. size of the harvest area. The cost for this unutilised time is included in the logging costs used for the conventional system in the calculations of the gross revenue for the drone per effective work hour.

For obvious reasons there are no data on the utilisation rate for a thinning drone. However, Conway (1982) states that the flight availability varies from 40 to 80 percent for logging helicopters during the helicopter season, if maintenance, etc. is done during adverse weather conditions. Considering other delays average utilisation is estimated at 50 percent, with a maximum utilisation of 70 percent (Conway, 1982). Assuming that the unutilised time for a thinning drone on average is one-third of the workplace time, then the gross revenue per workplace hour will be reduced from SEK 940 to 625 for the fast drone with a rapid positioning case, and from SEK 450 to around 300 in the case with normal speed and normal positioning time. Given that the cost of a machine operator is roughly SEK 400 per workplace hour, a drone operator must be able to operate multiple drones to enable profitable operations for the drone owner.

The results from the scenario “normal speed and normal positioning time” show, as did the study by Häggström and Svangärd (2022), that a single aerial drone, under the assumptions made, is not an economically viable option for thinning. If a faster drone could be developed with short positioning times the results would become more positive in pure coniferous stands, but the profitability is still doubtful. However, as the system is sensitive to increased transport distances, especially for smaller trees, even a faster drone may not be a solution at long distances unless complemented with some sort of load optimisation (cf. Dykstra et al., 1978).

If, as in central Europe (Schweier et al., 2023), minimum impact operations get government subsidies, or if landowners are prepared to pay more for the thinning service than the current market price, the results will be more positive for a drone contractor.

Small trees, especially those located under the canopy of larger ones, are a challenge for two reasons: 1) they may be difficult to locate and harvest, and 2) productivity will be low and thereby the potential revenue. There are also other trees, e.g. broadleaved or damaged trees, that will be a challenge for a harvester head that delimbs the trees from the top and down. Crooked, multi-topped or damaged trees pose a challenge for any harvester head, and probably more so for a harvesting head working from the top.

Like helicopters, aerial drones will be sensitive to adverse weather conditions and vertical distance, which has not been considered in the calculations. Powerlines, busy roads and populated areas will restrict where airborne equipment can be operated. Separate analyses of the expected effects of weather on the effective work time, and of the effects of areal restrictions on the area that can be thinned with airborne equipment, are necessary, to accurately estimate the feasibility of thinning using aerial drones.

One thing that would optimise the extraction performance is if the drone could work with an optimised load weight for each trip between the forest and the landing. Maximising payloads is one of the most important factors affecting productivity in helicopter extraction of logs (Conway, 1982; MacDonald, 1999). However, as the drone is designed to delimb, fell and extract the trees, achieving optimum payloads will be difficult, given the thinning instructions. One option could be to have a two-machine system, where a second machine fells the trees, delimbs and cuts them into logs, and places them in weight-optimised piles to improve aerial drone productivity (cf. Dykstra et al., 1978). The aerial drone would then extract these weight-optimised piles of logs to the landing.

The use of a ground-based machine for the felling and processing part would also solve many of the issues associated with excessively heavy trees and resolve the problem of having to delimb deciduous or damaged trees from the top down. Another advantage is that an optimal mix of log products can be produced, as in the current harvester and forwarder system. Today, felling and processing could be done by a small thinning harvester, but in the future, a small ground-based drone cooperating with the aerial drone might be more realistic.

4. Aerial drones in forestry from a biodiversity perspective

Emelie Fredriksson & Line Djupström

Background

Forest management in Sweden is almost entirely based on rotations of 70 to 100 years. It is common for stands to be treated with pre-commercial thinning followed by one or two thinnings, which have well-documented impacts on biodiversity, both at the local and landscape scales (Esseen et al., 1997). In terms of area, thinning is the most common harvesting operation, with approximately 40 percent of Swedish forests in the thinning phase, usually around 30 years old. The thinning phase of the rotation is the phase with the lowest amount of coarse woody debris (Ranius et al., 2003), a structural component of great importance for biodiversity (Stenbacka et al., 2010; Peltoniemi et al., 2013), and one that is currently in short supply in the modern forest landscape (Siitonen et al., 2021; Fridman et al., 2000).

Current forestry standards for thinning operations comprise guidelines aimed at both creating and protecting structures that hold biodiversity value, including creating high-cut stumps (Figure 4.1) and protection of old trees (Albrektson et al., 2012). The thinning stage specifically has enormous potential to add dead wood, which is lacking at a landscape level and beneficial to many species, such as beetles (Thibault et al., 2016;

Lindbladh & Abrahamsson, 2008). However, issues such as soil compaction, tree damage, and rutting are often challenging to mitigate when heavy machinery is used in the forest (Worrell & Hampson, 1997; Sirén et al., 2013). These issues can have significant impacts on the function of ecosystems and important structural components. In this section, we aim to evaluate, at a theoretical level, the potential differences between conventional thinning systems and airborne systems in terms of their biodiversity impacts.

Figure 4.1. High-cut stumps are a common Swedish conservation measure aimed at cutting trees at a height of 3-4 metres, thereby creating standing, sun-exposed deadwood. High-cut stumps are long-lasting substrates that provide habitats for extended periods. *(Credits: L. Djupström).*

Method

We conducted a literature review to evaluate and describe the potential impacts on biodiversity when thinning with an airborne system compared to a conventional thinning system using a ground-based harvester and a forwarder. To our knowledge, no direct effects of airborne systems on biodiversity have been studied, even historical attempts to harvest from the air using helicopters or balloons. We therefore focused on theoretical possibilities and the positive/negative effects that may arise when thinning does not involve conventional methods, such as potential reduction in soil compaction.

The literature was reviewed using the search engine Google Scholar with keywords related to forest thinning impacts on different types of biodiversity and the environment. This review was not conducted systematically, where a specific search string was used, and all results were evaluated. Instead, our goal was to gain an overview of the literature regarding the impacts of thinning using conventional methods, providing examples across a wide range of taxa and emphasising relevance to Sweden.

Results

Strip roads and soil impact

Thinning with drones is anticipated to yield positive environmental outcomes, primarily attributed to the elimination of strip roads. During mechanised logging operations, temporary logging roads (strip roads), typically 4-4.5 metres wide, are created. Even though strip roads are a temporary measure, they still impact the functioning of the forest ecosystem and alter local conditions in various ways. These strip roads change the structure and create a linear feature in the otherwise intact forest canopy, but mostly the driving of heavy machinery can lead to soil compaction, altering the soil structure and reducing its ability to absorb water, thereby impacting water filtration and erosion (Worrell & Hampson, 1997; Nikooy et al., 2020). Compaction can also increase surface runoff and nutrient leakage, affecting aquatic ecosystems (Worrell & Hampson, 1997).

The establishment and use of strip roads can result in direct damage to the trees' roots, and in turn, provide an entry for root rot (Wästerlund, 2020), possibly injuring trees of high future conservation value. Heavy machinery may destroy dead wood in the late successional stages already present in the stand. Heavily decayed coarse dead wood, both standing and lying (logs), is rare in Fennoscandia today, and is an important structure to preserve for both insects (Siitonen 2001) and polypores (Sippola et al., 2001). This also holds true for species that are sensitive to disturbances in general.

Canopy gaps, inevitably formed by strip roads, can also positively impact biodiversity. For instance, these openings can mimic natural small-scale disturbances, leading to higher diversity of saproxylic insects in stands with sun-exposed dead wood in strip roads (Joelsson, 2017). These gaps can play a significant role in establishment of early successional species in several ways. Increased light availability on the forest floor promotes light-demanding plant species with positive impacts on plant diversity and richness compared to non-thinned stands (Strengbom et al., 2018; Widenfalk & Weslien 2009). Increased sunlight warms the forest soil, which can activate seed banks and accelerate seed germination and enhance plant growth and establishment of new plants. When trees are removed, competition is reduced, nutrients become available, and early successional species can capitalise on this nutrient influx, allowing them to establish.

Using an airborne harvester could potentially mitigate some of the negative impacts directly linked to strip roads, especially those affecting the forest soil ecosystem. Harvesting with a drone would also provide greater flexibility to adapt the harvesting process to achieve stand-specific goals aligned with promoting biodiversity and ecosystem functions. The adaptation could be to choose trees to harvest, or leave standing those that have a positive effect on structure and spatial distribution, which may promote biodiversity.

Understorey vegetation cover

Since no machines are needed on the forest floor when using drones there will be no need to make strip roads and/or remove field layer trees or scrubs. Removal of smaller trees and shrubs is common in conventional thinning operations in Swedish forestry today (sight clearing or, in Swedish, “förröjning”, Albrektson et al., 2012) to increase visibility for machine operators and facilitate tree felling. Removal of understorey vegetation reduces the vertical variation in the stand, which has been shown to be important for both birds and pendulous lichens (Klein, 2020). From a biodiversity perspective the ability to keep a dense understorey layer when thinning with a drone could be positive also for species that require shelter from predators. The vegetation also acts as an important forage resource for ungulates.

Invasive species

A machine driving over the ground can entail an increased risk of spreading invasive plants, as seeds and other matter may be carried into the forest from one location to another on the tyres (Rauschert et al., 2017). This risk should be smaller with drones.

Environmental pollution from noise propagation

Wood harvesting, including forwarding operations, can be achieved by different systems depending on the site terrain characteristics. Nevertheless, the operations commonly use mechanised equipment that produces noise and generates vibrations, which may have a negative effect on sensitive wildlife. Noise creates disturbances and can stress animals, interferes with their communication and behaviour, and drives them away from important areas (e.g., Kight & Swaddle, 2011). The noise generated by petrol-driven chainsaws, nowadays rare in Swedish forestry, is familiar as one of the most significant noise sources in forest operations, even when compared to helicopters, for example based on the reaction of owls (Delaney et al., 1999).

The effects of aerial activity from small drones and other free-flight (hand-gliders, paragliders and powered derivatives) on wildlife have been reviewed by Mulero-Pázmány et al. (2017) and Tobajas et al. (2021). Mulero-Pázmány et al. (2017) found that birds are more prone to react than other taxa, and larger birds more than smaller birds. Tobajas et al. (2021) report that unrestricted flying activities disturb wildlife animals of ungulate species and species of raptors by causing adverse impacts such as heightened energy consumption, decreased feeding duration, abandonment of feeding zones, diminished breeding success, deterioration of physical condition, heightened risk of predation, and potential harm from flight-related accidents. Nevertheless, the inadequate research on various species and locations, coupled with the limited number of long-term studies, hinders a comprehensive evaluation of the present status concerning the influence of this activity on wildlife.

Along with the potential disturbance from the presence of flying drones in forests, aerial harvesting methods still necessitate the use of an electric chainsaw on the harvester head. However, the noise levels from such a saw are lower than the petrol-driven saws used in motor-manual felling and, possibly, the hydraulic-powered saws used by harvesters. However, disparities from ground-based thinning, encompassing variations in sound levels and operation duration, mandate thorough monitoring and analysis of the specific area. Only after such an assessment can any informed conclusions be drawn regarding the potential environmental impact.

Theoretical potential and uncertainties

We envision the potential for goal-oriented forest management as being more flexible and less spatially constrained when using a drone for thinning operations rather than a conventional harvester. This approach allows for extra consideration of buffer zones along waterways, selective clearing of important broadleaves such as oaks, and deliberate creation of dead wood, all of which are above the current requirements from for example FSC (Forest Stewardship Council, 2015). Creation of high-cut stumps and conservation of natural structures and processes in stands have been seen to be valuable for biodiversity, especially in mid-rotation stands where diversity was found to be generally low (Peltoniemi et al., 2013). There is also a significant opportunity to create gaps of varying sizes, depending on local conditions, to emulate small-scale natural disturbances, thereby positively impacting species that thrive in disturbed environments. For example, creating a mosaic of forest patches with different densities of trees through thinning has been seen to be positive for bats in Canada (Patriquin & Barclay, 2003).

Depending on the drone's range, there is also potential for implementing smaller nature conservation measures outside the actively thinned stand. However, to fully realise these potential benefits, effective tools for planning and the identification of structures, such as old broadleaves, from the air are necessary. There may be a negative impact in that areas that have not been accessible with traditional forestry machinery may now be harvested with the increased accessibility provided by drones. These areas often have high environmental values because they have been left undisturbed, and frequently host a wide variety of habitats due to, for example, varied topography. It is always important to assess the value and the need for conservation measures before tree harvesting takes place.

An airborne system executes a sequence that involves clearing a tree's branches during its descent, followed by precision cutting and lifting of the entire tree, including the top, from the forest floor. This process results in the creation of a 'bouquet' composed of small branches encircling the stump of the harvested tree. The tree top and branches, referred to as logging residue or slash, represent a woody residue with valuable potential for bioenergy applications. This utilisation is currently only observed in final felling operations. In Sweden, it is customary to leave approximately 20% of the woody residue, mainly treetops, in the forest (Skogsstyrelsen, 2008). This practice is rooted in environmental considerations, as it contributes to the nutrient cycle and increases the availability of deadwood. Adhering to Forest Stewardship Council (FSC) regulations, woody residues from broadleaved trees (excluding *Betula* spp.) must be retained, with treetops from all broadleaves falling under the same stipulation. It appears feasible that thinning with airborne systems could potentially leave treetops for conservation purposes.

Small-diameter deadwood can also hold significance for biodiversity of, for example, beetles (Brinn et al., 2011; Seibold et al., 2018) but not to the same degree as large-diameter dead wood (Heilmann-Clausen & Christensen, 2004), but this is rare. The impact of branches covering vegetation must be considered, especially lichen-rich ground in northern Sweden, as it is a declining and important resource for reindeer (Sandström et al., 2016). However, the specific impacts in this form of harvesting remain unknown until field studies can be conducted.

Conclusion

In summary we conclude that thinning with an airborne system compared with conventional methods has potential to reduce negative effects, especially in terms of no direct damage to the soil, water, structures such as logs, and cultural heritage. Airborne methods may also enable greater flexibility, both spatially and temporally, depending on local conditions and the specific goals for stands, in harvesting trees at different times of the year and in more difficult terrain (wet or steep). This unlocks possibilities to create and preserve structures important for biodiversity, emulating small-scale natural disturbances to a higher degree. However, the magnitude of these potential effects on biodiversity cannot be determined from a literature review, and must be evaluated with field trials comparing the two harvesting methods and monitored over time.

5. Effects on growth, stand development and stand economy – simulations in Heureka

Magnus Persson

Background

There are technological differences between a drone system and the conventional harvester/forwarder system, suggesting differences in how the thinning operations could be carried out (harvesting method). Strip roads account for 15-20% of the thinning intensity using a conventional harvesting system, and typically an additional 10-15% is harvested to create more growing space for the remaining trees between the strip roads. The drone system does not demand establishment of strip roads at first thinning, which allows a freer selection of trees and potentially lower thinning intensity (see discussion about tree selection in previous chapters). Another main difference between the drone system and a conventional harvester/forwarder system is the freedom of movement. Potentially, the drone system would likely be working in groups and should be able to operate over larger distances from the landing area than the conventional harvester/forwarder system. These two factors enable lower thinning intensities and more frequent thinning of a stand, given that forestry in the area is planned at the estate level and larger, and that an equivalent volume must be harvested in thinning during the rotation.

Objective

In this sub-project, harvesting using a drone system is compared to a conventional harvester-forwarder system. The primary objective is to determine whether there are any potential benefits directly related to harvesting technology, excluding the influence of forest management goals.

Materials

The stands used in the simulations represented young stands ready for early first thinning, i.e. at a dominant height of 12 metres (Table 5.). The stands were created based on what is defined as a mature thinning stand in the Swedish Forest Agency (Skogsstyrelsen) thinning guides (SKS, 1984). The basal area coinciding with the upper limit in the thinning guideline at 12-m dominant height for each site index (T22-T28, G26-G32) was used. Each stand was assumed to have 2,000 stems per hectare. The stands were assigned an average diameter, age, etc. using other forest models.

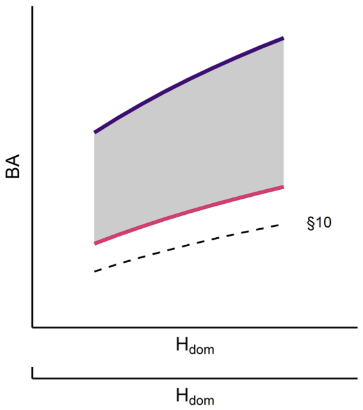


Figure 5.1. Thinning guide with basal area (BA) on the y-axis and dominant height (Hdom) on the x-axis, along with an upper target line (deep purple) and a lower target line (crimson red) representing the range in basal area. The dashed line represents Chapter 10 in the Swedish Forest Act.

Table 5.1. Summary of the stands: their site index, number of stems, basal area and DGV (basal-area weighted mean diameter).

Tree species	Site index (H100)	Number of stems	Basal area	DGV (basal-area weighted diameter)
Scots pine	T22	2,000	21.3	12.7
Scots pine	T24	2,000	22.2	12.9
Scots pine	T26	2,000	23.2	13.2
Scots pine	T28	2,000	24.1	13.4
Norway spruce	G26	2,000	25	13.8
Norway spruce	G28	2,000	25.4	13.9
Norway spruce	G30	2,000	25.8	14
Norway spruce	G32	2,000	26.1	14.1
			N =	8

Method

Assumptions

Given the assumptions above, moderate or heavy thinning can be avoided using the drone system. This could potentially lead to temporarily higher growth, as stand production is largely determined by the basal area (m^2 ha^{-1}) after thinning (Ekö, 1985; Pienaar, 1979). Throughout the thinning phase, these differences may speak in favour of more frequent and less intense thinning interventions.

The forest owner's management objective is summarised as being able to harvest approximately the same volumes during the thinning phase, which results in the forest looking roughly the same for the two different scenarios after the thinning phase is over. We also deemed it likely that forest managers and forest-owning companies will not change the forest management goals on the basis of a new harvesting technology. With no changes to the management objective and the potential differences in thinning methodology between conventional thinning and a drone system, it was assumed that the latter will conduct more frequent but less intense thinning compared to fewer and heavier thinning operations with the conventional harvester/forwarder system. We also assumed that drone systems will be capable of conducting both first and later thinnings.

Simulations

Simulation and optimisation of management was made in the forest decision support system Heureka PlanWise (Lämås et al., 2023). The Heureka system contains all forest growth and yield models necessary for accurately forecasting the state of a given forest over time for Swedish conditions, implementing silvicultural treatments and accounting for the growth response. PlanWise is normally used for forest planning problems, such as dealing with silvicultural treatments at estate level and using the optimisation module to render optimal management regimes based on a set of management restrictions and the objective function, which is normally maximum net present value.

The stands defined from the thinning templates were imported as stands into Heureka PlanWise (Table 5.1). From the stand attributes, individual trees were simulated, providing good material for further analysis. The simulated stands were used as a basis for evaluating the differences between the conventional harvester/forwarder system and a drone system. Two scenarios were constructed that relied on assumptions made based on how a drone system is thought to operate differently from the conventional harvester/forwarder system and that both harvesting systems were used to reach the same management goal. However, the way to attain those goals differed due to the technological differences. By not setting the same forest management goal, the demanded output from the thinning operations would change, resulting in a comparison of silvicultural treatments that would have confounded the effects.

The technological differences between the systems were implemented by adjusting the silvicultural rules defined in Heureka. Most rules followed the default settings, but some were changed to capture the proposed differences between the thinning technology/method of Conventional (CONV) and Drone (DRONE, Table 5.2). Fixed costs are integrated with the variable costs in Heureka, and they were assumed to be equal for the two systems as no data is available for drone systems.

Table 5.2. Diverging silvicultural rules for the two scenarios.

	Conventional (CONV)	Drone (DRONE)
Max number of thinnings	2	4
Min/Max thinning grade	25–40 %	12–12 %
Min height thinning (m)	11	11
Max height thinning (m)	15	15
Max height any thinning (m)	20	20
Thinning guide reduction upper	0.90	0.80
Harvest strip roads	Yes	No

First, the optimal thinning programme for CONV was carried out based on the silvicultural rules in Table 5.2, using a discount rate of 2.5%. The maximum and minimum thinning intensity for DRONE was then tried out manually. The maximum thinning intensity was set to 12% for all site indexes and tree species for DRONE, as it produced the most similar stands after the thinning phase (20-m dominant height). Harvest of strip roads was enabled for CONV, which meant that tree selection in the first thinning was limited in the zone between the strip roads. For DRONE, strip roads were not used, which meant more freedom in tree selection. Strip roads only affect cost calculations in Heureka and do not affect production.

Land Expectation Value

Normally, the net present value is calculated in Heureka PlanWise by combining the net present value of the first-generation forest and the Land Expectation Value (LEV) for the subsequent generation. The problem with this is that the initial stand density relative to the thinning template is essential for our analysis, and this is disregarded when the new generation of forest is simulated. In our case, the LEV calculation was adjusted to account for the circumstances of the first generation. The net present value was calculated separately for each management programme by discounting the revenue to year 0, for example when the previous stand was subject to final felling. The establishment costs prior to first thinning (20-40 years after stand establishment) were adapted from the reported forestry costs (Eliasson, 2021). Planting was assumed to take place at year 0 and pre-commercial thinning at years 3 and 10. LEV was derived by multiplying the calculated net present value from the first rotation with the eternity factor, meaning that the management regime in the first rotation was repeated forever. The choice of optimal management programme for each scenario was then based on this new calculation of the LEV.

Result variables

Scenarios were evaluated for a number of stand attributes that provide an understanding of how the different management scenarios affect different aspects of stand development (basal area, stem number, DGV, total carbon stock, standing volume), current annual increment, and assortments (pulpwood and timber). All result variables were reported by site index and tree species, and are defined in the glossary in the Appendix.

Results

Thinning regime

The results show that approximately the same stands could be created during the thinning phase in terms of basal area (Figure 5.2), stem number (Figure 5.3), total carbon stock (Figure 5.4), and standing volume (Figure 5.5) in both scenarios, but with different paths to the target. The stands in each scenario developed similarly during the thinning phase for each studied stand attribute, but the lowest levels were avoided in DRONE. The time of final felling was the same in most cases.

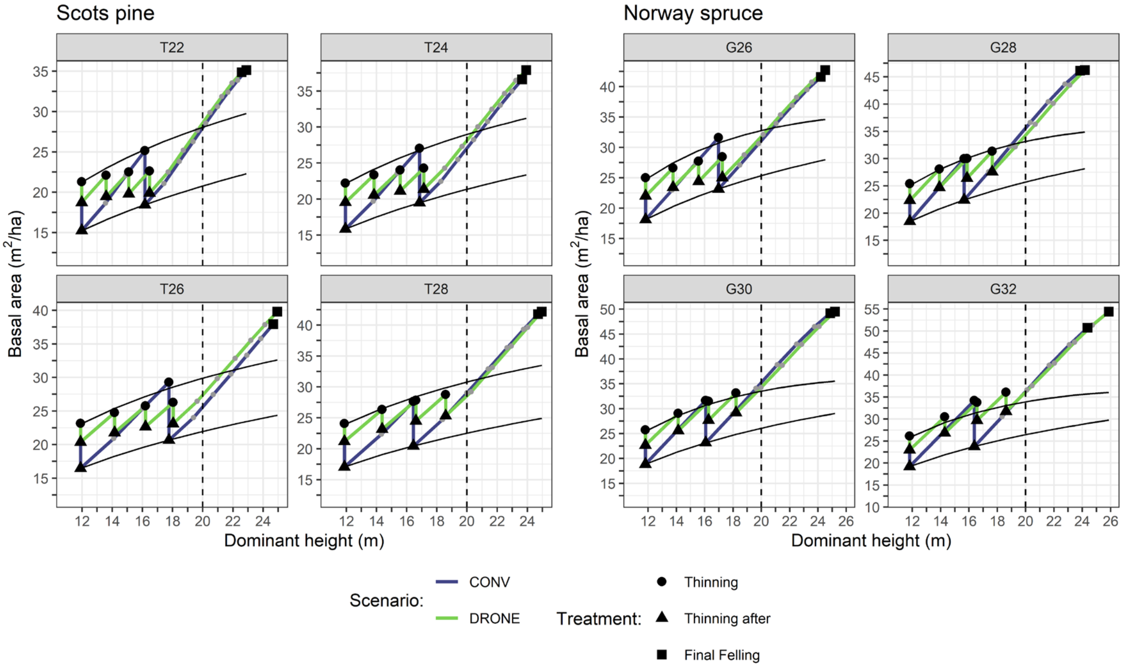


Figure 5.2. Basal area over dominant height for each site index and respective tree species.

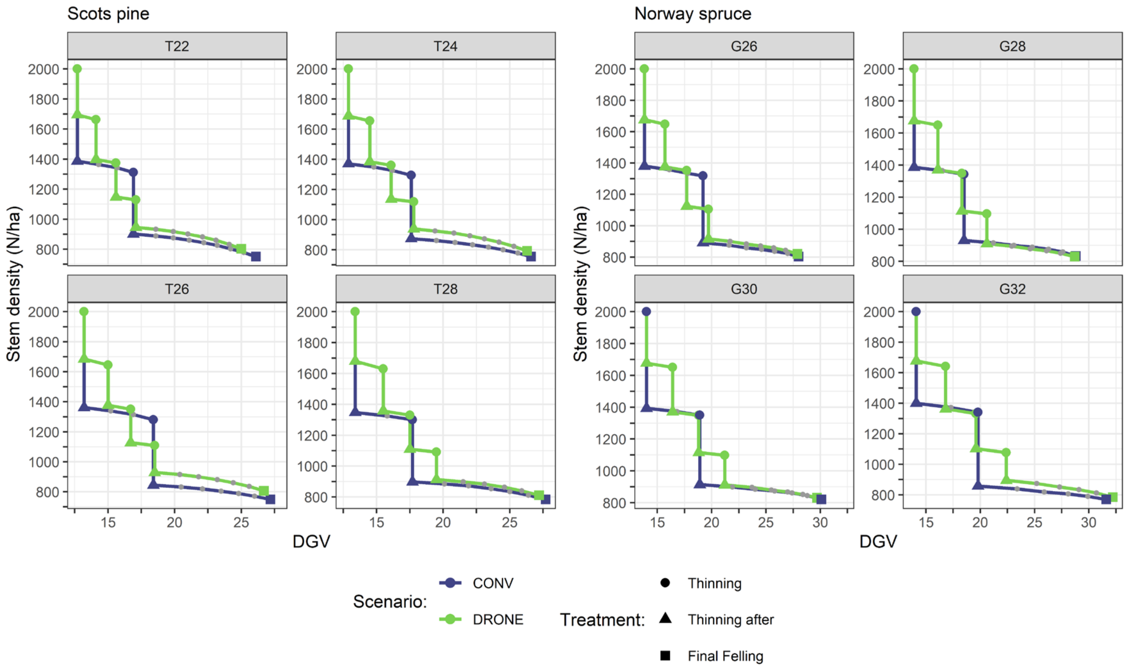


Figure 5.3. Number of stems over DGV for each site index and respective tree species.

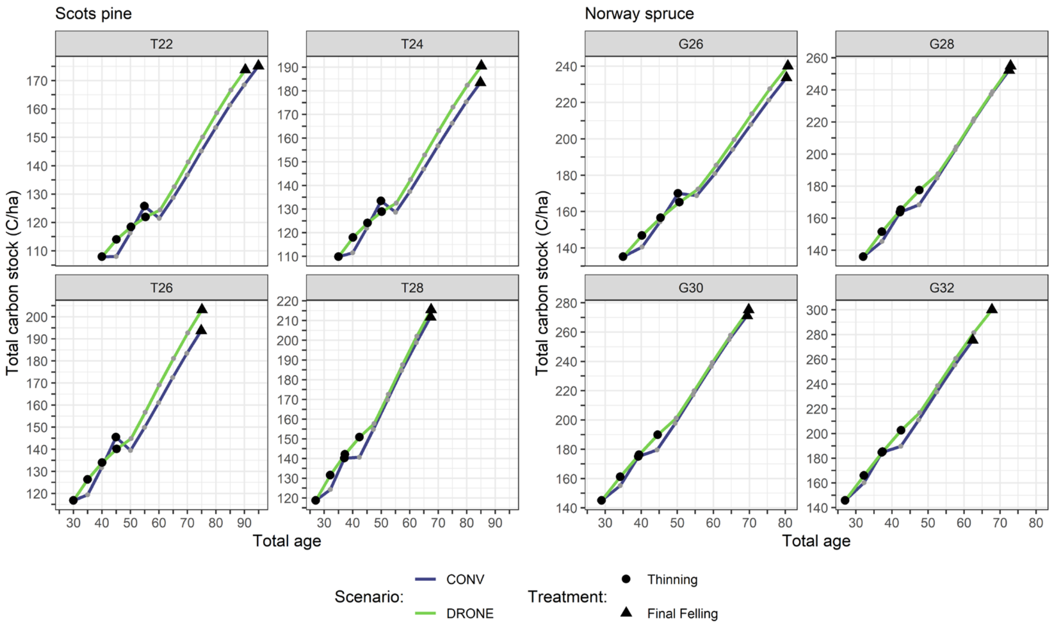


Figure 5.4. Total carbon storage over total age for each site index and respective tree species.

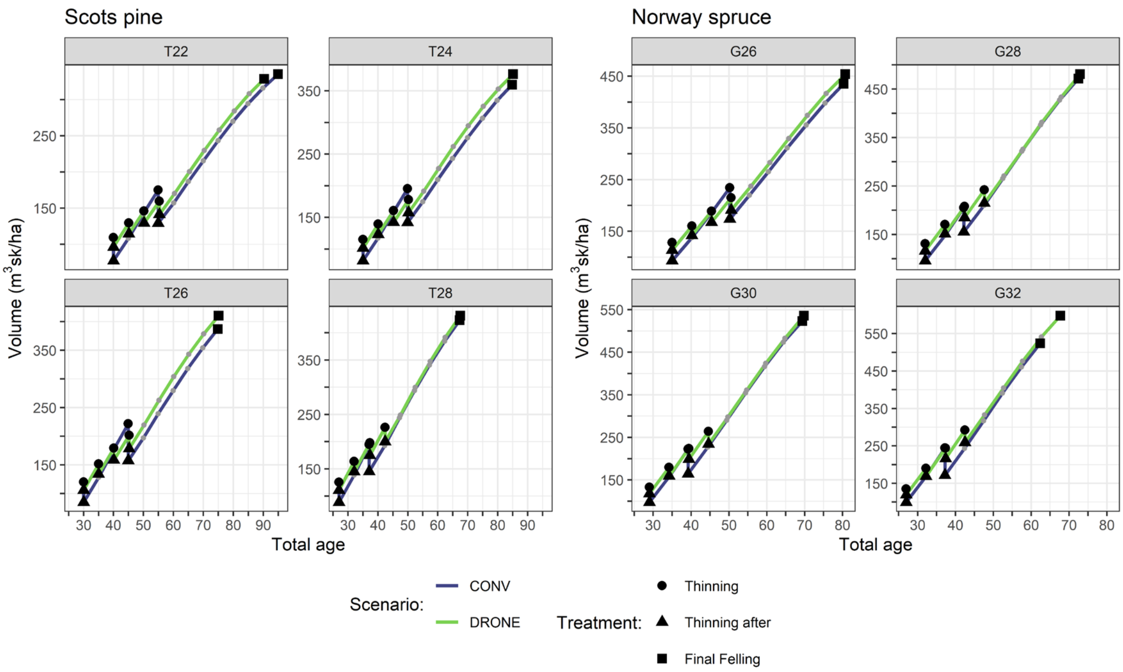


Figure 5.5. Standing volume over total age for each site index and respective tree species.

Growth

The current annual increment was generally higher for DRONE during the rotation, but the marginal difference compared to CONV did not result in any discernible differences in mean annual increment over the rotation (Figure 5.6).

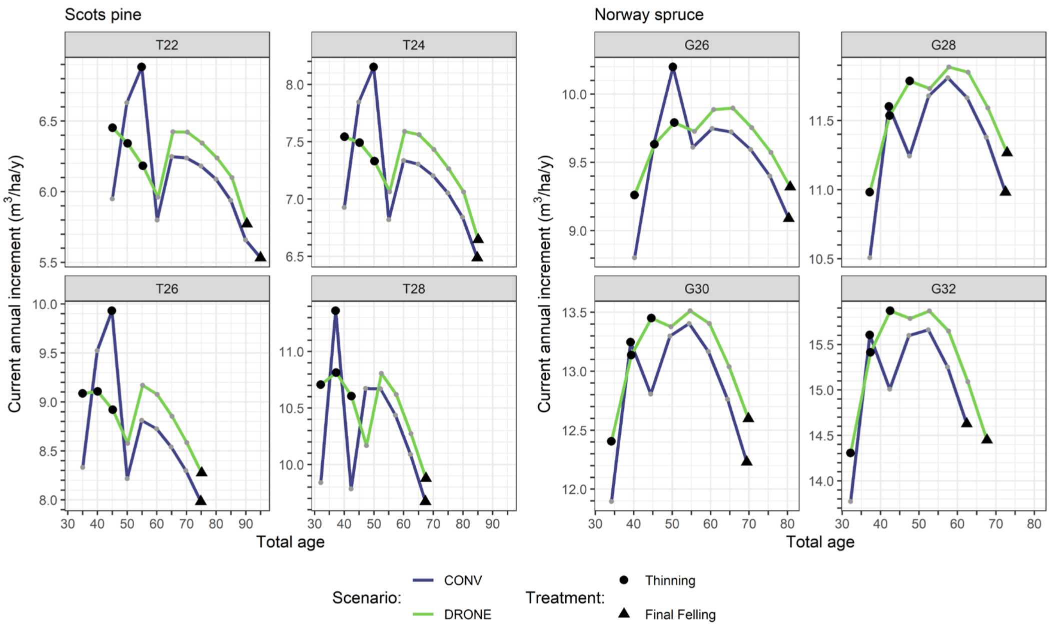


Figure 5.6. Current annual increment over total age for each site index and respective tree species.

Harvest

The harvested mean stem volume was generally slightly higher for CONV compared to DRONE, given that the thinning was conducted in the same period (Figure 5.7). This is because the thinning intensity was higher in conventional thinning. The harvested volume per assortment was also comparable over the rotation period (Figure 5.8).

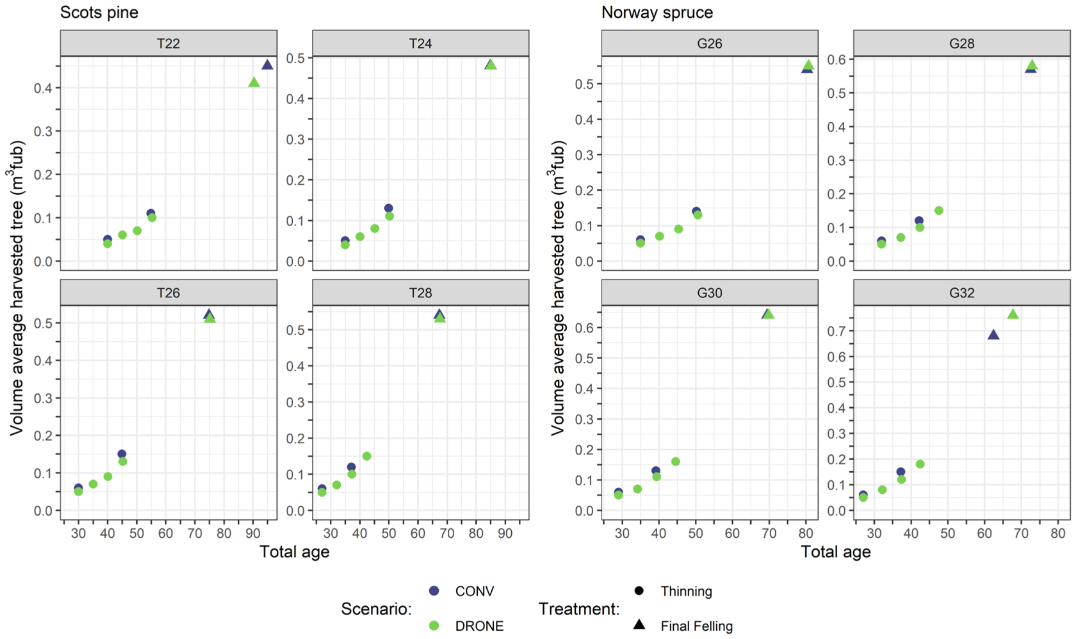


Figure 5.7. Volume average harvested tree over total age for each site index and respective tree species.

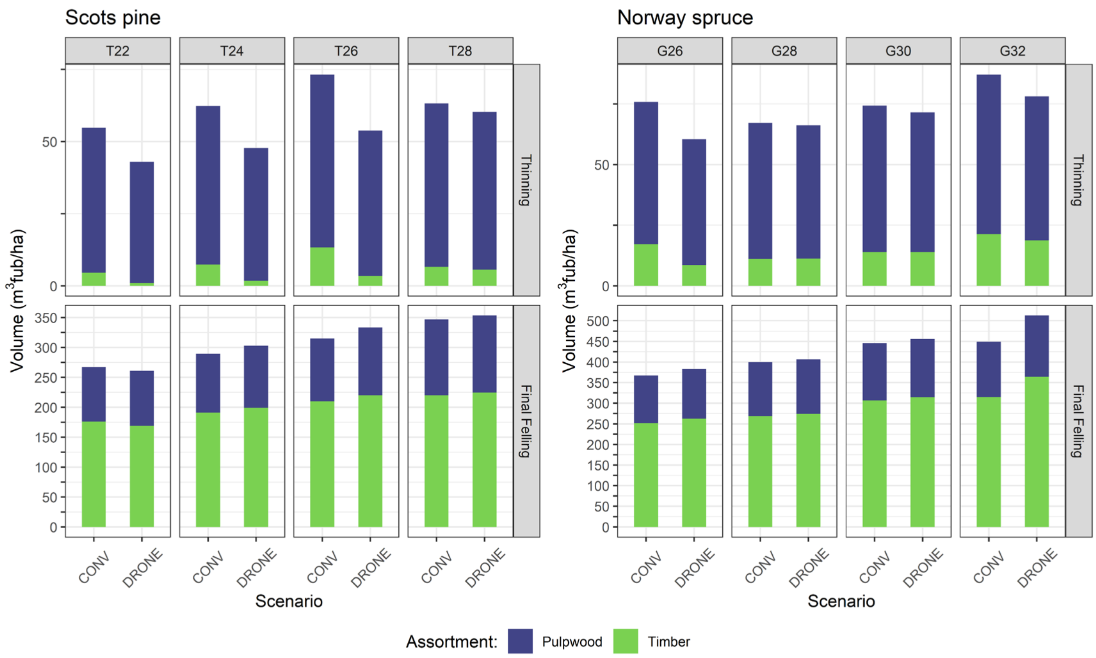


Figure 5.8. Volume of each assortment (timber and pulpwood) per treatment and scenario.

Discussion

Simulations

The potential effect of harvest method (conventional harvester/forwarder and the drone system) on a range of forest attributes was evaluated. The assumption incorporated in the silvicultural rules in Heureka PlanWise was that the drone system could thin more frequently and with lower thinning intensity. The results from our study are thought to represent thinning of average production stands across a wide range of site productivity, where the forest management objective was to maximise the Land Expectation Value while following the silvicultural recommendations.

This simulation study shows that differences in harvesting method will not produce a different forest in terms of basal area, stem density, standing volume, or total carbon stock. Consequently, the current annual increment, the mean annual increment, and the harvested volume per assortment were also similar over the rotation. The reason is that the temporarily higher growth while thinning with a low intensity was too small to make a difference. The result from our simulations therefore suggests that the difference in harvest methods did not create any added benefits given that the same forest management goal was pursued. The circumstances that may lead to differences in tree selection or added growth are likely to be found in stands of greater complexity than the normal production stand on flat terrain. Future evaluations should incorporate how terrain, tree size and tree species may affect productivity, and incorporate estimates of the productivity of several drones.

The study is limited by the fact that drone systems are under development and have not yet been tested operationally. The assumptions for the DRONE scenario were therefore based on what we knew about the drone system when we started the project. Insights from field experience could not be incorporated in any depth into the simulations in Heureka.

The method of manually deriving a thinning intensity for DRONE that ended up with the same stand after the thinning phase was crude. Another approach would be to define a restriction in the optimisation module. Heureka did not manage to produce a viable solution to this problem formulation, but this alternative method would likely produce a similar thinning regime to the one presented. We argue that a somewhat pure effect of the thinning frequency and thinning intensity was isolated using the current method, which could indicate the difference between the harvesting methods.

Future forest management trends affecting thinning

There are various trends in forestry today involving forest management that encompass higher stand densities (carbon storage) and lower stand densities (increased drought resilience), which are influenced by the thinning regime. Technological gaps might appear in the implementation of new thinning regimes that a drone system might be better (or less) suited to deal with.

In a warmer climate, reductions in summer rainfall and intensified droughts may affect forest health and ecosystem services in many regions including Fennoscandia (Spinoni et al., 2017). The heatwave in the summer of 2018 exemplifies how drought events may cause water shortage, which negatively affects tree growth, mortality and ecosystem functioning. However, thinning reduces competition for water, nutrients and sunlight (Zeide, 2001), resulting in improved growth conditions for the remaining trees (Aussenac

& Granier, 1988; Bréda et al., 1995). Thinned stands recover faster and are more resilient to drought-induced growth reductions (Sohn et al., 2016a; 2016b). Thinning is a promising adaptation and mitigation strategy to drought in young, coniferous production stands, such as the ones included in this study. The role of thinning in a warmer climate and the capability to perform site-specific thinning is therefore likely to become more important with time.

The interest in carbon-offset in European production forests is increasing, and entails maximising carbon storage over time. Biomass production is strongly related to stand Leaf Area (LA). Thinning reduces LA as trees are removed, so non-thinned stands have the highest biomass production and carbon storage. Also, it is likely that either private initiatives or governmental jurisdiction will provide an incentive to forest owners to increase carbon storage by reducing mid-rotation harvest intensities. A drone system is probably more capable of carrying out low-intensity thinning compared to the conventional harvester/forwarder system because of the increased freedom deriving from the lack of need for strip roads in the early thinning operations.

These trends will likely increase the need for precise information about specific trees in stands and their growing conditions. Equipping the drones with LiDAR-sensors and hyperspectral cameras will provide the foundation for estimating the size and vitality of single trees. In combination with returning to the same tree on multiple occasions, this might provide the possibility to optimise tree selection (harvest or retain a tree) over the rotation and to utilise more of the growth potential.

6. Salvage logging of spruce bark beetle-attacked trees using harvest drones – potential pest control

Petter Öhrn

Bark beetles in a changing world

During recent decades there has been a strong increase in disturbances caused by tree-killing bark beetles in all the world's coniferous forests (Hlásny et al., 2021) and this trend will most likely continue (Seidl et al., 2014). The Eurasian spruce bark beetle (*Ips typographus)* is the most devastating forest pest affecting the Norway spruce (*Picea abies* (L.) H. Karst). Across Europe, its infestations have led to the death of hundreds of millions of cubic metres of spruce wood in recent years (Patacca et al., 2023).

In Sweden, in the years between the drought event in 2018 and 2023, more than 34 million cubic metres of spruce has been killed (Wulff and Roberge, 2023), which represents 75 percent of all spruce wood killed by spruce bark beetle since the 1960s (Schroeder & Kärvemo, 2022). In Sweden alone, the economic loss of the damaged wood in recent years has been estimated at SEK 14 billion according to the Swedish Forest Agency (Skogsstyrelsen).

Bark beetle life cycle and phenology

The spruce bark beetle begins to swarm in spring during the first days with temperatures approaching 20°C (Öhrn et al., 2014). After emerging from overwintering, they start to fly, in search of suitable breeding sites within the forest.

Under low, *endemic* population levels, the beetles typically breed in the phloem under the bark of recently dead or dying Norway spruce trees and unbarked timber. When bark beetles reach *epidemic* outbreak levels, the beetles can overcome the defences of living trees. After three weeks, when the parent beetles finish mating and gallery construction, the parent beetles move on to initiate a sister brood.

Once the first brood (new generation) reaches full maturity, they have several options, depending on thermal conditions and photoperiod. In central Europe, the typical flight pattern involves a fully developed second generation and multiple sister broods. Conversely, at higher altitudes and further north in Europe (e.g. Sweden), it is more common to have just one generation with one or several sister broods (Öhrn et al., 2014). How warm the summer has been affects the timing and the proportion of beetles emerging to initiate a second brood. In Sweden, the new generation normally starts to emerge around the beginning of July (Öhrn et al., 2014), but flight activity is commonly low in the second half of the summer. Even during exceptionally warm summers only a minor part of the new generation in southern Sweden was estimated to reproduce before hibernation (Fritscher & Schroeder, 2022).

The spruce bark beetle overwinters as adult beetle and larvae, and pupae do not survive winter temperatures. Depending on climatic site conditions, the beetles either stay beneath the bark or emerge from the tree during late autumn to overwinter in the soil. In central Europe, the majority of the beetles spend the winter period beneath the bark of either standing or fallen trees (Faccoli, 2002). In the most northern parts of Europe, the spruce bark beetle hibernates under the snow cover within the soil (Annila, 1969). In a recent study conducted by SLU and Skogforsk in southern Sweden (Västmanland to Småland), we observed that, on average, 63 percent of the beetles stayed to overwinter beneath the bark of the infested tree (Weslien et al., 2022). The remaining 37 percent of the beetles left the trees at some point between the time of emergence of the new generation (around the beginning of July) and the onset of winter.

Bark beetle outbreaks are usually triggered by either storm felling (creating an abundance of defenceless breeding substrate), drought (weakened host trees), or a combination of both. However, the spatial configuration, where in the landscape the infested trees are situated, may differ depending on what triggered the outbreak. In a comparison between outbreaks following the storm Gudrun in 2005 and the drought 2018, the infestation risk during the storm-induced outbreak increased with shorter distance to protected areas, while the infestation risk during the drought-induced outbreak was more dependent on the distance to clear-cut areas (Kärvemo et al., 2023).

Figure 6.1. Dead spruce trees killed by spruce bark beetle in a forest just outside Uppsala. Photo: L. Djupström.

Techniques for early detection of bark beetle infested trees

Historically, ground-based human visual inspection has been the only method for detecting bark beetle-infested trees. However, bark beetle infestations can now be detected early with remote sensing and machine learning. A recent review describes the evolution towards automatic detection systems for bark beetle attacks on conifers in both Europe and North America (Marvasti-Zadeh et al., 2023).

At this point the resolution of satellite images is too low to detect bark beetle green attacks at single tree level. Higher resolutions, enough for early detection of bark beetle infestations in single trees, have been obtained only in a handful of studies of aerial detection using drones (Bárta et al., 2022; Huo et al., 2023; Klouček et al., 2019; Minařík et al., 2021). These studies could be valuable when developing harvest drone-based methods to control bark beetle control populations. One of the most recent studies, conducted in southern Sweden (Huo et al., 2023), showed that 15 and 90 percent of infestations were detected after 5 and 10 weeks after initiation of attack, respectively.

Another ground-based method involves using the highly developed nose of a dog (Vošvrdová et al., 2023). Volotiles from stressed bark beetle-attacked trees could also be traced with an electronic nose mounted on a drone (Hüttnerová et al., 2023).

Use of harvester drones as a pest management tool

In forest pest management timing is crucial for successful pest control, both the timing of the action within a season and the timing of the action in relation to bark beetle outbreak phase (Hlásny et al., 2021). On a seasonal scale and tree level the action must be done as early as possible before the new generation emerges from beneath the bark. For best population control effect this action must be done at an early, population build-up (*endemic*) stage before bark beetle populations reach *epidemic,* outbreak levels. Pest control efficiency is limited by availability of harvesting machinery during the limited time before the new generation of beetles leave the infested trees.

When the harvester head runs along the stem and debarks the tree the bark will fall to the ground. Bark beetle pupae and larvae will likely dry out and die from this treatment. However, fully developed beetles probably survive unless the debarking process applies sufficient pressure, leaving only small pieces of bark. Different pressures of debarking remain to be tested to further evaluate the method.

The effect of using harvest drones for pest control may not prevent bark beetle outbreaks but could possibly dampen the severity of future outbreaks. For efficient pest control, measures must be taken at a sufficiently large spatial scale, since bark beetles can fly long distances.

One limitation in the use of harvest drones for bark beetle control is that they can only be used on standing beetle-infested trees. Their use is most effective during a drought-induced outbreak when control measures are possible in the first year of outbreak. In contrast, the use of harvest drones for storm-induced outbreaks will not be possible until the second outbreak year, when beetles that were produced in the wind-felled trees will attack standing trees.

Pest control measures and modelling of bark beetle populations

The complexity of outbreak dynamics of bark beetles makes it hard to estimate the effect of various control measures on the development of the outbreak, but some attempts have been made to investigate this (Hlásny et al., 2021). There are some modelling studies on drivers of spruce bark beetle infestations on windthrown trees and the effects of timely removal of infested trees (Dobor et al., 2019; Hroššo et al., 2020; Jönsson et al., 2012). Dobor et al. (2019) estimated that, if less than 95% of the windthrown trees were salvaged (removed), there was no dampening of bark beetle infestations.

More applicable when estimating the effect of the use of harvest drones for reducing bark beetle damage is the IPS-SPREADS model (Infestation Pattern Simulation Supporting PREdisposition Assessment DetailS), showing that salvage cutting is most effective near the beetle source (Pietzsch et al., 2021). The model is a suggested tool for investigating different management measures on either windthrown or standing trees killed by beetles.

7. Concluding remarks

The absence of strip roads is the most obvious advantage of thinning with airborne systems. Strip roads typically cover 18 percent of the stand area after thinning in Swedish operations. Gains in timber production would be in the range of 5 to 10 percent per year for a period of 15 to 20 years. The absence of strip roads has other benefits, including a higher resilience to wind and snow damage. As strip road trees will not be an issue, there will be a freer choice regarding which trees to remove and which thinning method to use. The absence of strip roads is beneficial from a general environmental perspective, particularly for the soil ecosystem.

Another possible benefit of airborne systems is that logging damage, e.g. soil compaction, rutting and/or mechanical damage to residual trees, may be reduced, since there will be no ground-based machinery in the forest. This may help reduce the spread of, for example, root rot, but it will not eliminate the need for stump treatment, and recommendations on timing of operations will apply equally to airborne operations.

Airborne systems may enable an increased use of nurse crops. Nurse crops provide seedlings with shelter from frost and waterlogging, and increase stand production during the establishment phase. Establishment and management of nurse crops is complicated and/or costly, since shelter trees must be selected, retained and, later, gradually removed. The gradual removal is a complicated operation using ground-based systems. In today's forestry, nurse crops are sparingly used, and then mainly to protect spruce seedlings from frost. With an airborne system, the increased production could motivate greater use of the treatment.

Areas where entry using ground-based machinery is undesirable, but where small spruce trees need to be removed, such as protected areas and buffer zones, offer an opportunity for airborne systems. Operational goals in these areas are not primarily related to efficient timber harvesting, and site disturbance should be kept at a minimum. Conservation measures can readily be implemented at the micro-site level using airborne technologies.

The risk of spreading invasive species could be reduced, as the machinery has no ground contact except when landing in operational areas, and cannot normally spread organisms from one site to another.

There is an emerging field of research on remote sensing technologies for detection of beetle-infested trees. Timely removal of infested trees is considered a key measure to reduce bark beetle populations, but is hard to achieve in practice. Pest control efficacy is limited by harvesting machinery during the time window before the new generation of beetles leave the infested trees. Properly adapted, the use of harvest drones could contribute to pest control – probably not prevent bark beetle outbreaks but could possibly help to dampen the severity of future outbreaks.

The technological differences between an aerial drone system and conventional harvesting systems are not likely to result in changes in stand development or forest production under the same forest management goals.

Harvesting of small trees leads to low productivity and high costs, due to low load weights. Compared to the conventional system, a system with only one aerial drone is not an economically viable option for thinning in the analysed scenario "normal speed and normal positioning time". In the faster scenarios, the competitiveness of drone thinning operations is still doubtful. If an operator could handle multiple drones, the scope for competitive operations increases.

Small trees, especially those located under the canopy of larger ones, are technologically challenging for two reasons: 1) they may be difficult to locate and harvest, and 2) productivity will be low and thereby the potential revenue. Other trees, e.g. broadleaves or damaged trees, also present a challenge for a harvester head that delimbs the trees from the top and down. Crooked, multi-topped or damaged trees are a problem for any harvester head, and probably more so for a harvesting head working from the top.

Stand structure will change in stands thinned with airborne systems. The absence of strip roads will enable a more even spatial distribution of trees in the horizontal plane. As excessively large or small trees are left in the stand, diameter distributions will be wider, and species composition may be different from that of conventional operations. This is not necessarily a drawback from an environmental perspective, as understoreys, important structures providing shelter and/or food, can be kept intact.

Environmental drawbacks of airborne systems include the noise generated by the drone, and maybe its mere presence. The extraction of whole stems, if applied, means that treetops will not be left on the forest floor, where they form fine substrates. Drones may enable access to currently inaccessible areas, which can endanger disturbance-sensitive species if these refugia are not carefully considered.

The ability of an aerial drone system to thin with a lower intensity and manage stand density may facilitate adaptation toward climate change and mitigate competition-induced risks (drought, bark beetle, mortality). However, this shift relies on the development of methods that result in reduced variable and fixed costs and a high level of flexibility in harvesting technique compared to conventional harvesting systems. With that said, aerial drones do not necessarily have to carry harvester heads. They could instead be equipped with grapples and be used for extraction only. In such a system harvesting could be done by small harvesters operating from ghost trails. A grapple will be less heavy than a harvester head, enabling the drone to handle bigger trees. If a ground-based harvester is used, broadleaves and larger and/or deformed trees may no longer be an issue. Safety aspects dictate that airborne systems are unacceptable in inhabited areas or in areas used for recreation, unless the areas treated can be closed to public access during periods of operation.

Electricity-based technological development is in line with the objective of reducing carbon dioxide emissions and improving air quality. A transition to fossil-free vehicles in the forestry sector can reduce the sector's environmental footprint while benefitting its economy and future. The forest sector can strengthen its market position by adopting fossil-free vehicles, which can be a differentiating factor and increase the demand for forest-based products from environmentally conscious consumers and companies. If successful, drone-based harvesting technologies can help the forest sector strive to reduce emissions of CO_2 and other pollutants.

References

Agestam, E. 2015. Gallring. Skogsskötselserien Nr. 7. Skogsstyrelsen. Jönköping https: www.skogsstyrelsen.se/mer-om-skog/skogsskotselserien/skogsskotselserien--gallring/ [2024-02-07].

AirForestry Undated. Re-inventing forestry. https://www.airforestry.com/ [2024-02-07].

Albrektson A, Elfving B, Lundqvist L, Valinger E (2012) Naturhänsyn. Skogsskötselserien, Chapter 14. Second edition. https://www.skogsstyrelsen.se/mer-om-skog/skogsskotselserien/naturhansyn/ [2024-02-07].

Andersson, L. 1980. Skador efter körning med tunga maskiner I gallring. Omfattning, orsaker och effekter på beståndets tillväxt och kvalitet. Institutionen för skogsskötsel, Interna rapporter 1980-4. SLU, Umeå.

Annila, E. 1969. Influence of temperature upon the development and voltinism of Ips typographus L.(Coleoptera, Scolytidae), Annales Zoologici Fennici. JSTOR 6(2): 161–208.

Anon 1994. Skogsordlista. Tekniska nomenklaturcentralens publikationer 96 & Sveriges Skogsvårdsförbund.

Aussenac, G. & Granier, A. 1988. Effects of thinning on water stress and growth in Douglas-fir. Canadian Journal of Forest Research 18:100-105. DOI: 10.1139/x88-015.

Banu, T.P., Borlea G.F. & Banu, C. 2016. The use of drones in forestry. Journal of Environmental Science and Engineering 5(2016): 557-562. DOI: 10.17265/2162-5263/2016.11.007.

Bárta, V., Hanuš, J., Dobrovolný, L. & Homolová, L. 2022. Comparison of field survey and remote sensing techniques for detection of bark beetle-infested trees. Forest Ecology and Management, 506: 119984. https://doi.org/10.1016/j.foreco.2021.119984

Bergquist, J., Edlund, S., Fries, C., Gunnarsson, S., Hazell, P., Karlsson, L., Lomander, A., Näslund, B-Å., Rosell, S., Stendahl, J. 2016. Kunskapsplattform för skogsproduktion - Tillståndet i skogen, problem och tänkbara insatser och åtgärder. Meddelande 1. 2016. Skogsstyrelsen. Jönköping.

Bergkvist, I., Hallonborg, U., & Nordén, B. 2002. Valmet 801 Combi i gallring med fast lastutrymme för standardlängder. Arbetsrapport Nr. 518. Skogforsk, Uppsala. www.skogforsk.se/cd_20190114162210/contentassets/ff22339dda8c49e98f80d8c196b21d30/arbetsrapport-518-2002.pdf [2024-02-07].

Bigsby, H. & Ling, P. 2013. Long-term productivity of helicopter logging in Sarawak. International Journal of Forest Engineering 24(1): 24–30 DOI: 10.1080/19132220.2013.791197.

Björheden, R., Gustavsson, H., Henriksen, F., Lundström, H. & Olsson, A. 2018. Utvärdering av maskinsystemet MALWA för tidig gallring. Arbetsrapport 9722018. Skogforsk, Uppsala. https://www.skogforsk.se/contentassets/82a4696935a34522a13fad49f42bad42/arbetsrapport-972-2018.pdf [2024-02-07].

Bréda, N., Granier, A., & Aussenac, G. 1995. Effects of thinning on soil and tree water relations, transpiration and growth in an oak forest (Quercus petraea (Matt.) Liebl.). Tree Physiol 15:295-306. https://doi.org/10.1093/treephys/15.5.295.

Bredberg, C.J. 1972. Typbestånd i förstagallringar. Skogshögskolan, Institutionen för skogsteknik. Rapporter och uppsatser.

Brin, A., Bouget, C., Brustel, H. & Jactel, H. 2011. Diameter of downed woody debris does matter for saproxylic beetle assemblages in temperate oak and pine forests. Journal of Insect Conservation, 15(5), 653–669. https://doi.org/10.1007/S10841-010-9364-5/TABLES/5.

Bucht, S. 1981. Effekten av några olika gallringsmönster på beståndsutvecklingen i tallskog. Swedish University of Agricultural Sciences, Department of Silviculture Report nr 4.

Conway, S. 1982. Logging Practices - Principles of Timber Harvesting Systems. San Francisco, Miller Freeman Inc.

Deep Forestry 2022. Do you know every tree in your forest? We do! https://deepforestry.com/sv/ [2024-02-07].

Delaney, D. K., Grubb, T. G., Beier, P., Pater, L. L., & Reiser, M. H. (1999). Effects of Helicopter Noise on Mexican Spotted Owls. *The Journal of Wildlife Management*, *63*(1), 60-76. https://doi.org/10.2307/3802487.

Dobor, L., et al. 2019. Is salvage logging effectively dampening bark beetle outbreaks and preserving forest carbon stocks? Journal of Applied Ecology, 57(1): 67–76. https://doi.org/10.1111/1365-2664.13518.

Dykstra, D.P., Aulerich D.E. & Henshaw, J.R. 1978. Prebunching to Reduce Helicopter Logging Costs. Journal of Forestry 76(6): 362–364. https://doi.org/10.1093/jof/76.6.362.

Ekö, M. 1985. Produktionsmodell för skog i Sverige, baserad på bestånd från riksskogstaxeringens provytor. Swedish University of Agricultural Sciences, Department of Silviculture.

Eliasson, L. 2021. Skogsbrukets kostnader och intäkter 2020 (*Costs and revenues in Swedish forestry 2020*). Skogforsk.

Eliasson, L. 2022. Skogsbrukets kostnader och intäkter 2021 (*Costs and revenues in Swedish forestry 2021*). Skogforsk.

Eriksson, H., Johansson, U. & Karlsson, K. 1994. Effekter av stickvägsbredd och gallringsform på beståndsutvecklingen i ett försök i granskog. SLU, Inst. för skogsproduktion. Rapport nr. 38.

Esseen, P.A., Ehnström, B., Ericson, L., & Sjöberg, K. 1997. Boreal Forests. Ecological Bulletins, 46, 16-47. http://www.jstor.org/stable/20113207 [2024-02-07].

Faccoli, M. 2002. Winter mortality in sub-corticolous populations of *Ips typographus* (Coleoptera, Scolytidae) and its parasitoids in the south-eastern Alps. Anzeiger für Schädlingskunde. Journal of Pest Science, 75(3): 62–68. https://doi.org/10.1034/j.1399-5448.2002.02017.x

Ford-Robertson, F.C. (ed) 1971. Terminology of Forest Science, Technology Practice and Products. Society of American Foresters, Washington.

Forest Stewardship Council 2015. Forest Stewardship Council FSC INTERNATIONAL STANDARD (Vol. 005). https://ic.fsc.org/preview.fsc-principles-and-criteria-for-forest-stewardship-fsc-std-01-001-v5-2-en-print-version.a-4843.pdf [2024-02-07].

Forman, R.T. & Alexander LE (1998). Roads and their major ecological effects. Annual review of ecology and systematics, 29(1): 207–231. https://doi.org/10.1146/annurev.ecolsys.29.1.207

Fridman, J., & Walheim, M. 2000. Amount, structure, and dynamics of dead wood on managed forestland in Sweden. Forest Ecology and Management, 131(1-3), 23–36. https://doi.org/10.1016/S0378-1127(99)00208-X.

Fritscher, D. & Schroeder, M. 2022. Thermal sum requirements for development and flight initiation of new-generation spruce bark beetles based on seasonal change in cuticular colour of trapped beetles. Agricultural and Forest Entomology, 24(3), 405–421. https://doi.org/10.1111/afe.12503.

Föreningen skogen 2000. Skogsencyklopedin (Håkansson M. redaktör).

Grinddrone Undated. 15 uses of drones in forestry. https://grinddrone.com/applications/15-uses-of-drones-in-forestry [2024-02-07].

Grönesjö, R. 2016. Viktiga faktorer för skogsägare vid gallring. *Important factors for the forest owners in thinning*. B.Sc Thesis 2016:28, School of Forest Management, Skinnskatteberg, Sweden https://stud.epsilon.slu.se/9664/1/gronesjo_r_20160927.pdf [2024-02-07].

Grönlund, Ö. & Eliasson, L. 2019. Birch shelterwood removal – harvester and forwarder time consumption, damage to understory spruce and net revenues. International Journal of Forest Engineering, 30:1, 26–34, DOI: 10.1080/14942119.2019.1595943.

Häggström, K. & Svangärd L. 2022. Drönaranvändning i gallringsskog. Flygande gallring – en teoretisk analys av drönares potential. (*Drone usage in thinning forests*). SLU, Department of Forest Biomaterials and Technology. https://stud.epsilon.slu.se/17892/3/haggstrom-k-svangard-l-20220629.pdf [2024-02-07].

Han, H.S. & Kellogg, L. D. 2000. Damage Characteristics in Young Douglas-Fir Stands from Commercial Thinning with Four Timber Harvesting Systems. Western Journal of Applied Forestry 15(1): 27–33. https://doi.org/10.1093/wjaf/15.1.27.

Heilmann-Clausen, J., & Christensen, M. 2004. Does size matter?: On the importance of various dead wood fractions for fungal diversity in Danish beech forests. Forest Ecology and Management, 201(1), 105-117. https://doi.org/10.1016/J.FORECO.2004.07.010

Helms, J.A. 1998. The Dictionary of Forestry. CABI Publishing & Society of American Foresters.

Hlásny, T., König, L., Krokene, P. et al. Bark Beetle Outbreaks in Europe: State of Knowledge and Ways Forward for Management. Curr Forestry Rep 7, 138-165 (2021). https://doi.org/10.1007/s40725-021-00142-x.

Hroššo, B.; Mezei, P.; Potterf, M.; Majdák, A.; Blaženec, M.; Korolyova, N.; Jakuš, R. Drivers of Spruce Bark Beetle (*Ips typographus*) Infestations on Downed Trees after Severe Windthrow. *Forests* 2020, *11*, 1290. https://doi.org/10.3390/f11121290.

Huo, L., Lindberg, E., Bohlin, J. and Persson, H.J., 2023. Assessing the detectability of European spruce bark beetle green attack in multispectral drone images with high spatial- and temporal resolutions. Remote Sensing of Environment, 287: https://doi.org/10.1016/j.rse.2023.113484.

Hüttnerová, T., Paczkowski, S., Neubert, T., Jirošová, A. and Surový, P., 2023. Comparison of Individual Sensors in the Electronic Nose for Stress Detection in Forest Stands. Sensors, 23(4): 2001. https://doi.org/10.3390/s23042001.

Jacobson S., 2015. Lågskärm av björk på granmark – modellering av beståndsutveckling och ekonomisk analys (*The use of birch as a shelter in young Norway spruce stands – modelling stand development and economic outcome*). Skogforsk Arbetsrapport Nr. 876-2015.
https://www.skogforsk.se/contentassets/01d66d3c421c447eb6de2a687ed73374/arbetsrapport-876-2015-lagskarm-av-bjork-pa-granmark.pdf [2024-02-07].

Joelsson, K. 2017. Uneven-aged silviculture as a management tool to mitigate biodiversity loss. Swedish University of Agricultural Sciences, Umeå.

Johannesson T. & Hyll K. 2022. Högkapacitetsdrönare för skogsbrandsbekämpning – förutsättningar för användbarhet. Skogforsk Arbetsrapport 1106-2022. https://www.skogforsk.se/cd_20220214143520/contentassets/93507aa384e7433d99875bb4292f64a3/arbetsrapport-1106-2022.pdf [2024-02-07].

Johansson, T. 2014. Tillväxt och produktion hos skärmbestånd med björk och gran. Sveriges Lantbruksuniversitet, Institutionen för energi och teknik, Rapport 068, Uppsala.

Jönsson, A.M., Schroeder, L.M., Lagergren, F., Anderbrant, O. & Smith, B. 2012. Guess the impact of Ips typographus—An ecosystem modelling approach for simulating spruce bark beetle outbreaks. Agricultural and Forest Meteorology, 166-167: 188–200. https://doi.org/10.1016/j.agrformet.2012.07.012.

Jonsson R., 2023. Perso Jonsson R. 2023. Personal communication.

Kight, C.R. & Swaddle, J.P. 2011. How and why environmental noise impacts animals: an integrative, mechanistic review. Ecology Letters, 14: 1052–1061. https://doi.org/10.1111/j.1461-0248.2011.01664.x.

Klein, J. (2020). The forgotten forest: On thinning, retention, and biodiversity in the boreal forest [Swedish University of Agricultural Sciences]. http://urn.kb.se/resolve?urn=urn:nbn:se:slu:epsilon-p-107783 [2024-02-07].

Kouki, J., Löfman, S., Martikainen P., Rouvinen, S. & Uotila, A. 2001. Forest Fragmentation in Fennoscandia: Linking Habitat Requirements of Wood-associated Threatened Species to Landscape and Habitat Changes, Scandinavian Journal of Forest Research, 16:sup003, 27–37, DOI: 10.1080/028275801300090564.

Lageson, H. 1996. Thinning from below or above? Implications on operational efficiency and residual stand. Acta Universitatis Agriculturae Sueciae, Silvestria Nr. 14 Swed. Uni. Agr. Sci., 25 p.

Lageson H., 1997. Effects of thinning type on the harvester productivity and on the residual stand. Journal of Forest Engineering 8(2): 7–14. DOI 10.1080/08435243.1997.10702699.

Lindbladh, M., & Abrahamsson, M. 2008. Beetle diversity in high stumps from Norway spruce thinnings. Scandinavian Journal of Forest Research, 23(4), 339–347. https://doi.org/10.1080/02827580802282762.

Lundbäck, M., Häggström, C. & Nordfjell, T. 2021. Worldwide trends in methods for harvesting and extracting industrial roundwood. International Journal of Forest Engineering 32(3): 202–215 https://doi.org/10.1080/14942119.2021.1906617.

Kärvemo, S., Huo, L., Öhrn, P., Lindberg, E. & Persson, H. 2023. Different Triggers, Different Stories: Bark-Beetle Infestation Patterns after Storm and Drought-Induced Outbreaks. Forest Ecology and Management, 545. https://doi.org/10.1016/j.foreco.2023.121255.

Klouček, T. et al. 2019. The Use of UAV Mounted Sensors for Precise Detection of Bark Beetle Infestation. Remote Sensing 11(13): 1561. https://doi.org/10.3390/rs11131561.

Lämås, T., Sängstuvall, L., Öhman, K., Lundström, J., Årevall, J., Holmström, H., Nilsson, L., Nordström, E.-M., Wikberg, P.-E., Wikström, P., & Eggers, J. 2023. The multi-faceted Swedish Heureka forest decision support system: context, functionality, design, and 10 years experiences of its use. Frontiers in Forests and Global Change, 6. https://doi.org/10.3389/ffgc.2023.1163105.

Lundmark T., Bergh J., Hofer P., Lundström A., Nordin A., Poudel B.C., Sathre R., Taverna R. & Werner F. 2014. Potential roles of Swedish forestry in the context of climate change mitigation. Forests 5(4): 557–578. https://doi.org/10.3390/f5040557.

Lundqvist, L., Mörling, T. & Valinger, E. 2014. Spruce and birch growth in pure and mixed stands in Sweden. The Forestry Chronicle 90(1): 29–34.

MacDonald, A. J. 1999. Harvesting Systems and equipment in British Columbia. Victoria, B.C. Ministry of Forests. 1999, Harvesting systems and equipment in British Columbia (gov.bc.ca) [2024-02-07].

Marvasti-Zadeh, S.M., Goodsman, D., Ray, N. & Erbilgin, N. 2023. Early Detection of Bark Beetle Attack Using Remote Sensing and Machine Learning: A Review. arXiv preprint arXiv:2210.03829 https://doi.org/10.48550/arXiv.2210.03829.

Minařík, R., Langhammer, J. & Lendzioch, T. 2021. Detection of Bark Beetle Disturbance at Tree Level Using UAS Multispectral Imagery and Deep Learning. Remote Sensing, 13(23): 4768 https://doi.org/10.3390/rs13234768.

Mulero-Pázmány, M., Jenni-Eiermann, S., Strebel, N., Sattler, T., Negro, J.J. & Tablado, Z. 2017. Unmanned aircraft systems as a new source of disturbance for wildlife: A systematic review. PLoS ONE 12(6): e0178448. https://doi.org/10.1371/journal.pone.0178448.

Nikooy, M., Tavankar, F., Naghdi, R., Ghorbani, A., Jourgholami, M. & Picchio , R. 2020. Soil impacts and residual stand damage from thinning operations, International Journal of Forest Engineering, 31:2, 126-137, DOI: 10.1080/14942119.2020.1744954.

Nordén, J., Penttilä, R., Siitonen, J., Tomppo, E. & Ovaskainen, O. 2013. Specialist species of wood-inhabiting fungi struggle while generalists thrive in fragmented boreal forests. J Ecol, 101: 701–712. https://doi.org/10.1111/1365-2745.12085.

Öhrn, P., Långström, B., Lindelöw, Å. and Björklund, N., 2014. Seasonal flight patterns of *Ips typographus* in southern Sweden and thermal sums required for emergence. Agricultural and Forest Entomology, 16(2): 147–157.

Patacca, M. et al. 2023. Significant increase in natural disturbance impacts on European forests since 1950. Global Change Biology, 29(5): 1359–1376.

Patriquin, K.J. and Barclay, R.M.R. 2003). Foraging by bats in cleared, thinned and unharvested boreal forest. Journal of Applied Ecology, 40: 646–657. https://doi.org/10.1046/j.1365-2664.2003.00831.x.

Peltoniemi, M., Penttilä, R., & Mäkipää, R. 2013. Temporal variation of polypore diversity based on modelled dead wood dynamics in managed and natural Norway spruce forests. Forest Ecology and Management, 310, 523–530. https://doi.org/10.1016/J.FORECO.2013.08.053.

Philip M.S. 1994. Measuring Trees and Forests. CABI International.

Pienaar, L. V. (1979). An Approximation of Basal Area Growth after Thinning Based on Growth in Unthinned Plantations. Forest Science, 25(2), 223–232. https://doi.org/10.1093/forestscience/25.2.223.

Pietzsch, B.W., Peter, F.J. & Berger, U. 2021. The Effect of Sanitation Felling on the Spread of the European Spruce Bark Beetle—An Individual-Based Modeling Approach. Front. For. Glob. Chang, 4: 103. https://doi.org/10.3389/ffgc.2021.704930.

Ranius, T., Kindvall, O., Kruys, N., & Jonsson, B. G. 2003. Modelling dead wood in Norway spruce stands subject to different management regimes. Forest Ecology and Management, 182(1-3), 13–29. https://doi.org/10.1016/S0378-1127(03)00027-6.

Rauschert, E. S. J., Mortensen, D. A., & Bloser, S. M. 2017. Human-mediated dispersal via rural road maintenance can move invasive propagules. Biological Invasions, 19, 2047–2058. https://doi.org/10.1007/s10530-017-1416-2.

Sandström, P., Cory, N., Svensson, J., Hedenås, H., Jougda, L. & Borchert, N. 2016. On the decline of ground lichen forests in the Swedish boreal landscape: Implications for reindeer husbandry and sustainable forest management. Ambio 45, 415–429. https://doi.org/10.1007/s13280-015-0759-0.

Schroeder, L.M. & Kärvemo, S. 2022. Rekordstort utbrott av granbarkborre – orsaker och vad man kan göra Friska skogar – så når vi dit – KSLAT nr 7-2022, Stockholm.

Schweier, J., Werder, M. & Bont, L. G. 2023. Timber Provision on Soft Soils in Forests Providing Protection Against Natural Hazards: A Productivity and Cost Analysis Using the Koller 507 in the Horizontal Yarding Direction in Switzerland. Small-scale Forestry 22(2): 271-301.10.1007/s11842-022-09526-8. https://doi.org/10.1007/s11842-022-09526-8.

Seibold, S., Hagge, J., Müller, J., Gruppe, A., Brandl, R., Bässler, C., & Thorn, S. 2018. Experiments with dead wood reveal the importance of dead branches in the canopy for saproxylic beetle conservation. Forest Ecology and Management, 409, 564–570. https://doi.org/10.1016/J.FORECO.2017.11.052.

Seidl, R., Schelhaas, M.J., Rammer, W. & Verkerk, P.J. 2014. Increasing forest disturbances in Europe and their impact on carbon storage. Nat Clim Chang, 4(9): 806–810. https://doi.org/10.1038/nclimate2318.

Siitonen, J. 2001. Forest Management, Coarse Woody Debris and Saproxylic Organisms: Fennoscandian Boreal Forests as an Example. Ecological Bulletins 49: 11–41. DOI: 10.2307/20113262.

Sippola, A. L., Lehesvirta, T., & Renvall, P. 2001. Effects of selective logging on coarse woody debris and diversity of wood-decaying polypores in eastern Finland. Ecological Bulletins, 243–254.

Sirén, M., Ilomäki J.A., Mäkinen H., Lamminen S. & Mikkola T. 2013. Harvesting damage caused by thinning of Norway spruce in unfrozen soil, International Journal of Forest Engineering, 24:1, 60–75, DOI: 10.1080/19132220.2013.792155.

Skogen. 2017. Södra investerar i fler drönare. Tidningen Skogen, https://www.skogen.se/nyheter/sodra-investerar-i-fler-dronare [2022-09-21].

Skogskunskap. 2016. Gallringsmall för barr och löv - Skogskunskap. https://www.skogskunskap.se/rakna-med-verktyg/skogsvard/gallringsmall/ (accessed 2024-01-09).

Skogsstyrelsen. 2008. Rekommendationer vid uttag av avverkningsrester och askåterföring. Skogsstyrelsen, Jönköping. Meddelande Nr. 2-2008.

Sohn, J. A., F. Hartig, M. Kohler, J. Huss, & J. Bauhus. 2016. Heavy and frequent thinning promotes drought adaptation in Pinus sylvestris forests. Ecological Applications 26:2190–2205. https://doi.org/10.1002/eap.1373.

Sohn, J. A., S. Saha, & J. Bauhus. 2016. Potential of forest thinning to mitigate drought stress: A meta-analysis. Forest Ecology and Management 380:261–273. https://doi.org/10.1016/j.foreco.2016.07.046.

Spinoni, J., Vogt, J.V., Naumann, G., Barbosa, P. & Dosio, A. 2018. Will drought events become more frequent and severe in Europe? Int. J. Climatol, 38: 1718–1736. https://doi.org/10.1002/joc.5291.

Stampfer, K., Gridling, H. & Visser, R. 2002. Analyses of Parameters Affecting Helicopter Timber Extraction. International Journal of Forest Engineering 13(2): 61–68. https://doi.org/10.1080/14942119.2002.10702463.

Stenbacka, F., Hjältén, J., Hilszczański, J., & Dynesius, M. 2010. Saproxylic and non-saproxylic beetle assemblages in boreal spruce forests of different age and forestry intensity. Ecological Applications, 20(8), 2310–2321. https://doi.org/10.1890/09-0815.1.

Strengbom, J, Axelsson, E.P., Lundmark, T., Nordin, A. 2018. Trade-offs in the multi-use potential of managed boreal forests. J Appl Ecol. 55: 958–966. https://doi.org/10.1111/1365-2664.13019.

Tham, Å. 1988. Yield prediction after heavy thinnings of birch in mixed stands of Norway spruce (Picea abies (L.) Karst.) and birch (Betula pendula Roth & Betula pubescens Ehrh.). SLU, Institutionen för skogsproduktion, Rapport 23, Garpenberg, 36 pages.

Thibault, M., & Moreau, G. 2016. The amplitude of dead wood resource pulses produced by plantation thinning mediates the assembly of wood-boring beetles. Ecosphere, 7(2), e01215. https://doi.org/10.1002/ECS2.1215/SUPINFO.

Tobajas, J., Guil, F., & Margalida, A. 2022. Effects of free-flight activities on wildlife: A poorly understood issue in conservation. Environmental Conservation, 49(1): 8–16. doi:10.1017/S0376892921000412.

Transportstyrelsen. 2022. Drönare – Utbildningsmaterial. Revision 2022-MAR-30. A2-A1A3 utbildningsmaterial 2022-MAR-30 (transportstyrelsen.se), [2022-09-21].

Uusitalo J, 2010. Introduction to Forest Operations and Technology. JVP Forest Systems OY. Tavastehus, Finland.

Valinger, E., & Pettersson, N. 1996. Wind and snow damage in a thinning and fertilization experiment in Picea abies in southern Sweden. Forestry: An International Journal of Forest Research, *69*(1), 25–33. https://doi.org/10.1093/forestry/69.1.25.

Vošvrdová, N. et al. 2023. Dogs trained to recognise a bark beetle pheromone locate recently attacked spruces better than human experts. Forest Ecology and Management, 528: 120626. https://doi.org/10.1016/j.foreco.2022.120626.

Weslien, J., Schroeder, M. and Öhrn, P. 2022. Effekt på granbarkborren och dess fiender vid vinteravverkning av dödade granar, Skogforsk. https://www.skogforsk.se/kunskap/kunskapsbanken/2022/effekt-pa-granbarkborren-och-dess-fiender-vid-vinteravverkning-av-dodade-granar/ [2024-02-07].

Widenfalk, O., & Weslien, J. 2009. Plant species richness in managed boreal forests—Effects of stand succession and thinning. Forest Ecology and Management, 257(5): 1386–1394. https://doi.org/10.1016/j.foreco.2008.12.010.

Wilhelmsson E., Möller J. & Ahrlinger J. 2019. Betalningsgrundande eller betalningsstödjande virkesmätning med skördare. (Cut-To-Length harvester measurements for roundwood payment to forest owners or for supporting industrial pile measurements). Arbetsrapport 1032-2019. Skogforsk.

https://www.skogforsk.se/cd_20200203142819/contentassets/3fece182fb8f458dbdf3e59a81d8625a/arbetsrapport-1032-2019.pdf [2024-02-07].

Worrell, R. & Hampson, A. 1997. The influence of some forest operations on the sustainable management of forest soils— a review, Forestry: An International Journal of Forest Research, Volume 70, Issue 1, 1997, Pages 61-85. https://doi.org/10.1093/forestry/70.1.61.

Wulff, S. and Roberge, C. 2023. Nationell riktad Skogssadeinventering (NRS) - Inventering av granbarkborreangrepp i Götaland och Svealand 2023, Institutionen för skoglig resurshushållning SLU, Umeå. https://www.slu.se/institutioner/skoglig-resurshushallning/miljoanalys/skogsskadeovervakningen/ [2024-02-07].

Wästerlund, I. 2020. *Soil and root damage in forestry: reducing the impact of forest mechanization*. Elsevier.

Zeide, B. 2001. Thinning and Growth: A Full Turnaround. Journal of Forestry 99:20–25.

Appendix

Glossary

Term	Definition/Explanation	In Swedish
Assortment	Timber or lumber with properties in accordance with given specifications or rules (TNC 1996). Pulpwood (Dbh < 13 cm), Timber (Dbh >= 13 cm)	Virkessortiment
Basal area	The cross-sectional area of all stems in a stand measured at breast height, expressed per unit of land area (Helms, 1998)	Grundyta, uttrycks vanligen i m^2 per hektar, ett mått på beståndstäthet
Basal area weighted mean diameter (DGV)	Mean diameter weighted by tree basal area. Always higher than the arithmetic basal area, as the larger trees are heavier (cm).	Grundytevägd medeldiameter.
Brood	Collective offspring from the same generation that develop, hatch and mature at about the same time (Helms, 1998)	Kull
Buffer zone	Vegetation strip or management zone of varying size, shape and character, created to mitigate the impacts of actions on adjacent land (Helms, 1998)	Buffertzon
Conventional thinning system	In this study thinning using harvesters and forwarders of about 20 metric tonnes (TNC, 1996)	Normal markbaserad gallring
Current annual increment (CAI)	The current annual volume growth (m^3sk ha^{-1} y^{-1})	Löpande årlig tillväxt (m^3sk ha^{-1} y^{-1})
Cut-to-length	A harvesting system in which felled trees are processed into logs at the stump before they are transported to the landing (Helms, 1998)	Sortimentshuggning
Cymose and racemose growth	**Cymose growth** means that the top buds die off each year and are replaced by the highest side buds. It is common for several side shoots to take over the height growth, resulting in the formation of forks on the trunk (e.g. birch, hazel, maple, and willow). **Racemose growth** is growth where the top shoot continuously grows with a continuous stem shaft as a result, so-called monopodium (e.g. alder, ash, aspen, spruce and pine). (TNC, 1996)	Cymös och racemös tillväxt
Dbh	The diameter of a tree measured at breast height (4.5 ft / 1.3 m) from the ground. On sloping ground the measurement is taken from the uphill side (Helms, 1998)	Brösthöjdsdiameter
Delimb	Removing the branches from a stem	Kvista

Dominant height	Average height of the 100 trees per hectare with the greatest diameter at breast height (Philip, 1994)	Övre höjd
Edge effect	The modified environmental conditions or habitat along the margins (edges) of forest stands or patches (Helms, 1998)	Kanteffekt
Extraction	The primary transport of logs and trees as in forwarding, skidding or yarding (Helms, 1998)	Primär transport, dvs terrängtransport
Extraction rate	Proportion of growing stock extracted	Virkesuttagsnivå
Fennoscandia	Finland, Norway and Sweden	Finland, Norge och Sverige
Forage	Browsing material and herbage that is available either natural or produced seasonally or annually (forage crop) on a given area or range that can provide food for grazing animals or be harvested for feeding (Helms, 1998)	Foder
Forwarder	A machine that loads and transports logs by carrying them completely off the ground (Helms, 1998)	Skotare
Ghost trail	The path or movement of a machine that operates independently of strip roads	Beståndsgående
Grapple	Hinged jaws or arms capable of being opened and closed and used to grip logs or trees during skidding or loading (Helms, 1998)	Grip
Harvester	A machine that fells trees and processes them into logs at the stump (Helms 1998)	Skördare
Harwarder	A machine capable of harvesting and hauling to roadside (Uusitalo, 2010)	Drivare
Invasive species	Species that have typically been introduced by humans to a new environment and that have a negative impact on native species population.	Invasiva arter
Land Expectation Value (LEV)	Summary of past and future cashflow streams discounted to the present value (SEK ha^{-1})	Markvärde
Landing	A cleared area in the forest or adjacent to a road to which logs are yarded, forwarded or skidded for reloading on to trucks for transport (Helms, 1998)	Avlägg
LiDAR	Light Detection and Ranging (LiDAR). A remote sensing device or technology for measuring distances and directions. LiDAR systems use a light beam in place of a microwave beam to obtain measurements of speed, altitude, directions and range of a target (Helms, 1998). The technology is used to produce high-resolution digital models.	LiDAR

Linear feature	A geographical feature that can be represented by a line or set of lines, for example rivers and power lines (Helms, 1998)	
Logging	The felling, forwarding or skidding, and on-site processing and loading of trees or logs (Helms, 1998)	Avverkning
Mandatory trees	Trees that have to be removed regardless of thinning form, e.g. trees on strip roads, large and/or deformed trees	Tvingande träd
Motor-manual	A logging operation where trees are cutting using a chainsaw and manual accessories like wedges, measuring tapes, felling levers, etc.	Motor-manuell
Nurse crop	A crop of trees (in Sweden often birch), shrubs or other plants, either naturally occurring or introduced, used to nurture, improve survival, or improve the form of a more desirable tree or crop when young by protecting it from frost, insolation, wind or insect attack (Helms, 1998)	Lågskärm
Pendulous lichen	Lichen with a hanging growth form, often from the genus *Usnea*	Hänglavar
Polypores	Morphological group of fungi with shelf-like fruiting bodies	Tickor
Pre-commercial thinning	The removal of trees not for immediate financial return but to reduce stocking to concentrate growth on more desirable trees	Röjning
Primary extraction	Off road transport of logs	
Natural pruning	The process of natural branch death and shedding caused by physical and biotic agents such as wind, snow or ice breakage (Helms, 1998)	
Residual stand	A stand composed of trees remaining after any type of intermediate harvest (Helms, 1998)	Kvarvarande bestånd efter åtgärd
Rotation	In even-aged forest management the period between regeneration, establishment, and final felling (Helms, 1998)	Omloppstid
Roundwood	A length of cut tree, generally with a round cross section, such as a log or bole (Helms, 1998)	Rundvirke
Salvage logging	The removal of dead trees or trees damaged or dying because of injurious agents other than competition, to recover economic value that would otherwise be lost (Helms, 1998)	Tillvaratagande av skadade träd, t.ex. vindfällen, brandskadade eller insektsskadade
Saproxylic insects	Insects that are dependent on dead or decaying wood for at least a part of their life cycle	Vedlevande insekter

Selection harvesting	Individual trees of all size classes are removed more or less uniformly throughout the stand to promote growth of remaining trees and to provide space for regeneration (Helms, 1998)	Blädning
Shelterwood	The cutting of most trees, leaving those needed to produce sufficient shade to produce a new age class in a moderated environment (Helms, 1998)	Skärmställning/timmer-ställning
Self-thinning	A natural process of density-dependent mortality in a stand of trees	Självgallring
Silviculture	The art and science of controlling the establishment, growth, composition, health and quality of forests and woodlands to meet diverse needs and values of landowners and society on a sustainable basis (Helms, 1998)	Skogsskötsel
Site index	A species-specific measure of actual or potential forest productivity (site quality, usually even-aged stands), expressed in terms of the average height of trees included in a specified stand component (defined as a certain number of dominants, co-dominants. or the largest and tallest trees per unit area) at a specified index or base age (Helms, 1998)	Ståndortsindex
Stand	A contiguous group of trees, sufficiently uniform in age-class distribution, composition and structure, and growing on a site of sufficiently uniform quality to be a distinguishable unit (Helms, 1998)	Bestånd
Stand density	A quantitative measure of stocking expressed either absolutely in terms of number of trees, basal area or volume per unit area, or relative to some standard condition (Helms, 1998)	Beståndstäthet
Stem number (N)	Number of trees per hectare (N ha^{-1}).	Stamantal
Strip road	An access cut in the forest for forwarding or skidding (Helms, 1998)	Stickväg
Stump treatment	Application of a control agent on fresh stump surfaces to reduce infections of *Heterobasidion* root rot	Stubbehandling
Successional stage	The change in species community over time, which occurs after a disturbance that alters the condition of the existing habitat	Successionsstadium
Thinning	A silvicultural treatment to reduce stand density of trees, primarily to improve growth, enhance forest health, or recover potential mortality (Helms, 1998)	Gallring
Thinning quota		

Thinning regime	A term comprising the type, grade and frequency of thinnings for a given area, generally along with their year of commencement and sometimes termination (Helms, 1998)	Gallringsprogram
Total carbon stock	The amount of carbon (tone C ha^{-1}) in trees and dead wood, stumps and the soil	Totala kollagret i levande träd, död ved, stubbar och markkol.
Volume average harvested tree	The mean volume (m^3 sub) of harvested trees	Medelvolymen fast mätt under bark för de avverkade träden, också kallad “Medelstam”
Wolf tree	A generally predominant or dominant tree with a broad spreading crown that occupies more growing space than its more desirable neighbours (Helms, 1998)	Varg