Forest operations in multifunctional forestry

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Cover: Blueberry-picking in a voluntary set-aside forest intended for nature conservation management, eight years after a large removal of Norway spruce.
(photo: Örjan Grönlund)

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Abstract

Forests provide a variety of ecosystem services and traditional forest management is largely based on the extraction of one product, wood. Multifunctional forestry, forest management aimed at benefitting multiple ecosystem services, has emerged as awareness has grown of other forest ecosystem services. Nature conservation management is a type of multifunctional forestry promoting ecosystem services other than harvest of wood, most commonly biodiversity and recreation. While the benefits of multifunctional forestry and nature conservation management is recognised, there are knowledge gaps regarding how to perform these operations. The overarching objective of this thesis is to increase knowledge and improve implementation of multifunctional forest operations in Sweden. This is addressed through four studies aiming at answering questions related to how forest operations can be implemented in multifunctional forestry. The findings indicate that many conservation values in forest land can be identified using commonly available GIS-data. In most cases, nature conservation management operations are not complicated, but forest managers are disincentivised by conflicting goals and fear of high costs and criticism. The conclusion from detailed studies of operations is that costs in multifunctional operations are higher than conventional operations, but when the entire management system is analysed, effects on net revenues may be small. The general conclusion is that, in many cases, multifunctional forestry is not limited by the operations but rather a lack of clear goals and strategies for achieving goals and evaluating their attainment.

Keywords: Natural disturbances; natural disturbance emulation; thinning; time studies; StanForD; thematic analysis; GIS; harvester; forwarder; forest management

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Avverkning i skogsbruk med flera mål

Sammanfattning

Skogen producerar många olika ekosystemtjänster. Ursprunget till dagens konventionella skogsbruk är att främja en enda ekosystemtjänst, trä (timmer, ved, biobränsle). Skogsbruk med flera mål har utvecklats som en följd av att kunskapen om andra ekosystemtjänster har ökat. Naturvårdande skötsel kan betraktas som skogsbruk med flera mål där virkesproduktion inte är ett av brukandets mål. Trots att det finns omfattande forskning som visar på värdet av skogsbruk med flera mål och naturvårdande skötsel så finns det betydande kunskapsluckor gällande hur dessa åtgärder ska utföras. Det övergripande syftet med denna avhandling är att bidra till ökad kunskap om och omfattning av skogsbruk med flera mål i Sverige. Detta görs genom fyra studier som undersöker delar av frågan om hur kunskap om avverkning i konventionellt skogsbruk kan tillämpas i skogsbruk med flera mål. Resultaten pekar på att bevarandevärden i skog i stor utsträckning kan beskrivas med fritt tillgängliga GIS-data. Vidare framgår att naturvårdande skötsel ofta inte är komplicerat men att åtgärderna uteblir på grund av målkonflikter samt rädsla för höga kostnader och kritik. Slutsatserna från detaljerade analyser av avverkning i åtgärder med flera mål visar att kostnaderna ofta är högre än i konventionella åtgärder men att effekten på skogsbrukets lönsamhet kan vara liten, i synnerhet om hela brukandet beaktas. Den övergripande slutsatsen är att skogsbruk med flera mål ofta inte begränsas av teknik och arbetsmetoder utan oftare av att det saknas strategier för hur mål sätts upp och hur måluppfyllnaden utvärderas.

Ämnesord: naturliga störningar; gallring; tidsstudier; StanForD; tematisk analys; GIS; skördare; skotare; skogsskötsel.

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Preface

Långt bortom ängar och berg fanns en skog. I skogen levde stora och små djur. Somliga hade sina bon under jorden, andra på marken och en del levde i träden.

Och högt över trädtopparna seglade kungsörnar på breda vingar. Kungsörnar tycker om att flyga högt. Alla utom …

- Lars Klinting

Contents

List of publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I. Grönlund Ö., Di Fulvio F., Bergström D., Djupström L., Eliasson L., Erlandsson E., Forsell N., Korosuo A. (2019). Mapping of voluntary set-aside forests intended for nature conservation management in Sweden. Scandinavian Journal of Forest Research. 34(2):133-144. https://doi.org/10.1080/02827581.2018.1555279

II. Grönlund Ö., Erlandsson E., Djupström L., Bergström D., Eliasson L. (2020). Nature conservation management in voluntary set-aside forests in Sweden: practices, incentives and barriers. Scandinavian Journal of Forest Research. 35(1-2):96-107. https://doi.org/10.1080/02827581.2020.1733650

III. 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. https://doi.org/10.1080/14942119.2019.1595943

IV. Eliasson L., Grönlund Ö., Lundström H., Sonesson J. (2020). Harvester and forwarder productivity and net revenues in patch cutting. International Journal of Forest Engineering, https://doi.org/10.1080/14942119.2020.1796433

Papers I-IV are reproduced with the permission of the publishers.

The contribution of Örjan Grönlund to the papers included in this thesis was as follows:

I. Initiated the study and, together with co-authors, drew up funding proposal. Carried out data collection. Performed analysis in collaboration with co-authors. Prepared manuscript with support from co-authors.

II. Responsible for planning, funding, and data collection. Performed analysis and prepared manuscript with support from co-authors.

III. Responsible for planning and funding of the project. Collected data together with colleagues. Performed analysis and prepared manuscript in collaboration with co-author.

IV. Main responsibility for preparing the manuscript and contributed to the analysis.

Definitions

In this thesis the following concepts are central, and are defined as follows:

Multifunctional forestry: Forestry intentionally promoting several ecosystem services within a stand.

Multifunctional forestry intended for harvest of wood: Forestry intended for promotion of several ecosystem services, one of which is harvest of wood.

Nature conservation management (NCM): Operations intended to promote ecosystem services other than harvest of wood.

1. Introduction

1.1 Forest ecosystem services

The UN-initiated Millennium Ecosystem Assessment (2005) defines ecosystem services as “the benefits people obtain from ecosystems”. Forests are the source of many ecosystem services, and a sustainable use of forest resources relies on simultaneous production of multiple ecosystem services (United Nations, 1992). The multiple ecosystem production in forests is implied in many of the Sustainable Development Goals (Sachs *et al.*, 2019). The Millennium Ecosystem Assessment (2005) presents a structure that divides ecosystem services into four groups, with forest context examples from Pettersson *et al.* (2018); provisioning services (e.g. wood production), regulating services (e.g. water purification and regulation), cultural services (e.g. facilitating recreation), and supporting services (e.g. biodiversity). All ecosystem services in an area are connected, and the extraction of one influences other ecosystem services (TEEB, 2010). Quantifications and appraisals of ecosystem services is a large field of research that has devised an array of methods suitable, not without flaws, when analysing effects on ecosystem services, e.g. from different management strategies (Norgaard, 2010).

While the human use of wood has long traditions, it was not until there was a scarcity of forest land that practices developed aimed at controlling forest establishment, composition, and growth i.e. silviculture and forest management were born (Baker *et al.*, 2009). The general purpose of forest management is to maximise profitability and supply industries with raw materials, thereby securing one of the provisioning ecosystem services (Puettmann *et al.*, 2015). Most other ecosystem services are difficult to quantify (Nilsson *et al.*, 2001) and monetise, while many do not primarily relate to a specific stand, e.g. carbon sequestration, decomposition, and water purification (Sukhdev *et al.*, 2014).

As a consequence of the challenge to monetise many ecosystem services and the long time frames in forest management, there is often a difference between an individual short-term optimal forest management and a long-term optimum that benefits societies. For example, a small-scale forest management operation with a short time horizon would neither prioritise reforestation nor consider potentially negative effects on biodiversity. To address this, and to promote society's interest, forestry legislation developed alongside forest management (Wiersum, 1995; Fernow, 1907).

In the Scandinavian countries, the initial goal of forest legislation was to prevent deforestation. The first forestry acts were introduced at different times during the 19th and 20th century; in Denmark 1805 (Fritzbøger, 2018), in Finland 1851 (Kotilainen & Rytteri, 2011), in Sweden 1903 (Nylund, 2009), and in Norway 1965 (Frivold & Svendsrud, 2018).

Revised and expanded in several stages since 1903, mainly 1923, 1948, 1979 and 1993, the Swedish Forestry Act (SFS, 1979:429) has provided the legal framework for forest management in Sweden for more than a century (Nylund, 2009).

1.2 Swedish forests and forestry

Situated in northern Europe, most forests in Sweden are in the boreal forest zone (i.e. the Taiga) while the southern regions are in the boreal-nemoral zone. The former is characterised by a large element of coniferous species, while the latter contains a mixture of deciduous and coniferous trees.

Sixty-nine percent, 28 million hectares (ha), of Sweden is covered with forest. Of this area, 23.6 million ha are defined as productive forest land since annual growth is greater than one cubic metre (m^3) per ha. The most common tree species in Swedish forests are Norway spruce (*Picea abies* (L.) Karst.), Scots pine (*Pinus sylvestris* L.) and birch (*Betula pendula* Roth. and *Betula pubescens* Ehrh.), making up 40, 39 and 13% of the standing volume, respectively (Nilsson et al., 2020).

Even-aged forest management is common practice in production-oriented forest management. In northern, central, and most of southern Sweden, forest management concerns a small number of tree species, mainly Norway spruce, Scots pine, and the locally predominant birch species, downy birch and silver birch. In some parts of southern Sweden, oak (*Quercus robur* L.) and beech (*Fagus sylvatica* L.) can be added to the species of importance. In most cases, stands are artificially regenerated by means of planting genetically improved seedlings, and the main source of revenue is the final felling (Albrektson *et. al.*, 2012). In thinning and final felling operations, mechanised cut-to-length methods are used (Brunberg, 2016), while some non-industrial private forest owners carry out manual cut-to-length operations in their forests using chainsaws and farm tractors or quad bikes (Edlund, 2019; Lindroos *et. al.*, 2005).

The average annual cut in Sweden in the past five years has been more than 80 million m^3 (Nilsson *et al.*, 2020), of which slightly more than half was Norway spruce, one-third was Scots pine, and the remainder deciduous trees. Two-thirds of these volumes originates from approximately 200 000 ha of final felling, while the remaining third originates from the approximately 300 000 ha of thinning carried out. Approximately half of the forest land in Sweden is owned by ~300 000 non-industrial private forest owners while the other half is owned by a set of large forest companies, state-owned forest companies, dioceses, common forests, and regional companies. While forest companies aim to maximise revenues and secure wood supply to their industries, there is greater diversity regarding the aim for the management among small-scale forest owners (Ingemarson *et al.*, 2006).

The latest major revision of the Swedish Forestry Act, in 1993, removed the detailed regulations in the wood production-oriented 1979 Forestry Act. The term *sector responsibility* was introduced, implying the responsibilities for the sector to act in accordance with the intent of the law, even if there were few specific regulations (Bush, 2010). This was at a time when there was an increased interest in government through governance (Rhodes, 1996), a method considered particularly suited for the government of natural resources (Ostrom, 1990).

Sparked by the debate regarding conservation starting in the 1970s, the 1993 Forestry Act had greater emphasis on other ecosystem services than production of wood, and forest owners were to give environmental and conservation objectives the same weight as production goals. Retention forestry (i.e. a practice where non-timber ecosystem services are to be considered in all operations) was introduced in Sweden (Simonsson *et al.*, 2015).

In Sweden, the area of forest certified under forest certification schemes is increasing, and in 2019, 63% of the productive forest land in Sweden was certified by FSC and/or PEFC (The Swedish Forest Agency, 2020). These are high proportions, both in relation to other European countries and on a global scale (Kraxner *et al.*, 2017). While it can be argued that the certification standards poorly reflect evidence-based knowledge (Angelstam *et. al.*, 2013) and implementation of certification standards in large organisations is a challenge (Keskitalo & Liljenfeldt, 2014; Högvall Nordin, 2006), forest certification has played an important role in strengthening non-timber ecosystem services in Swedish forestry (Johansson, 2013).

The 2020 FSC Sweden certification scheme (FSC, 2020) requires forest owners to set aside at least 5% of the productive forest land, in what is referred to as voluntary set-asides. Another stipulation is that the aim of management should be a combination of wood production and other ecosystem services on a further 5% of the productive forest land.

Pettersson *et al.* (2018) has analysed the status of forest ecosystem services in Sweden, implicitly evaluating whether the Swedish national strategy is efficient for producing sufficient levels of all ecosystem services. The status of ten of the 30 ecosystem services is classified as ‘sustainable’, while seven face major challenges. The status of the remaining 13 ecosystem services is classified as ‘intermediate’. One of the conclusions of the mapping is the need to adapt practices in Swedish forestry to improve conditions for other ecosystem services.

1.3 Forest management

On the most fundamental level, there are two forest management systems: even-aged (rotation) forestry and uneven-aged (selection) forestry. The former is characterised by a cyclic rotation where treatment units are single-storied for most of the cycle. Even-aged forest management is the dominant method for forest management intended for wood harvest in much of the world (Robinson, 1988). Uneven-aged forestry uses selection cutting to create full-storied treatment units (Lundqvist, 2017). Both types of forestry involve what Albrektson *et al.* (2012) refer to as different management philosophies where forest management is based on moral or philosophical principles, e.g. strategies aiming for ‘no clearcuts’ or ‘thinning for maximal timber quality’.

Both even-aged and uneven-aged forestry are characterised by aims to maximise profitability and ensure a sustainable wood supply. However, in recent decades, uneven-aged forestry has been seen as an alternative that avoids the negative effects associated with even-aged forest management (O'Hara, 2014). Uneven-aged forest management is part of the broad concept of continuous cover forestry (CCF). Many studies have explored the various differences between even-aged forestry and CCF, e.g. biodiversity (Nolet *et al.*, 2018; Schall *et al.*, 2018; Kuuluvainen *et al.*, 2012; Lindenmayer & Franklin, 2002), recreation values (Gundersen & Frivold, 2008), and nitrogen leaching (Gundersen *et al.*, 2006). Some researchers consider CCF to be too broad a term, so drawing general conclusions about its benefits and drawbacks is a challenge (Pommerening & Murphy, 2004).

Uneven-aged forestry is only possible with late-succession species. In order to avoid issues associated with final felling where management also involves pioneer species, several even-aged forestry management methods have been introduced or reintroduced, e.g. shelterwoods (Raymond *et al.*, 2009; Bergqvist, 1999; Hannah, 1988; Keenan, 1986) and patch cuttings (Erefur, 2010).

The objective of even-aged forestry is wood harvest. This management has negative effects on some ecosystem services, while other ecosystem services are unaffected or benefit from even-aged forestry. As even-aged forestry is common in much of the world, the ecosystem services that are unaffected or benefit from even-aged forest management need less promotion under current conditions. Accordingly, the efforts that are made to promote other ecosystem services are aimed at introducing other practices, i.e. alternative management strategies or exempting areas from management.

1.4 Forest conservation

Globally, around two billion ha forest land are within protected areas, equivalent to 15% of the total forest land, and of this area, 700 million ha are within formal preserves, IUCN categories I-IV (Lausche & Burhenne-Guilmin, 2011). South America is the region with highest proportion of forest land in formal preserves (31%) while Europe has the lowest proportion (5 %) (FAO & UNEP, 2020). The remaining protected areas are in IUCN categories V and VI, which include ‘Protected area with sustainable use of natural resources’ (Dudley *et al.*, 2013).

In Sweden, formal preserves comprise 2.3 million ha, of which 1.4 million ha are productive forest land (The Swedish forest agency, 2019). Formal preserves are found throughout the country but make up more of the forest land in northern Sweden in proximity of high mountains, than in other regions (The Swedish forest agency, 2019).

Voluntary set-asides have been instigated by forest certification, and surveys indicate that these areas are increasing, comprising 1.2 million ha of productive forest land in the most recent survey (Eriksson, 2019; Claesson & Eriksson, 2017; Stål *et al.*, 2012; The Swedish Forest Agency, 2008; The Swedish Forest Agency, 2002). Voluntary set-asides have been one of the main instruments for certification-driven improvement of biodiversity (Elbakidze *et al.*, 2016; Elbakidze *et al.*, 2011). Voluntary set-asides also occupy a middle ground in terms of continuity; the selection is not permanent but investigations indicate a slow turnover (Finnström & Tranberg, 2014).

The concept of tree retention has been introduced with the aim of providing habitat lifeboats during the reforestation phase in even-aged forest management for species living in mature forests (Lindenmayer *et al.*, 2012; Rosenvald & Lõhmus, 2008; Franklin *et al.*, 1997). Tree retention has been required in all forest operations in Sweden since the 1993 revision of the Forestry Act. The interpretation and implementation of tree retention vary but, on average, 3-5% of the area is retained in final felling (Gustafsson *et al.*, 2012), and The Swedish Forest Agency (2019) found 0.43 million ha currently preserved through tree retention. As most current stands were cut in final felling prior to 1993, these areas currently have no tree retention. Claesson *et al.* (2015) estimated that, when tree retention is fully implemented, 1.6 million ha will be preserved through tree retention.

The different forms of protection result in different levels of continuity, size, and frequency, and serve different functions. Consequently, there are systematic differences regarding data availability between areas with different form of protection, e.g. on conservation values. Formal preserves are larger, fewer, better described, and intended as permanent habitats for long periods of time. In comparison, retained patches are small, occurring in almost all forest stands, and often less clearly defined and described, and the patch is intended as a lifeboat habitat for which the major benefit is attained within 20 years. Voluntary set-asides are somewhere between the two extremes in all these aspects (Simonsson *et al.*, 2016).

1.4.1 Disturbances in ecosystems

There are many definitions of disturbances in ecosystems. One often used is that presented by Pickett and White (1985): ‘any relatively discrete event that disrupts the structure of an ecosystem, community, or population, and changes resource availability or the physical environment’. It can be argued that disturbances are central in all ecosystems (Sousa, 1984). Deriving from this view, a sub-discipline within ecology, disturbance ecology, has evolved (Turner, 2010) and remains relevant (Newman, 2019). Different disturbances have different scales, and Drever *et al.* (2006) illustrate these relationships for disturbances in boreal forests in one, fairly simple, picture (Figure 1).

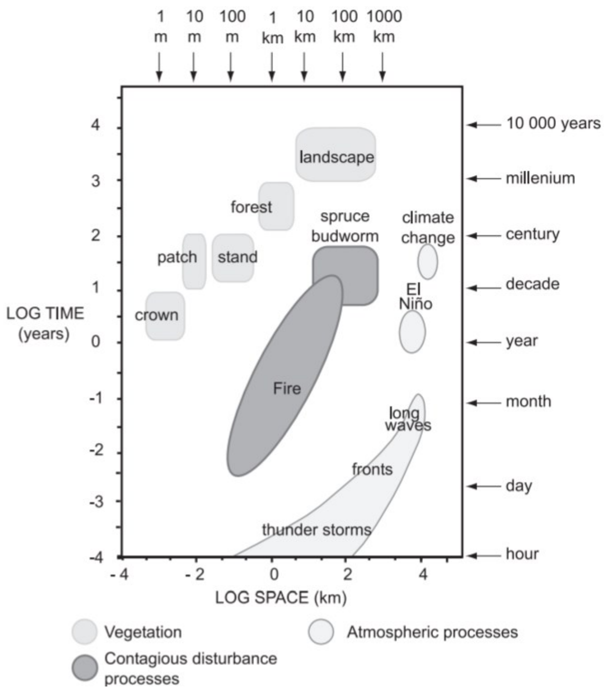

Figure 1. The time-size relationship between disturbances that effect boreal forests (Drever *et al.*, 2006).

When using the term disturbances, it is often implied that these are ‘natural’. Natural disturbances as described by Pickett and White (1985) have since been referred to as simply ‘disturbance’. As the understanding of human influence on nature has grown, disturbance ecology argues that there is a need to recreate/simulate/emulate disturbances to avoid loss of biodiversity.

Several theories have been presented in support for this approach; the most frequently cited are the intermediate disturbance hypothesis (Connell, 1978), the coarse and fine filter metaphor (Hunter Jr. *et al.*, 1988), the historic range of variability (Keane *et al.*, 2009; Morgan *et al.*, 1994) or the natural range of variability (Landres *et al.*, 1999).

1.4.2 Nature conservation management (NCM)

The initial challenge in the management of protected areas is to determine which ecosystem services that are to be promoted. The second is to determine whether those ecosystem services require human intervention. Another challenge is to determine which actions are most likely to result in the intended outcomes.

While the importance of natural disturbances is recognised, several approaches have argued in favour of human intervention to reach this state. While Pickett and White (1985) and later Attiwill (1994) described this as nature conservation management (NCM), several other concepts have been introduced, e.g. natural disturbance-based management (NDBM) or natural disturbance emulation (NDE) (Kuuluvainen & Grenfell, 2012; Drever *et al.*, 2006).

The process of creating management plans for protected areas is complex, and there are many aspects to consider (cf. Nitare *et al.*, 2014; Götmark, 2013; Alexander, 2008; Lindenmayer & Franklin, 2002). Human interventions can only partly emulate the natural processes. In the process of evaluating management, studies have used both simulations (Seidl *et al.*, 2011) and evaluation through field trials (Haeussler & Kneeshaw, 2003; McRae *et al.*, 2001; Burton *et al.*, 1999).

In Sweden, there has been a shift in disturbances over recent centuries. Human interventions have reduced the frequency of wildfires (Östlund *et al.*, 1997) while mechanisation of agriculture has resulted in less grazing of cattle on forest land (Lagerås, 2007). Consequently, voluntary set-asides in Sweden are divided into two groups: areas intended for free development (i.e. non-management), and areas where NCM is required to create or uphold intended values. In the Swedish context (as well as in this thesis), NCM includes all operations intended for promotion of ecosystem services other than harvest of wood.

While Nitare *et al.* (2014) present approaches to attain biodiversity values through NCM, Westin (2014) argues for the need for adapted NCM to preserve cultural values, and Andersson *et al.* (2016) describe biotopes requiring consideration in forest operations. One issue about NCM in Sweden is the lack of knowledge regarding these areas and the management carried out. It has been estimated that NCM is not implemented to the extent needed to prevent losses of conservation values (Swedish environmental protection agency, 2012; Regeringskansliet, 2001).

1.5 Forest operations

Forest operations research is the term for describing (and studying) the tasks set out in forest management (Heinimann, 2007; Samset, 1992). The most fundamental goal of operations is to fully reach the management goals. Operations in themselves often have several goals, and the design of operations relies on a trade-off between goals. Since forest management relies on a series of operations carried out at different times, one intervention cannot be expected to fulfil all goals (Albrektson *et al.*, 2012). In even-aged forestry the management cycle contains many different interventions (e.g. soil preparation, planting, pre-commercial thinning, thinning, and final felling) throughout the rotation period, whereas in uneven-aged forestry there are fewer types of interventions (in an idealised situation only thinning). The conditions and operations in one intervention are influenced both by previous and subsequent interventions, as well as operations by other actors within interventions (e.g. forwarder work in final felling is influenced by the work carried out by the harvester, which in turn has been influenced by previous thinnings and considerations for future operations). The possibilities and limitations differ between management strategies and operations. The driving force for forestry has been harvesting operations since they result in the yields and revenues that justify all other interventions.

In forest operations, efficiency and productivity are key concepts. Efficiency can be defined as the input per produced unit for a given production system while productivity is the inverse (e.g. hours per m^3 versus m^3 per hour) (Björheden *et al.*, 1995). The actual productivity reached in operations is then a result of the interactions between human, technological, environmental, and organisational factors (Häggström & Lindroos, 2016).

Reducing costs in harvesting operations has been, and remains, a driving force in the development of forest operations (Ager, 2014). Minimising costs is also a key factor in the design of operations and choice of machinery.

Comparisons of costs, i.e. benchmarking, between countries and regions is useful for identifying state-of-the-art and potential areas of development (Di Fulvio *et al.*, 2017; Ackerman *et al.*, 2014; Miyata, 1981; Stridsberg & Algvere, 1964). One general conclusion from these kinds of comparisons is that, in countries with high labour costs, highly efficient (i.e. expensive) machinery is implemented.

In Sweden, costs of harvesting operations comprise more than half of the costs for forestry (Eliasson, 2020). In addition to forestry costs (Table 1), average road transport costs in 2019 were €7.9-10.5 m^{-3} solid. Harvesting operations therefore comprise approximately 40% of the industry wood procurement costs.

Table 1. Forestry costs (€ m^{-3} solid under bark) in Sweden. Conversion rate €1 = SEK10. Data from Eliasson (2020)

Cost	Southern Sweden	Northern Sweden
Harvesting operations	13.3	13.2
Regeneration and early stand-management	5.9	5.4
Forest roads	2.5	3.3
Miscellaneous	0.6	0.7
Over-head	1.8	2.1
Total cost, at landing	**24.1**	**23.6**

The initial determinants for the choice of technology in harvesting can be separated into stand factors, e.g. ground conditions and size of the trees that are to be harvested, and organisational factors, e.g. type of operation, legislation, and harvesting method. When harvesting operations are to be undertaken, there are two main types of logging systems: whole-tree logging and cut-to-length methods, where the latter involves bucking trees crosscut into logs before extraction from the forest to the landing (Sundberg & Silversides, 1988). Legislation on road transports often prevents transport of full-length trees and may thereby necessitate some cross-cutting and delimbing of the whole-tree logs at the landing before onward transport.

Cut-to-length methods are often carried out using a two-machine system with a harvester for felling, delimbing, and bucking the trees and a forwarder for terrain transport of logs to landing. Mechanised cut-to-length methods are cost-effective (Eliasson *et al.*, 2019) and reduce risk of work-related accidents (Axelsson, 1998) but rely on highly skilled operators (Purfürst &

Erler, 2011; Ovaskainen *et al.*, 2004) and high investment costs (Spinelli *et al.*, 2011; Gellerstedt & Dahlin, 1999).

The technological development and mechanisation of forest operations over the past half-century has reduced harvesting costs and improved the work environment (Eriksson, 2016). Current forest technology and work methods are mainly developed for operations in homogeneous even-aged forests. The choice of technology often depends on terrain, costs, and availability. In flat terrain, wheeled machines dominate, with tracked machines as an option in more challenging terrain (steeper, or with lower bearing capacity) (MacDonald, 1999), and in very steep terrain, cable systems have been used for a long time (Cavalli, 2012; Studier & Binkley, 1976). A variety of machines have been developed for addressing challenges in logging, e.g. lightweight machines (Lazdinš *et al.*, 2016), pendulum arm forwarders (Gelin *et al.*, 2020), rubber-track forwarders (Gelin & Björheden, 2020), and cable logging systems for flat terrain (Erber & Spinelli, 2020). All of these have been developed to reduce ground disturbances from forest operations, which lead to fewer limitations on logging and subsequently lower costs and impact. Practices have also developed where machinery initially designed for other purposes, e.g. excavators and farming tractors, are adapted for forestry.

For harvesters, much of the observed variation in productivity (time consumption) can be attributed to the positive correlation between productivity and the volume/size of the harvested tree (Figure 2) (c.f. Nurminen *et al.*, 2006; Brunberg, 1997; Kuitto *et al.*, 1994; Brunberg *et al.*, 1989). The above cited sources have also identified several additional site-specific attributes as influencing harvester productivity, e.g. number of assortments harvested, terrain conditions, and tree species composition in the stand.

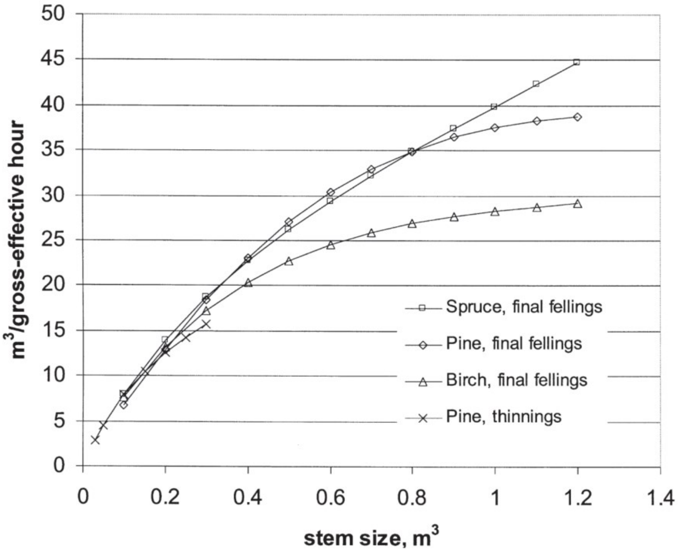

Figure 2. Relationship between time consumption and average tree size in final felling and thinning of coniferous trees. The number of assortments is two for pine, spruce and birch in final felling and one for pine in thinning (Nurminen et al., 2006).

Harvester productivity in even-aged thinnings has been found to be in the order of 30% lower than those for final felling of trees of equal size (Jonsson, 2015; Nurminen *et al.*, 2006; Eliasson, 1998; Brunberg, 1997; Kuitto *et al.*, 1994). The lower productivity in thinning and shelterwood establishment operations can be explained by the restrictions in movements caused by residual trees and regeneration (Eliasson, 1998). Eliasson (2020) found that average harvesting costs varied greatly between thinning and final felling, mainly due to different sizes of harvested trees (Table 2).

Table 2. Harvesting costs in Sweden. Conversion rate €1 = SEK10. Data from Eliasson (2020).

	Final felling		Thinning	
	Southern Sweden	Northern Sweden	Southern Sweden	Northern Sweden
Harvesting costs (€*m^{-3} solid)	9.8	10.6	20.7	19.9
Average harvested tree volume (m^3 solid)	0.43	0.24	0.10	0.092

Several large-scale field studies have developed models for forwarder time consumption (Nurminen *et al.*, 2006; Brunberg, 2004; Kuitto *et al.*, 1994; Bergstrand, 1985; Lönner, 1964). Briefly, the factors found influencing forwarder productivity are logging type (final felling or thinning), wood concentration along strip road, size and arrangement of piles, extraction distance, terrain conditions, load size, average tree size, and number of assortments.

As conditions vary between logging sites (no two forests are alike), the operator also has a significant effect on productivity. Not only is there a difference between operators but large differences can be observed within work carried out by the same operator over time, both short and long term (Purfürst & Erler, 2011; Purfürst, 2010; Ovaskainen *et al.*, 2004; Gullberg, 1995; Samset, 1990).

The development of forest machines is ongoing, and has reached a state where the operator in many cases has become the limiting factor for productivity (Häggström, 2015). Research has therefore also focused on reducing operator work load, e.g. through improved work methods (Grönlund *et al.*, 2015; Bergström, 2009; Bergström *et al.*, 2007), decision support systems (Rönnqvist *et al.*, 2021), and automation or autonomous systems (Parker *et al.*, 2016).

It is also worth noting the concluding remarks by Nurminen *et al.* (2006) in a study of harvester and forwarder performance: "Durability of machinery, operative planning and the operators' skills have a crucial effect on long-term productivity". It is therefore important to consider the entire system when determining its viability.

Motor-manual operations can mainly be divided into operations carried out with chainsaw and operations carried out with clearing saw. Productivity in chainsaw operations is mainly influenced by the size of the trees harvested, distance between trees, and intensity of removal (Behjou *et al.*, 2009; Lortz *et al.*, 1997; Kilander, 1961). Clearing saws are mainly used in pre-commercial thinning in even-aged forestry. Time consumption in pre-commercial thinning is mainly determined by height and number of trees per ha in the area (Uotila *et al.*, 2014; Ligné, 2004; Bergstrand, 1986). While pre-commercial thinning is carried out on more than 200 000 ha annually in Sweden (Nilsson *et al.*, 2020), the use of chainsaw is limited to non-industrial private forest owners and niche cuttings, e.g. some nature conservation operations and salvage logging.

Alternative systems for forest harvesting using other equipment than wheeled harvesters and forwarders are not implemented on a large scale in Sweden, much due to the versatility of the harvester forwarder system, the comparatively flat terrain and the use of frozen ground for operations on sensitive soils. In other countries, conditions (topography, climate, soils, and/or legislation) are different, and these alternative systems are more common (Mederski *et al., 2020*). Increasing industry demand for a steady flow of raw material and milder winters have stimulated an interest in machinery and decision support systems that reduce the impact of forest operations in Sweden (Mohtashami *et al.*, 2017; Mohtashami *et al.*, 2012). However, the trend is leaning more towards improving the two-machine system rather than introducing new systems. This may be due to a combination of tradition and the fact that two-machine systems are flexible and, in most cases, cost-efficient; the high costs in some operations are compensated by versatility.

1.6 Forest operations in multifunctional forestry

Multifunctional forestry is used to describe forestry intended for promotion of more than one ecosystem service (Sabogal *et al.*, 2013). The concept covers many practices, and there are many similar, largely overlapping terms, e.g. multiple-use, multipurpose, diversified, and integrated forestry, or forest management. There has been a scientific discussion regarding whether multifunctional forestry should be defined on stand or landscape level. Vincent and Binkley (1993) presented the idea that a landscape level is suitable, and these ideas have been developed by Binkley (1997) and Zhang (2005). Others argue that several ecosystem services should be produced simultaneously in the same area in order to be considered multifunctional forestry (Campos Arce *et al.*, 2001; Panayotou & Ashton, 1992).

The production of one forest ecosystem service affects the status of other ecosystem services (Felton *et al.*, 2016; Nordin *et al.*, 2011). Several investigations have used simulations and optimisations to analyse management strategies for maximisation or trade-offs between different ecosystem services. Examples are a literature review on balancing cultural values with other ecosystem services (Roos *et al.*, 2018), case-studies on modelling maximum carbon sequestration (Diaz-Balteiro *et al.*, 2017), carbon stock and carbon sequestration (Gusti *et al.*, 2020), carbon stock, carbon sequestration, and biodiversity (Díaz-Yáñez *et al.*, 2019), recreation and wood production (Eggers *et al.*, 2018), economic, ecological, and social sustainability (Eggers *et al.*, 2019), and wood production, biodiversity, reindeer husbandry, carbon sequestration, and recreation (Eggers *et al.*, 2020).

While even-aged, single-species forestry is dominant, other management philosophies are also implemented in Sweden. Two shelterwood methods are used, mainly to promote regeneration: young and middle-aged birch shelterwoods aimed at promoting regeneration of Norway spruce while increasing stand yields (Holmström, 2015; Bergqvist, 1999; Mård, 1997), and mature Norway spruce or Scots pine shelterwoods aimed at promoting natural regeneration and reducing mortality in artificially regenerated saplings (Erefur, 2007; Glöde, 2001).

Although limited in terms of implementation, other management strategies in Sweden have been studied, e.g. full-storied uneven-aged forestry (cf. Lundqvist, 2017; Ahlström & Lundqvist, 2015; Lundqvist, 1991) and progressive patch cutting (Erefur, 2010). Interest has also grown among the general public and non-industrial private forest owners to diversify from even-aged forestry (Claesson *et al.*, 2015).

Although not uneven-aged forestry, patch cutting is considered a continuous cover forestry management system, one that partly emulates the partial and small-scale disturbances suggested to be the most common natural disturbance regime in boreal forests (Kuuluvainen & Siitonen, 2013; Kuuluvainen & Aakala, 2011). As an alternative compared to thinning, harvesting operations in patch cutting has been found less costly in southern Europe (Mercurio & Spinelli, 2012), western Canada (Phillips, 1996) and Norway (Suadicani & Fjeld, 2001; Fjeld, 1994), but costlier than final felling. Productivity in shelterwood felling of mature trees has been found to be more influenced by residual trees compared with final felling (Laitila *et al.*, 2016; Niemistö *et al.*, 2012; Eliasson *et al.*, 1999).

Selection cuttings, i.e. thinning operations, in uneven-aged forestry share many characteristics with thinnings in even-aged forestry, so productivity is similar (Andreassen & Øyen, 2002). The main difference between the systems is frequency between removals and size of removal, which has been modelled and/or simulated in numerous studies under different conditions

(Rämö, 2017). In conclusion, the question of overall profitability when comparing systems is complex.

There are few published scientific studies of operations in NCM. As Armsworth (2014) notes, “Among relevant studies, there is surprisingly little attention given to the costs that conservation organisations actually face. Instead, there is a heavy reliance on untested proxies for conservation costs.” Apart from the investigations by Nordén *et al.* (2019) in restoration of deciduous preserves and set-asides, and a study by Santaniello *et al.* (2016) of effects on harvester productivity from different levels of tree retention, no studies have been found.

In conclusion, multifunctional forestry has been found beneficial for many ecosystem services, and is encouraged by legislators. However, management is not being carried out to the extent needed to avoid losses of conservation values and it is clear that there are knowledge gaps in the field. Despite extensive literature on *what* should be done in multifunctional forestry and nature conservation management, and literature on *how* to perform tasks in wood harvest operations, there is a lack of knowledge in the crossover between the two, i.e. *how* should operations in multifunctional forestry be carried out? And what are the costs and revenues associated with these operations?

2. Objectives and goals

The overarching objective of this thesis is to increase knowledge about, and improve implementation of, multifunctional forest operations in Sweden. This is attained through the following more specific aims:

- To provide a comprehensive description of areas in Sweden intended for NCM at county, regional and national level (Paper I).
- To describe current NCM practices in voluntary set-aside areas in Sweden (Paper II)
- To identify factors in current Swedish forestry affecting whether or not NCM is being practised in voluntary set-aside areas (Paper II).
- To analyse time consumption and net revenues for harvester and forwarder work in two examples of multifunctional forestry operations: (a) removal of birch shelterwoods (Paper III), and (b) patch cutting of an old mixed coniferous stand (Paper IV).

All studies were carried out in Sweden. While the results from Paper I and Paper II are applicable in Sweden, results from Paper III and Paper IV could be applied more broadly in boreal forests.

3. Materials and methods

The aim of the thesis is to address a diverse set of issues and the most pressing knowledge gaps. Various methodologies have been applied in the studies that make up this thesis.

3.1 Description of areas intended for NCM (Paper I)

Five Swedish forest companies each provided spatial data (polygons and accompanying stand registry attributes) on all their voluntary set-aside areas currently intended for NCM. The companies together own approximately 8 million ha of productive forest land (34% of Sweden's total productive forest land) spread over the entire country, but with greater representation in the northern parts. Of this area, 136 672 ha, comprising 1.7% of the companies' holdings, were intended for NCM. The data covers 26 953 stands with an average area of 5 ha and a median area of 2.4 ha. The data was divided into four regions, from south to north; south, mid, mid-north, and north-north. No analysis was done at company level, i.e. it was assumed that there are no systematic differences between companies' implementation of NCM.

A set of 40 forest types with their own separate identifiers and goals was devised after combining information about the habitats requiring conservation measures (Andersson *et al.*, 2016) with publicly available forest company voluntary set-aside guidelines (The Church of Sweden, n.d.; Holmen skog, 2017; SCA skog, 2017; Sveaskog, 2016; Grönlund, 2014; Skellefteå Kraft, 2013; Aulén, 2012). Thirty-one of the 40 forest types were described as requiring NCM, at least under certain conditions, to attain or maintain intended values.

A set of six NCM area categories were created based on these 31 forest types, by grouping them according to their main attributes. The six area categories were complemented by a category for stands that met none of the listed criteria (Table 3). The forest types in each area category had common denominators in terms of aims and management strategies or stand characteristics. Each area category included criteria deemed identifiable given the available data, and chosen to prevent overlaps between area categories.

Table 3. Names, titles and a brief description of the criteria for identification of each category (Grönlund *et al.*, 2019).

Category	Designation in text	Criteria
Areas with high degree of formal protection	Protected	Areas overlapping nature reserves, national parks or some other formally protected forest
Areas close to anthropogenic activity	Anthropogenic	Stands within 300 metres (m) of residential buildings and stands overlapping areas or within 20 m of lines and points identified as being sites with cultural heritage value
Areas close to water	Water	Stands within a 30-m buffer zone of water surfaces
Areas with limited accessibility	Accessibility	Areas with limited accessibility due to low bearing capacity, high ground roughness, or steep slopes
Old coniferous forests	Coniferous	Stands where ≥ 70 % of standing volume is coniferous species and stand age ≥ 120 years
Old deciduous forests	Deciduous	Areas where ≥ 25 % of standing volume is deciduous species and stand age ≥ 60 years
Zero-category stands	Zero	Stands meeting none of the above criteria

The purpose of the categorisation was to group and thereby attempt to explain the reasons why the forest companies chose to assign the analysed stands/areas to NCM. Each category was identified applying the different criteria for each category on each polygon in the dataset. If a stand or parts of it met the criteria for a category, the entire stand was classified as being intended for NCM on these grounds. Accordingly, some stands met the criteria of no area categories and were classified as ‘zero-category stands’ while others could meet the criteria of several area categories. The number of category criteria met by a stand was interpreted as proxy for conservation complexity in the stand. Stands were accordingly assigned a NCM complexity value, ranging from 0 to 6, the value not considering the combination of NCM area categories present in each stand.

3.2 Interview survey with NCM practitioners in Sweden (Paper II)

Data regarding current practices and factors influencing the decision to carry out NCM were collected through qualitative interviews, a method suitable for the mapping of less investigated fields of research (Brinkmann, 2015). When selecting interviewees, the following three selection criteria were applied:

(1) To ensure reliability of data, only interviewees with experience of NCM work were recruited.

(2) The data needed to cover various aspects of NCM. As noted, e.g. by Jensen (2003) and Erlandsson *et al.* (2017), practitioners' perspectives vary according to profession. Therefore, a set of interviewee profession groups was defined prior to selection.

(3) The descriptions of NCM ideals in Sweden presented by Nitare *et al.* (2014) identify differences in expected measures and outcomes following the natural climate borders. In Sweden, this is mainly a division between the southern broad-leaved nemoral forests and the northern boreal forests. Interviewees' geographical area of operations therefore had to be considered.

After summarising the criteria, eight interviewee cohorts were defined (Table 4). Interviewees were either: (a) machine operators employed by forest companies or contractor companies; the machine operators could also be contractor company owners; (b) forest managers employed at forest companies, responsible for the contact with machine operators; (c) nature conservation experts within forestry companies; or (d) officials within the Swedish Forest Agency.

In order to gain wide representation from populations not known, a group of interviewees included in the analysis was generated through purposive sampling (Robinson, 2014). They were recruited through an advertisement posted on 25 August 2016 on the Facebook page of the Swedish Forestry Research Institute (Skogforsk), asking people with experience of NCM to contact the project manager. According to Facebook statistics, the advertisement had been viewed 15 984 times by 15 June 2018. This resulted in 23 people contacting the project manager. Applying the criteria stated above (mapping of prior work experience, professional role, and geographical area of operations), 14 interviewees were recruited.

After these interviews, two methodological conclusions were drawn that indicated a need for additional interviews: (1) interviewee profession groups b and c were defined differently in different companies, causing the groups to partly overlap – nature conservation experts at some companies were, for example, doing much of the NCM fieldwork, and (2) more data collection was considered necessary to reach desired representation within all interviewee cohorts (selection criteria 2 and 3). Thirteen additional interviewees were therefore recruited through snowball sampling (Robinson, 2014). After 27 interviews, no new data were collected and data saturation (Glaser & Strauss, 1967) was attained.

Table 4. Sampling matrix, including the final number of interviews within each cohort of interviewee profession and climate region where they are operating (Grönlund *et al.*, 2020).

	Operator	Forest manager	Nature conservation expert	Swedish Forest Agency officials	∑
Nemoral forests	4	5	2	5	**16**
Boreal forests	2	1	4	4	**11**
∑	**6**	**6**	**6**	**9**	**27**

Interviews were semi-structured and contained three parts: (1) a general introduction concerning the interviewee's background, current work and experiences with NCM, (2) an in-depth description of the interviewee's process regarding decisions for NCM planning/preparations, execution and follow-up/evaluation, and (3) visions and ideas for future development of NCM. An interview guide (provided in the Appendix of Paper II) was prepared, with sets of open-ended questions for each part.

Interviews lasted 60-150 min. Sixteen interviews were held face-to-face and 11 were held by telephone, when requested by the interviewee. The interviewee was invited to select the interview location. Six interviews were held outdoors while walking in forests and were therefore not recorded. During these interviews, detailed notes were taken instead. Detailed notes were also taken during one telephone interview that could not be recorded due to a technical malfunction. In three interviews with machine operators and two interviews with forest managers, a colleague of the intended interviewee was also present. These interviews were not treated differently, but all questions were asked to both interviewees and presented as one interview in the study.

Notes from the interviews not recorded were processed within 24 h and supplemented with remembered details to form a complete record. The recorded interviews were processed within one week. Prior to publishing the results, all interviewees were given the opportunity to read the report and check that they had not been misquoted or that their anonymity had not been compromised.

The analysis of current practices involved entering the responses from all interviewees in an Excel worksheet, divided into the interviewee cohorts (Table 4). Generalisations and trends were identified and mostly presented as intervals. Due to the small number of interviewees in each cohort, results were grouped, and no quantitative analysis was carried out and no conclusions drawn.

A thematic analysis of the data, as described by Braun and Clarke (2006), was carried out to identify key factors affecting decisions regarding NCM. This analysis was done in four steps: (1) initial coding, (2) searching for themes, (3) reviewing themes, and (4) defining and naming themes. All interviewee responses were initially coded (step 1), where codes were used to accommodate the same thing being said but using different phrasings.

After this initial coding, all codes were grouped into factors that in turn were sorted under generic themes (step 2). This process enabled patterns and general trends to be identified, thereby pinpointing the key factors affecting decisions regarding NCM. The process was iterative and, as recommended by Braun and Clarke (2006), both the coding and grouping into factors and themes were revisited (step 3). Finally, patterns in the data were identified, and themes representing the entire data set were defined (step 4).

3.3 Multifunctional operations (Papers III and IV)

3.3.1 Birch shelterwood removal

Studies of harvesting and forwarding were carried out on ten study plots in six forest stands in southern Sweden. The time studies were carried out in daylight conditions in May and June 2014 (six study plots), May 2016 (two study plots), and November 2017 (two study plots). In all operations, medium-sized harvesters and forwarders were used, but there were different machines and operators in different years.

All study plots had been planted with spruce and contained an equally old overstory of naturally regenerated birch. Harvester operators were instructed to remove all birch trees except in spots without understory spruce. In patches with dense spruce, the crop was thinned in accordance with conventional instructions, i.e. to achieve a stand with 1300-1600 spruce trees ha^{-1} post thinning. Due to differences in market conditions and stand characteristics, both whole tree bioenergy and pulpwood assortments were produced on study plots treated in 2014, while only pulpwood assortments were produced on the study plots treated in 2016 and 2017. The harvester sorted the assortments in piles, and the material was forwarded one assortment at a time.

Prior to harvest, 50-123 m of strip roads in homogeneous birch shelterwood areas were identified in the field. The harvested area along each strip road was regarded as a study plot. The width of the plot equalled the working width of the harvester, on average 17.3 m. This resulted in study plots ranging between 0.08 and 0.23 ha. To describe the stands, 4-6 sample plots covering 23-49% of the study plots were placed systematically using a random starting point.

In these 100 m^2 sample plots, diameter at breast height (dbh) and tree species were recorded for all trees with dbh ≥ 4 cm, i.e. all trees viable for whole-tree harvest. The number of trees with dbh < 4 cm on each sample plot was recorded. In each sample plot, height was recorded on 5-10 sample trees per species, covering all diameter classes. Birch height sample trees were selected in all sample plots, but spruce heights were sampled only in study areas where a commercial removal of spruce would take place. In the remaining study plots, average spruce height was estimated. The observed diameter-height relationship from all sampled trees was used to estimate heights of remaining trees in the sample plots.

In 2014, damage to residual trees was surveyed on six 50-m^2 sample plots in each study plot, after harvesting and after forwarding. In the sample plots, dbh, species, height and damage were recorded for all trees. Damage was classified into 'broken top' and 'other'. Damage observed after harvest was recorded, to avoid being counted again after forwarding. In 2016-2017, rows of 2 by 2 m plots perpendicular to the strip road were surveyed every 8 m, alternating between the sides of the strip road. Dbh, species, height, distance to nearest cut tree, distance to strip road and vitality were recorded for all trees. The cause, type and magnitude of all damage was recorded for all trees.

Continuous time studies of harvesting and forwarding were carried out using an Allegro hand-held computer running SDI, Skogforsk's time study software. On all study occasions, harvester work was split into seven work elements and forwarder work was split into 11. If more than one work element was performed simultaneously, the work element with the highest priority was recorded. All elements were measured as effective times, excluding all delays (E_0). In the analysis of harvester work elements, boom out, felling, boom in, and processing were totalled to give a boom cycle time. In the analysis of forwarder work elements, boom out, gripping, rearrangement on ground, boom in, release and rearrangement in bunk, and movement while loading, were totalled to give a loading time.

In the calculations of economic data, an exchange rate of €1 = SEK10 was used. Harvester cost was set to €110 $E_{15}h^{-1}$ (efficient hours, including delays shorter than 15 minutes) and forwarder cost €90 $E_{15}h^{-1}$. Relationships between study time and $E_{15}h$ according to Kuitto *et al.* (1994) were applied. Transport time was calculated to 0.538 min m^{-3}, based on Brunberg (2004). An unloading time of 0.564 min m^{-3} was used, based on Nurminen *et al.* (2006). Birch pulpwood price was set to €36 m^{-3} solid and bioenergy price of €20 m^{-3} solid, in accordance with published prices in the study area region (Södra, 2018b; Södra, 2018a). Conversion from oven-dry tonne (odt) to m^3 was based on Lehtikangas (1999).

3.3.2 Patch cutting

The study was carried out during January and February 2018 in the provinces of Västmanland and Uppsala in central Sweden. Patch cutting was studied in one harvesting site on 9-24 January. As a reference, final felling was studied at three sites during the period 29 January to 16 February. All operations were carried out using the same single-grip harvester and forwarder and the same machine operators. During these periods, harvester data was collected in the form of time-stamped hpr-files, and time studies were performed of the forwarding work. This resulted in a data set consisting of 48 harvester shifts, 27 in normal final felling and 21 in patch cutting, and 44 forwarder loads. The harvester was operated by two operators, both with at least ten years of experience as harvester operators, each operating the machine for 24 shifts. The forwarder was studied with its normal full-time operator.

The landowner had decided on patch cutting, removing 50% of the area in the patch cutting site. After deduction of unproductive areas, partial areas on the site boundary and voluntary set-aside areas for nature conservation, a net area of 10.8 ha was selected for cutting, made up of 80 30×45 m plots in a chequerboard pattern.

For safety reasons, all data on harvester time consumption per tree – species, volume, and number of assortments for each tree – was collected from the machine computer. Data was collected in the StanForD 2010-standard (Arlinger, 2020; Möller *et al.*, 2013) as time-stamped hpr-files. This data set comprised approximately 18 150 trees, 11 500 in final felling and 6 650 in patch cutting.

For each tree, the machine computer recorded the time in seconds (s) as the time between the end of processing of the previous tree and the end of the processing of the current tree. This necessitated filtering the data to remove trees harvested after a longer break or when a delay had occurred during the harvest; here, this filtering involved removing all trees with a processing time equal to or longer than 600 s. The average processing time per tree during a shift was then calculated as an arithmetic mean of all trees with a time less than 600 s, and shift level averages for both stem volume and number of logs per tree were calculated.

Terrain transport was analysed in three steps: (1) an analysis of how the studied patch cutting affected the terrain transport distance compared to final felling of the same site using the BestWay software (Rönnqvist *et al.*, 2021); (2) a time study of the forwarding work; and (3) a theoretical analysis using the productivity norm presented by Brunberg (2004) comparing total time consumption and costs for forwarding in patch cutting and final felling.

The average costs for final felling in southern Sweden in 2018 (Eliasson 2019) were used as a basis for calculating the differences in operational costs. Average harvested stem volume in the patch cut areas was similar to averages for southern Sweden in 2018, 0.44 m^3, while the harvested volume per ha was higher than the average for southern Sweden (216 m^3 ha^{-1}) (Eliasson, 2019). As the national statistics indicate only a minor difference in indirect costs between thinning and final felling, it was assumed that these costs do not differ between patch cutting and final felling. Using the national statistics, the total cost difference between treatments was calculated through the productivity ratio previously observed.

Net revenues were calculated assuming wood prices in the national statistics (Eliasson, 2019), and volumes harvested for each assortment as indicated in the analysed hpr-files.

Swedish kronor (SEK) was converted to Euro (€) using the conversion rate €1 = SEK10.

4. Results

4.1 Multifunctional forestry intended for NCM

4.1.1 Areas intended for NCM (Paper I)

From the areas analysed, 86% met the criteria of at least one NCM area category. The most common category was old coniferous stands, whose criteria were met in 43% of the stand area (Table 5).

Table 5. Areas, number of stands and proportions of the analysed dataset meeting the criteria of each category. Protected=Areas with high degree of formal protection, Anthropogenic=Close to anthropogenic activity, Water=Close to water, Accessibility=Areas with limited accessibility, Deciduous=Old deciduous forest, Coniferous=Old coniferous forest and Zero=No area categories applying.

Category	Area meeting criteria (ha)	Percentage of total area (%)*	Number of stands	Percentage of total number of stands (%)*
Protected	36 135	26	6 038	22
Anthropogenic	34 175	25	7 961	30
Water	33 116	24	6 104	23
Accessibility	19 358	14	4 247	16
Deciduous	22 537	16	6 322	23
Coniferous	58 553	43	8 168	30
Zero	19 163	14	4 569	17
Total	136 672		26 953	

* totals exceed 100% since stands could meet the criteria of several of the area categories simultaneously (Grönlund *et al.*, 2019)

Old coniferous stands were strongly represented in the northern parts of Sweden while all other area categories, except Accessibility, were more abundant in the southern part of the country.

NCM complexity, i.e. the number of area categories occurring within each stand, followed a south–north gradient with lower complexity being more common in northern Sweden; this area mostly comprised coniferous stands (Figure 3). NCM complexity levels one and two were most common – 10 862 stands covering 56 577 ha (41% of the area analysed) were of complexity level one, while 8 165 stands covering 43 247 ha (32% of the area analysed) were complexity level two. No stands met the criteria of all six area categories.

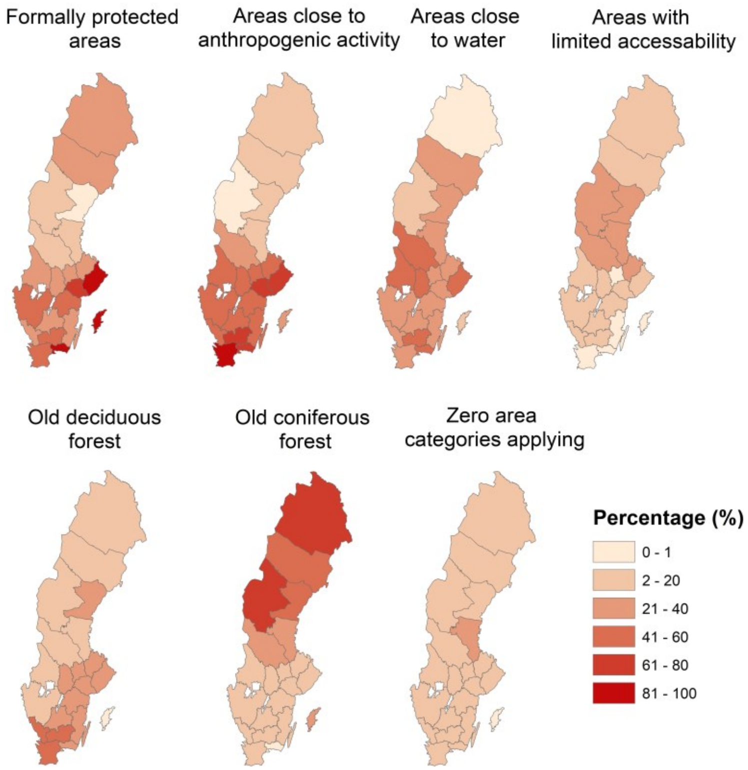

Figure 3. Percentage of the total NCM area within each county meeting the criteria of various numbers of area categories, i.e. at different complexity levels (Grönlund *et al.*, 2019).

In the regions South and Mid, Anthropogenic is a core category, both at low and high complexity. In higher complexity, it appears along with either Deciduous, Water or Protected. In Regions North-Mid and North-North, Coniferous is the core category, mainly appearing with Protected and Accessibility (Figure 4).

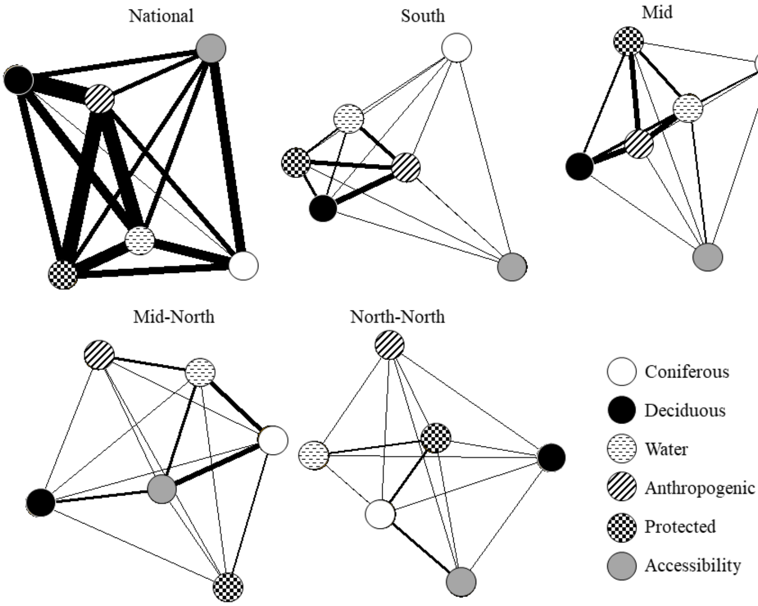

Figure 4. Affiliation network plots of all area categories, shown by region. Thicker lines indicate that the two area categories in the nodes connected by the line appear more frequently than pairs along thinner lines. Positioning and distance between nodes shown have no significance. Coniferous=Old coniferous forest, Deciduous=Old deciduous forest, Water=Close to water, Anthropogenic=Close to anthropogenic activity, Protected=Areas with high degree of formal protection, and Accessibility=Areas with limited accessibility (Grönlund *et al.*, 2019).

4.1.2 NCM practices in Sweden (Paper II)

Although the terminology varied, all interviewees clearly distinguished between two types of NCM: restoration NCM and preservation NCM. Restoration NCM was described as taking place in areas that have needed NCM for a long time, and where the conservation values are suffering from lack of NCM. A common example mentioned by interviewees was former farmland and pasture in southern Sweden where Norway spruce spontaneously established when farming stopped in the 1950-1970s. The resulting increased competition for light was detrimental for the old oaks and ground flora that had been growing in these open fields, thereby making removal of large volumes of spruce trees urgent. Preservation NCM measures are implemented in areas where (1) there has been sufficient disturbance to maintain conservation values, or (2) the original conservation values can be increased by management. Using the example above, preservation NCM would take place if grazing had ended in the 2000s, and operations would consist of removing smaller Norway spruce and other trees in time to avoid fading vitality in the oaks and to maintain high flora biodiversity.

When asked about what NCM operations are carried out, all interviewees described the same two, often concurrent, measures as being by far the most common NCM in Sweden: (1) creation of dead wood and (2) removal of Norway spruce to secure the survival of light-demanding species. This may seem an oversimplification, but the interviewees generally agreed that removal of spruce is the most common measure. They also considered this activity to be sufficient, at least at the current stage when NCM is carried out to such a small extent and activities need to be prioritised.

According to the interviewees, NCM forestry in Sweden generally follows the same procedure, regardless of the measure to be carried out and location in the country. This procedure is similar to that in conventional timber production thinnings. Before the NCM activity, a forest manager from a forestry company or wood buying organisation plans the measures in the field. The planning results in both written instructions with maps and in-field markings of the important items to consider during operations that may not be evident to the machine operators.

The major difference between conventional thinning and NCM, apart from the inherent different purposes, is the level of detail in the planning of the measures and written instructions to the operators. Both machine operators and in-field forest managers stressed the need for correct instructions with sufficient detail to attain the desired results. Forest managers and operators shared the view that it is challenging to find a balance between providing specific instructions while providing leeway for the operator to, for example, select strip roads and decide which trees to remove. Production of an overly detailed instruction document was considered very time-consuming and its benefits questionable, since machine operators see the results of the ongoing operation and can adapt their work accordingly, while a forest manager could fail to notice certain details.

In mechanised NCM, i.e. operations involving harvesters and forwarders, the interviewees preferred the activities to be carried out in late summer, commonly August-September, and to some extent during winters when there are good ground conditions with little snow cover and frozen soil, mainly January-March. The reason for this short time period is that there are many restrictions for when NCM is best carried out or even allowed.

4.1.3 Factors impacting decisions on NCM (Paper II)

The interview data helped identify several factors affecting whether NCM operations are implemented. When the factors were sorted into themes, and divided into barriers vs. incentives for NCM activities, there were substantially more barriers, and these were also mentioned more frequently (Figure 5). Incentives comprise requirements from certification standards and the dedication of individuals. Barriers can be attributed to the combination of four themes: (1) the short time span in each year suitable for the tasks, (2) the lack of incentives to invest the resources needed, (3) experienced or anticipated risk for costly operations, and (4) experienced or anticipated criticism.

Figure 5. Factors and overarching themes presented by interviewees affecting decisions on whether or not to perform NCM (Grönlund *et al.*, 2020).

4.2 Multifunctional forestry operations (Papers III and IV)

4.2.1 Birch shelterwood removal

Average harvester time consumption was 1300 s odt^{-1} (2.8 odt E_0h^{-1}), at removal of 3000 stems ha^{-1} and 30 odt ha^{-1}. Harvester operators used multi-tree felling in 23-83% of the crane cycles, and the average number of trees per crane cycle in each study plot ranged from 1.2 to 2.8. Total harvesting time per odt was significantly affected by the covariates ‘harvested number of trees ha^{-1}’ and ‘harvested biomass ha^{-1}’, while there was no significant effect of removal method.

Of the 22 forwarder loads studied, 16 were pulpwood loads and six whole-tree energy wood loads. Time consumption for pulpwood loading was significantly affected by the parameter amount of harvested biomass per 100 m of strip road, but not by the number of birch trees harvested ha^{-1} ($p = 0.899$) or removal method ($p = 0.193$). However, there was a significant correlation between removal method and number of birch trees ha^{-1} prior to logging ($p = 0.0001$).

On study plots harvested in 2014, the residual stand had, on average, 2030 trees ha^{-1}, of which 8.5% were damaged. On plots harvested in 2016/2017, there were 2235 trees ha^{-1} post-harvest, of which 14.5% were damaged. On plots harvested in 2014, there was a tendency for damage frequency to be higher in plots bordering close to the plot edge than in plots bordering close to the strip road, $\chi2$ (1) = 2.74, $p < 0.10$. On plots harvested in 2016/2017, none of the analysed variables in the ANOVA (r^2=0.35) had a significant effect on damage frequency, but there were tendencies for a negative relationship between damage frequency and distance to nearest harvested tree ($p = 0.16$), while there was a positive relationship between average height of trees in the plot and damage frequency (p =0.15). Nineteen percent of the 54 damaged trees observed were damaged in both operations, while 69% were damaged only by the harvester and 13% were damaged only by the forwarder.

With total cost ranging from €1282 to 3586 ha^{-1} and revenues ranging from €595 to 4314 ha^{-1}, only the largest removals per ha resulted in profitable operations. Harvester costs, on average, made up 61% (ranging from 47 to 71%) of operational costs in pulpwood removal, while in combined removals the corresponding number was 80% (ranging from 77 to 83%).

4.2.2 Patch cutting

The patch cutting treatment and average stem volume had significant effects on harvester mean time per tree in patch cutting. There was also a weak tendency towards an operator effect and an operator by treatment interaction. The weak operator effect motivated use of the operator as a random factor in the mixed analysis, which showed a significant treatment effect corresponding to a 9.2 s per tree increase in the mean time per tree in patch cutting compared to final felling. In the observed interval of 0.30-0.60 m^3 average tree volume, patch cutting productivity was therefore 20-15% lower compared to final felling.

The BestWay GIS-analysis of terrain transport distances found that patch cutting increased forwarding distance by 29%. Secondly, the time study found that loading and unloading times were 16% greater in patch cutting than in final felling, which was reduced to 12% in the theoretical analysis after compensation for different terrain conditions. Thirdly, the theoretical analysis found that total forwarder time consumption was 16% higher in patch cutting area than in final felling areas.

Compared to the €9.29 m^{-3} that is the average cost for final felling operations in southern Sweden, patch cutting increased the costs for harvesting and forwarding by €1.71 m^{-3}, or 18%. The average wood value at landing in the patch cutting site was €49.15 m^{-3} and the observed increase in operational costs corresponded to a 4.3% reduction in net revenues after patch cutting compared to final felling in the site. The observed difference in costs can mainly be attributed to the increased harvester time consumption caused by the need to consider residual trees. Difference in forwarder time consumption is the result of longer forwarding distances and more time-consuming loading.

5. Discussion

Forest operations in both multifunctional forestry intended for harvest of wood and NCM present different challenges for forest managers compared to traditional forestry intended for wood harvest only. Conventional forest operations have developed through a combination of forest management and forest technology, aiming at silvicultural methods producing high-value stands and efficient forest operations, which in turn result in low harvesting and logistics costs. The system is aimed at maximising forest owners' long-term net revenues and securing the wood supply for industry.

Forest operations in multifunctional forestry face different challenges. The first is to determine what the primary goal is, and how to measure and evaluate goal attainment. Another challenge is in the execution of management where multifunctional forestry requires collaboration between other fields than in conventional operations – e.g. nature conservation and forest technology, two fields with different history and traditions. Since resources are limited, these collaborations are necessary for successful management.

5.1 Description of areas intended for NCM

Identifying conservation values and deciding on management needs for protected forests is a complex process. Attempts have been made to use remote sensing technology to identify explicit conservation values (Lindberg *et al.*, 2015; Eldegard *et al.*, 2014; Ørka *et al.*, 2012). An alternative approach is to consider remote sensing as a tool supplementing the more costly field inventories (Wikberg *et al.*, 2009). Aligning with the first approach, Paper I demonstrates a simple method for describing conservation values using data freely available for the whole of Sweden (e.g. data on standing volume and tree species composition from the Swedish national forest inventory, data on protected areas from IUCN, and land use maps from the Swedish Mapping Cadastral and Land Registration Authority).

Claesson and Eriksson (2017) noted that voluntary set-asides are generally sited on low productivity soils, possibly to reduce revenue losses caused by exempting the areas from conventional management. These areas may also be voluntary set-asides because they have been less affected by harvesting operations than other areas, due to lower profitability in general caused by higher costs for logging. This could imply longer continuity and higher conservation values, and thus areas intended for free development rather than NCM. In Paper I, the category of limited accessibility is a proxy for areas where forest operations may be costlier than average. The results do not indicate that areas meeting the criteria for limited accessibility, regardless of conservation values, have been systematically set aside for NCM.

Previous quantifications of NCM areas in Sweden have involved surveys (Eriksson, 2019; Claesson & Eriksson, 2017; Stål *et al.*, 2012; The Swedish Forest Agency, 2008; The Swedish Forest Agency, 2002; The Swedish Forest Agency, 1998). The latest survey indicates that an estimated 40% of voluntary set-asides in southern Sweden and 20% in northern Sweden were intended for NCM. This roughly translates to the conclusion that 1.2-2.4% of Swedish forest land is voluntary set-aside NCM forests. The analysis in Paper I shows that 1.7% of the participating companies' holdings are set aside for NCM. However, these holdings represent a larger proportion of the total forest land in the northern part of the country than in the southern.

Inherent in decision making regarding NCM are questions of resource efficiency. Initially, there is the complex issue of deciding which areas to protect, which also includes issues of how to balance ecosystem services (cf. Adame *et al.*, 2015; Lundström *et al.*, 2011; Wikberg *et al.*, 2009). Preserves in the less populated northern parts of Sweden are more often intended for biodiversity conservation, while those in the south tend to be instigated for recreation (Götmark & Nilsson, 1992). Even though preserves are generally larger in northern Sweden, the smallest preserves are often created to promote biodiversity (Götmark & Thorell, 2003). A similar pattern was observed in Paper I regarding complexity (a proxy for conservation values). However, voluntary set-asides intended for NCM were, on average, small (compared to formal preserves) and distributed evenly in the landscape.

5.2 Management of areas intended for NCM

The results in Paper I indicate that conservation complexity increases along a north-south gradient. The results in Paper II suggest that increased complexity also results in higher operation costs. Land values are higher in southern Sweden, so it is reasonable to assume that both costs and gains from setting aside areas increase along this north-south gradient.

Interviewees' division of NCM operations into restoration NCM and preservation NCM can both be considered rehabilitation of forested areas, using the terminology presented by Stanturf *et al.* (2014). This indicates that, even though management may be needed, forests with high conservation values can be attained within a reasonable time frame and at relatively low costs in Swedish forest land intended for NCM.

It was not clear whether the general and simplified task of removing spruce highlighted by interviewees in Paper II is a generalisation applicable to all available NCM or if it was limited to the areas that were treated. It could be that the interviewees had slightly confounded the NCM operations needed with what is actually being carried out, which in many instances is the removal of spruce. On the other hand, there is a reason for this emphasis on spruce. Spruce is a late-successional species that has become more common in Sweden over a long time period (Lindbladh *et al.*, 2014). Subsequently, there is a need to remove late-successional species in certain areas, while in areas containing values associated with late-successional tree species, there is often no need for management (Attiwill, 1994; Pickett & White, 1985).

Paper II identified a dilemma regarding NCM: should the management rely on general skills among all operators or use specialised NCM operators? The aim to introduce all (or most) operators to NCM has several potential benefits: (1) it creates a large capacity to execute NCM, so the small time-window for NCM would be less limiting; (2) all operators already need to understand NCM, since they are expected to implement tree retention in all operations; and (3) aggregated NCM harvesting costs are expected to be lower since there will be fewer relocations when NCM can be carried out in coordination with conventional operations in nearby stands. However, a specialised NCM operator approach has some benefits: (1) the NCM quality will likely be higher, and (2) there is less need for detailed instructions, since skilled operators are capable of making decisions, which will reduce the workload for forest managers.

Interviewees also highlighted the lack of resources (sorted into the theme 'time and effort') as a barrier to NCM. This could be a result of the low priority given to NCM operations. Forest managers are generalists with broad responsibilities, requiring knowledge about silviculture, forest technology, wood supply, logistics, business management, and ecology. A forest manager with specialist knowledge and greater commitment in one area will probably invest more energy into that part of the management, with the risk of lower quality in other aspects if resources are limited (Pregernig, 2001). Operators and contractor companies also face this type of balancing. As seen in similar conditions by Erlandsson *et al.* (2017), contractor companies are likely to specialise in areas that are appreciated by the customer. The interviewed operators were committed to NCM, and admitted that this interest might have a negative effect on their productivity in conventional timber-focused operations.

Forest managers expressed that NCM is challenging for those who lack knowledge (or merely experience) of NCM operations. Contributing to this view was that all systems used (e.g. for planning, execution, and follow-up) are designed for wood harvest operations. Since current systems were less helpful, operations relied to a large extent both on personal commitment and skills. Accordingly, a major development of NCM would be planning systems capable of handling the differences that NCM entails, i.e. more detailed planning, tailored operations, and follow-up on other matters than standing trees. Since detailed planning results in much information that is to be conveyed to harvester operators, features such as head-up-display (Nordlie & Till, 2015) or geofencing (Zimbelman & Keefe, 2018) could prove helpful in limiting operator workload.

Interviewed forest managers also refrained from NCM on the grounds of anticipated or experienced high costs. Payment for NCM services was, in most cases, based on hourly rates, and total time consumption was hard to estimate. This payment model places the economic uncertainty on the buyer of services, rather than on the contractor company. In conventional operations, piece-work rate payment is common practice. The stated reason for preferring hourly rates for NCM operations was that no contractor should be pressured to reduce conservation ambitions because of economic restrictions. Despite good intentions, the subsequent uncertainty regarding operational costs on the buyers' side could be part of the uncertainty contributing to decisions not to implement NCM. Certification (which is the main driver for NCM) is mainly intended to increase the value of the company trademark (Johansson, 2013). Referring NCM costs to departments gaining from NCM (i.e. marketing or sales departments) might create better incentives and possibly increase the extent of NCM.

Even though the interviewees considered NCM operations as being a small part of Swedish forestry, no estimations were presented as to the actual extent of current NCM efforts. Assuming that the proportions of formal preserves and retention areas intended for NCM are equal to those in voluntary set-asides (20-40%), approximately 0.6-1.1 million ha in Sweden are intended for NCM. Based on rules of thumb presented by the interviewees in Paper II, each stand intended for NCM needs treatment every 20-30 years on average. Consequently, a conservative estimate is that NCM operations are needed on 25 000-35 000 ha in Sweden every year. Assuming another rule of thumb presented, that the removal is 50-100 m^3 ha^{-1}, annual harvest could be 1.5-3.0 million m^3. As a point of reference, ~300 000 ha are thinned yielding 20-25 million m^3 (Nilsson *et al.*, 2020).

5.3 Ecosystem services and multifunctional forestry

Forecasting stand level short-term effects on ecosystem services from multifunctional forestry presents a challenge. Making long-term projections over large areas in complex system such as forests is close to impossible (TEEB, 2010). There is a need for this type of analysis, since refraining from assessments due to uncertainty is worse. The common strategy is scenario-analysis, e.g. in the reoccurring Swedish SKA analysis (Claesson *et al.*, 2015).

In areas where it has been deemed necessary, multifunctional forestry and NCM are crucial for promotion of (intended) ecosystem services. A lack of management in these areas results in failing ecosystem services. The continued lack of management will result in forest land being neither a source of wood production nor the intended ecosystem services, i.e. a state most undesirable for society, at least in countries like Sweden where land utilisation is high.

As Bergseng *et al.* (2012) concluded, a forest owner aiming for maximum (short-term) profitability from wood harvest does not benefit from implementing multifunctional forestry. As a society, however, the calculations can be different (Daigneault *et al.*, 2017), so there are mechanisms in place to promote other ecosystem services. Legislation requires certain considerations, while certification requires efforts that are compensated for (at least in part) by greater value for certified timber.

An endless debate is whether efforts made are sufficient or too intrusive, e.g. on land ownership. It is, however, worth noting that the forest owner aiming for short-term revenues does not appear to lose much from implementing adapted multifunctional methods, since costs in operations only make up a part of all costs associated with forest management. While the goal for shareholder-owned companies is maximised profitability, that does not mean short-term maximisation of revenues in all decisions. Multifunctional forestry may be rational in many cases. Private non-industrial forest owners could have more short-term perspectives, but many appreciate other ecosystem services and consider future generations in decision making (Lodin, 2020; Danley, 2019; Bowditch, 2016). In addition, there are substantial gains from considering other ecosystem services in urban and peri-urban forestry (Salbitano *et al.*, 2016; Hartig *et al.*, 2014; Escobedo *et al.*, 2011).

The combination of forest legislation without detailed regulation and diversity in ownership of forest land has facilitated variation in management strategies in Sweden. Even though small-scale private non-industrial forest owners often manage for profitability, many consider other ecosystem services (Hugosson & Ingemarsson, 2004) and management often deviates from the practices that would maximise profitability, creating unintended variation (Lodin *et al.*, 2020). In addition, a significant proportion of forest land is owned by actors who, to a varying degree, prioritise other ecosystem services, e.g. municipalities and public agencies. Consequently, there is inherent diversity in Swedish forestry practices.

Current policy in Sweden (the Forestry Act and certification schemes) mainly consider the stand level composition of ecosystem services. There are 16 Swedish environmental objectives (the Swedish Environmental Protection Agency, 2018), e.g. 'conserve all naturally occurring species in viable populations', 'reduce climate impact', 'sustainable forests', and 'thriving wetlands'. When reviewing the details of these objectives, there are obvious goal conflicts. While all goals are on a national level, how should conflicting goals be addressed at everyday, small-scale level? In Paper I, roughly half of the area analysed met the criteria of more than one category.

While a rough metric, this indicates that management of at least half of voluntary set-aside intended for NCM needs to consider and balance several ecosystem services. Interviewees in Paper II supplemented this view with testaments of the challenges in balancing the public's expected view on what is beneficial for biodiversity and what are proven to be viable strategies.

The use of wood from voluntary set-asides is restricted in Swedish certification standards. As a consequence, some forest owners refrain from monetising any wood harvested in voluntary set-asides. This is justified by an ambition to avoid ambiguity regarding the intent of the operations. NCM is not to be perceived as 'timber harvest disguised as nature conservation'. It could be argued that these practices are misguided. If NCM could result in increased revenues, it could remove barriers for management, which in turn would increase the amount of NCM carried out and benefit the intended conservation objectives.

5.4 Multifunctional forestry intended for wood harvest

Depending on how 'conventional forestry' is defined, there are several other management possibilities. In Sweden, conventional forestry, on a stand level, implies planting of one (coniferous) species with associated even-aged forest management. Alternative strategies rely either on other tree species (or a combination of several), other management systems (i.e. refraining from clear-cuts), or a combination of these (Albrektson *et al.*, 2012).

Both birch shelterwoods and patch cuttings as investigated in this thesis are examples of forest management that differs from common practice in Swedish single-species even-aged forestry. They are both examples of management methods instigated by the philosophical approaches described by Albrektson *et al.*, (2012). Birch shelterwoods (as described in Paper III) were introduced to address silvicultural challenges, e.g. regeneration on sites prone to late spring frost. Shelterwoods could, however, also provide increased production of other ecosystem services, e.g. recreation values, since the time from clear-cut to established stand is shorter than in conventional management and the visual impression of forest that appears to be less managed is preferred over single-species stands (Lindhagen & Hörnsten, 2000). Patch cutting (e.g. as described in Paper IV) has been practiced for a long time with different strategies in different parts of the world, see e.g. the review by Lundqvist, (2017) for more details on the development of similar practices. As the implementations are different, general conclusions are few, but the continuity in tree cover created appears beneficial both for wood-living species and recreation, while effects from management on groundwater are smaller, compared to conventional practices.

A birch shelterwood removal could be considered as an extreme thinning from above, with the aim to convert a two-storied stand to a single-story spruce stand. This make consideration of the residual stand a crucial part of the felling. In some plots in Paper III, the average height difference between the two species was quite small. Laitila *et al.* (2016) and Niemistö *et al.* (2012) both examined the effects on harvester performance when either performing thinning of a shelterwood or making deliberate efforts to spare the residual stand. In both studies, considering the residual stand did have a significant effect on harvester performance, but other parameters, e.g. average harvested stem volume and number of trees removed, were more important.

On average, 7-17% of the residual trees were damaged in the studied shelterwood removals. Niemistö *et al.* (2012) reported damage frequencies between 14 and 44% after felling of birch shelterwoods, depending on stand characteristics before harvest and whether special consideration was taken to the residual stand. Investigations of damage frequency among residual trees in felling of uneven-aged stands have found a range of damage frequencies: 1-5% (Sirén, 2000), 4-7% (Modig *et al.*, 2012), 11% (Fjeld & Granhus, 1998), 19-25% (Sirén *et al.*, 2015), 18-61% (Surakka *et al.*, 2011), and 17-76% (Granhus & Fjeld, 2001). It should be noted that all damage frequency investigations in uneven-aged stands were carried out after removal of much larger trees than in the present study, and there were significant differences in conditions among the residual stands regarding tree sizes and stand densities between studies.

Harvester productivity is strongly influenced by average tree volumes but, when comparing harvest of trees of equal size, productivity in thinning has been found to be 10-30% lower than in final felling (Brunberg, 2007; Nurminen *et al.*, 2006; Brunberg, 1997). The pattern also holds true in forwarding, but more as a result of consideration for residual trees and smaller removals per ha, or other metrics reflecting similar aspects (Proto *et al.*, 2018; Eriksson & Lindroos, 2014; Brunberg, 2004; Bergstrand, 1985). The results presented in this thesis confirm these findings.

In Paper III, harvester productivity was less than half of that reported by Niemistö *et al.* (2012) in felling of birch shelterwood. This is an effect of the considerably larger birch trees harvested in the Finnish study. However, the productivity observed in Paper III is similar to that found in studies of small-tree harvest (cf. Laitila & Väätäinen, 2013; Belbo, 2010).

The observed harvester productivity in patch cutting was 15-20% lower compared to final felling, assuming equal size of the trees removed in both treatments. This was not unexpected, since harvester work is more restricted in the patch cutting treatment. There were fewer restrictions to felling in untreated patches than is to be expected in later treatments, where there will be saplings or small trees in adjacent patches. Earlier studies show that harvester productivity decreases when saplings and young trees must be considered (Glöde & Sikström, 2001; Sikström & Glöde, 2000; Glöde, 1999; Fjeld, 1994).

The most important factors influencing forwarding loading time in patch cutting (Paper IV) were wood concentration, in m^3 per m of strip road or m^3 per ha, and number of assortments in the load. These are the same factors observed in earlier studies when predicting loading times (Bergstrand, 1985; Kuitto *et al.,* 1994; Brunberg, 2004; Manner *et al.,* 2013; Eriksson and Lindroos, 2014; Cadei, 2020).

While the number of assortments should not be affected by the cutting treatment, the wood concentration per m of strip road can be affected even though the wood concentration per ha treated is unaffected. If the harvester (which most often made two roads in each patch) manages to concentrate all wood in a patch to a single strip road running diagonally through the rectangular patch, wood concentration would be higher than in a final felling with about 12-14 m between strip roads. On the other hand, if two forwarder strip roads are needed through each patch, wood concentration along strip roads would likely be lower than in an ordinary final felling. As the BestWay analysis found, the overall road distance is longer in patch cutting, as the roads must pass through the corners of the patch to continue to the next patch. Unfortunately, this also limits the possibilities to select a strip road localisation that reduces the risk of rutting (Mohtashami *et al.*, 2017; Mohtashami *et al.*, 2012).

Rectangular patches in a chequerboard pattern have been found to be more suitable for regeneration and mechanised operations than circular patches (Erefur, 2010). However, other geometrical shapes could prove even better. Cutting in parallel strips resolves issues of wood concentration, but this creates a long line of sight, which is unfavoured for recreation (Lindhagen, 1996). Strips in a zig-zag pattern could possibly address this issue, with unknown effects on the issue of orientation, as highlighted by Roach (1974). However, this is an issue that is less significant in modern machines equipped with positioning devices. Apart from suggested developments, examinations of other types of machinery are also relevant. Harvesting in which, e.g., autonomous forwarding shuttles (Hellström *et al.*, 2009) or harwarders (Wester & Eliasson, 2003) are used may alter conditions and influence the design of an ‘optimal’ pattern for cutting.

The observed logging costs in Paper III ranged from €39 to 158 odt^{-1} and are in line with, or considerably higher than, the average for thinning in southern Sweden in 2017, €51 odt^{-1} (Eliasson, 2018). The average tree size harvested in the current study (0.015-0.060 m^3) was considerably smaller than the average size reported in the national statistics for southern Sweden (0.095 m^3), which to a large extent can explain these cost differences.

In Paper IV, comparisons between patch cutting and final felling found harvesting costs to be, on average, 18% higher in patch cutting. The findings in this thesis accordingly suggest that costs for multifunctional forestry are, on average, higher than in conventional operations with similar tree sizes. However, this interval is wide, and interviewees in Paper II suggested that there are examples of much more costly multifunctional operations, e.g. prescribed burning and tailored operations intended for creating habitats for highly niched species. As uncertainty regarding costs rather than the actual costs were emphasised by interviewees in Paper II, further investigations should focus at least as much on cost predictions as on cost reductions.

5.5 A vision for multifunctional forestry in Sweden

The following section is a vision for multifunctional forestry of the future in Sweden, based on the findings in this thesis.

The overarching vision is that there is high production of all forest ecosystem services in Sweden. Since this implies many conflicting goals, the vision is that the inevitable trade-offs are part of the public debate, and society has decided what levels are desirable for all ecosystem services. This will result in multifunctional forestry being carried out to the extent desirable for society, and all ecosystem services are at levels that maximise society's benefits from forests, given the obvious constraints, e.g. available area.

Key for this vision is that conservation values are known in all stands intended for multifunctional forestry, possibly applying the methodology presented in Paper I. After this analysis, more detailed assessments are made, combining national forest inventory and lidar-data on areas identified as containing more conservation values than average forests.

The vision foresees that operations in multifunctional forestry will be carried out all year round since soil damage is not an issue thanks to efficient planning and machines with low ground pressure. Planning of multifunctional operations is done in detail in the field by forest managers, but much has been done in advance with GIS-data. Digital planning tools for use in the field enable the planner to specify which trees or areas are to be harvested and which are to be left. Thanks to augmented reality, the planner can visualise the post-operations stand while planning.

For this vision to become reality, the following are needed:

- Investigations of both spatial (how much is there and where are they?) and conservation attributes (what is in these stands?) in areas intended for multifunctional forestry.
- Creation of policy frameworks that acknowledge that (1) there are limits to ecosystem service production in forest land, (2) performing adapted management and methods will increase the total ecosystem service capacity, and (3) there are no 'true' values of ecosystem services – a key task for decision makers is to make decisions on trade-offs.
- Development of planning tools and decision support systems capable of handling and conveying various types of information between forest managers and operators.

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6. Conclusions

These are the five main conclusions from this thesis:

- The combined findings in this thesis suggest that NCM, in general, increases in complexity and is associated with higher costs along a north-south gradient in Sweden. As this also coincides with increasing land values, it reaffirms the need for strategies to maximise the benefits from conservation efforts.
- If multifunctional forestry is carried out to the extent intended, it will make a significant contribution to Swedish forestry. It is estimated that 5-15% of annual harvest from thinning in Sweden is (or could be) from areas intended for NCM, while there are no estimates of areas intended for other multifunctional forestry operations.
- Even though the intent of NCM is to benefit a variety of ecosystem services under different conditions, the operations carried out in Sweden are aimed at removing spruce and creating dead wood. This could be a result of confusion between what is needed and what is actually being carried out.
- Costs in multifunctional operations are higher than in conventional even-aged forestry but, when the entire management system is analysed, the effect on net revenues may be small.
- The general conclusion is that, in many cases, multifunctional forestry is not limited by the operations but rather a lack of clear goals and strategies for achieving goals and evaluating their attainment.

The main conclusions are based on the following conclusions from the studies presented in the thesis:

- Conservation values in forest land can be mapped using GIS-data already available for all forest land in Sweden. Performing this analysis could improve national or corporate strategies and subsequently increase implementation of multifunctional forestry.
- There was no support for the suggestion that voluntary set-asides intended for NCM are more common on low productivity soils or in areas with limited accessibility.
- In voluntary set-asides, there are factors incentivising and factors acting as barriers for NCM operations. The barriers could be addressed through:
    - Research on detailed estimates for time consumption, costs, and revenues in NCM, regarding planning and execution of both motor-manual and mechanised operations.
    - Utilising the wood harvested in NCM that do not benefit intended ecosystem services, i.e. much of the Norway spruce harvested.
    - Forestry companies designating a separate, not necessarily large, budget for NCM.
    - Mapping and analysis of causes and extent of criticism directed toward those involved in NCM.
    - Examinations of the extent to which the NCM carried out is the one most needed, i.e. is there efficiency in allocation of efforts?
    - Systems adapted for planning and follow-ups in NCM.

- The main findings from shelterwood removals are:
    - Harvester and forwarder productivity did not differ much from what would be expected in thinning of even-aged trees, assuming similar tree size and stand density.
    - Damage among residual trees was notable and mostly caused by the harvester, but the levels of damage did not jeopardise the wood production of the future stand.
    - Profitability in shelterwood management was lower compared to single-story spruce stands, making shelterwoods mainly suitable in areas where regeneration has been found challenging or where there is an appreciation of other ecosystem services.
- The main findings from patch cutting are:
    - Harvester productivity in patch cutting was significantly lower than in final felling. However, it was higher than what would be expected for thinning operations under similar conditions.
    - Forwarding distance was significantly longer, and restrictions when planning the road network meant increased risk of soil damage.
    - Costs were higher than in final felling, but the effect on net revenues in operations was small.
    - There is need for investigations examining long-term effects on ecosystem services production, risk of damage (e.g. wind damage) and operations in later stages of patch cutting.

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Popular science summary

Forests provide a variety of ecosystem services and traditional forest management is largely based on the extraction of one product, wood. Multifunctional forestry, forest management aimed at benefitting multiple ecosystem services, has emerged as awareness has grown of other forest ecosystem services. Nature conservation management is a type of multifunctional forestry promoting ecosystem services other than harvest of wood, most commonly biodiversity and recreation. While the benefits of multifunctional forestry and nature conservation management is recognised, there are knowledge gaps regarding how to perform these operations.

The overarching objective of this thesis is to increase knowledge and improve implementation of multifunctional forest operations in Sweden. This is addressed through four studies aiming at answering questions related to how forest operations can be implemented in multifunctional forestry.

Paper I used GIS-data from Swedish forest companies to map and describe conservation values in voluntary set-asides intended for NCM. The dataset comprised roughly 27 000 stands (polygons) in more than 130 000 ha. Paper II used interview survey with 27 professionals in Swedish forestry working with NCM to investigate practices and identify factors influencing the decision to perform NCM. In Paper III, data from detailed time studies were used to analyse time consumption and net revenues in operation when removing birch shelterwoods. Paper IV used harvester data and time studies in comparing harvester and forwarder time consumption in patch cutting and final felling.

The main conclusions from this thesis are that:

- Conservation values in forest land can be mapped using GIS-data already available for all forest land in Sweden. Performing this analysis could improve national strategies and subsequently increase implementation of multifunctional forestry.
- Even though the intent of NCM is to benefit a variety of ecosystem services under different conditions, the operations carried out are aimed at removing spruce and creating dead wood. This could be a result of confusion between what is needed and what is actually being carried out.
- In most cases, nature conservation management operations are not complicated, but forest managers are disincentivised by conflicting goals and fear of high costs and criticism.
- If multifunctional forestry is carried out to the extent intended, it will make a significant contribution to Swedish forestry. It is estimated that 5-15% of annual harvest from thinning in Sweden is (or could be) from areas intended for NCM, while there are no estimates of areas intended for other multifunctional forestry operations.
- Costs in multifunctional operations are higher than in conventional even-aged forestry but, when the entire management system is analysed, the effect on net revenues may be small.
- The general conclusion is that, in many cases, multifunctional forestry is not limited by the operations but rather a lack of clear goals and strategies for achieving goals and evaluating their attainment.

Populärvetenskaplig sammanfattning

Skogen producerar många olika ekosystemtjänster. Ursprunget till dagens konventionella skogsbruk är att främja en enda ekosystemtjänst, trä (timmer, ved, biobränsle). Skogsbruk med flera mål har utvecklats som en följd av att kunskapen om andra ekosystemtjänster har ökat. Naturvårdande skötsel kan betraktas som skogsbruk med flera mål där virkesproduktion inte är ett av brukandets mål. Trots att det finns omfattande forskning som visar på värdet av skogsbruk med flera mål och naturvårdande skötsel så finns det betydande kunskapsluckor gällande hur dessa åtgärder ska utföras.

Det övergripande syftet med denna avhandling är att bidra till ökad kunskap om och omfattning av skogsbruk med flera mål i Sverige.

Detta görs genom fyra studier som undersöker delar av frågan om hur kunskap om avverkning i konventionellt skogsbruk kan tillämpas i skogsbruk med flera mål.

I den första studien gjordes en GIS-analys av den del av svenska skogsbolags frivilliga avsättningar där avsikten är att tillämpa naturvårdande skötsel. En databas med cirka 27 000 bestånd (polygoner) fördelade på drygt 130 000 hektar analyserades. Den andra studien var en intervjustudie med 27 yrkesverksamma personer inom svenskt skogsbruk som alla arbetar med naturvårdande skötsel. Syftet med intervjuerna var att beskriva hur naturvårdande skötsel utförs i Sverige samt undersöka vilka faktorer som inverkar på beslutet att genomföra naturvårdande skötsel eller att avstå. Den tredje studien använde högupplösta tidsstudier av skördarens och skotarens arbete vid avveckling av lågskärm av björk för att kartlägga tidsåtgång och kostnader i samband med åtgärderna. I den fjärde studien analyserades tidsåtgång för skördare och skotare vid avverkning i ruthuggning och detta jämfördes med tidsåtgången i slutavverkning.

De viktigaste slutsatserna från denna avhandling är att:

- Det är möjligt att använda fritt tillgängliga GIS-data för att beskriva bevarandevärden i all svensk skogsmark. En kartläggning av denna typ skulle ge förbättrade möjligheter till en nationell strategi för dessa värden vilket troligtvis också skulle medföra att skogsbruk med flera mål skulle öka i omfattning.
- Även om naturvårdande skötsel utförs för att gynna många olika ekosystemtjänster så består de främst i att avverka gran, för att gynna lövträd, och skapa död ved. Det är möjligt att denna förenklade bild beror på att det förekommer en förväxling av vad som behövs och vad som faktiskt utförs.
- Naturvårdande skötsel är i de flesta fall inte komplicerat men de som har ansvar för att åtgärderna inte utförs hindras av motstridiga mål, risken för höga kostnader och en oro för kritik.
- Om skogsbruk med flera mål skulle utföras i den utsträckning det är avsett så skulle det utgöra en påtaglig del av svenskt skogsbruk. Uppskattningen är att 5-15% av den årliga volymen som avverkas i gallringar i Sverige skulle kunna komma från naturvårdande skötselåtgärder. Utöver detta tillkommer övrigt skogsbruk med flera mål, på vilket det inte finns uppskattningar av omfattningen.
- Kostnaderna för åtgärder i skogsbruk med flera mål är högre än i konventionella åtgärder men vid en analys av skogsbrukets lönsamhet är skillnaderna små.
- Den övergripande slutsatsen är att skogsbruk med flera mål ofta inte begränsas av teknik och arbetsmetoder utan oftare av att det saknas strategier för hur mål sätts upp och hur måluppfyllnaden utvärderas.

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Mapping of voluntary set-aside forests intended for nature conservation management in Sweden

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ABSTRACT

In Sweden, an estimated 0.3–0.6 million hectares (1.2–2.4% of the entire Swedish forest area) of forests are voluntary set-asides for nature conservation management (NCM). Even though these areas are crucial in Swedish biodiversity conservation, no analysis has yet been carried out of their conservation values and spatial distribution. The aim of this study was to comprehensively describe areas intended for NCM in Sweden. Based on existing habitat descriptions, six NCM area categories were defined. The occurrence of each category was determined through GIS analysis of a spatially explicit dataset containing information on 26,953 stands (136,672 ha) set aside for NCM. Of the analysed area, 86% met the criteria of at least one category. The most common category was "Old coniferous forests", which was found to be abundant in northern Sweden, and often the only category met in stands. Out of the remaining five categories, four were more frequent in southern Sweden. In the southern regions, stands often met the criteria of two or three categories simultaneously. This mapping is a resource for further research and development of policies and strategies aimed at increasing the extent and improving the quality of nature conservation management.

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Introduction

Conserving forest biodiversity is a critical task, and setting aside forest areas for conservation purposes is one of the main tools used to address this challenge (Secretariat of the Convention on Biological Diversity 2014). Land owner voluntary set-aside (VSA) forests are one of the components in forest conservation (Lindenmayer 2006; Gustafsson and Perhans 2010) and an important complement to formal reserves (Simonsson et al. 2015). VSA areas generally occupy the middle ground between formally protected reserves and production forests in terms of biomass density, dead wood volumes and tree age, where formal reserves have higher volumes and age. VSAs are also generally smaller than formally protected reserves (Elbakidze et al. 2011, 2016; Simonsson et al. 2016).

The instigation of VSAs has been led by forest certification (Johansson 2013; Kraxner et al. 2017). Eleven percent of global forest land is certified through either of the international certification schemes FSC or PEFC (FAO 2015), while in Sweden, 61% of forest land is certified (FSC 2010; PEFC 2012). The Swedish certification schemes require landowners to exempt a minimum of 5% of the productive forest land (annual mean growth greater than 1 cubic metre per hectare) from conventional timber production to create VSAs (FSC 2010; PEFC 2012). The latest mapping indicates that 1.2 million ha of forests in Sweden (5.2% of the total Swedish forest land) are designated VSAs (Claesson and Eriksson 2017).

From a forest management perspective, two different approaches are applied for VSA areas in Sweden; stands left for free development (i.e. unmanaged) and stands in need of active management, i.e. nature conservation management (NCM) to reach or maintain desired values. This distinction is motivated by the fact that different species are adapted to different environments, e.g. some species depend on forest cover continuity, dead wood and large trees while others are directly dependent on disturbance.

Natural disturbances, e.g. wildfires, storms, flooding, snow breakage, insects and fungi outbreaks and forest grazing by livestock, have been a reoccurring element in many forests throughout history (Pickett and White 1985; Attiwill 1994). However, human efforts over the past two centuries to limit the effects of the main natural disturbances in Sweden, i.e. wildfires and insect outbreaks, have been successful (Eidmann 1992; Linder and Östlund 1998). This prevention has been beneficial for timber production but the absence of disturbances risks changing the structure in the forest (Hunter 2009). Natural disturbances can be recreated/simulated by NCM (Pickett and White 1985; Attiwill 1994).

Even though there is little general knowledge about how NCM areas in Sweden should be and are managed, previous evaluations on formal and voluntary reserves indicate that NCM is not being carried out to the intended extent (The Swedish Government Office 2001; The Swedish Environmental Protection Agency 2012).

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The difference between the VSA concepts of free development and NCM have large implications for attainable goals, actual management and subsequent administrative processes. Certification schemes and previous research have yet to describe these differences in terms of how these concepts are implemented. However, efforts are being made to describe the desired goals in conservation forestry. In a joint collaboration between The Swedish Forest Agency and forestry stakeholders, indicators, strategies and concepts for management suggestions have been identified for a set of forest types in need of special consideration, i.e. care demanding habitats (Andersson et al. 2016). Most of the major Swedish forest companies and forest owner associations also have VSA management guidelines (e.g. Aulén 2012; Skellefteå Kraft 2013; Grönlund 2014; Sveaskog 2016; Holmen skog 2017; SCA skog 2017; The Church of Sweden n.d.). To date there have been no investigations on a national level of the characteristics and conservation values of areas in Sweden currently intended for NCM.

The aim of this study was to give a comprehensive description of areas in Sweden intended for NCM at county, regional and national level. The knowledge generated is one of the initial steps in the development of policies and strategies aiming to increase the extent and quality of the NCM measures being carried out.

Material and methods

Collection of data on current NCM stands

Five Swedish forest companies each provided spatial data (polygons and accompanying stand registry attributes) on all their VSA areas currently intended for NCM. The companies together own approximately 8 Mha of productive forest land (34% of Sweden's productive forest land) spread over the entire country, but with greater representation in the northern parts. Of this area, 136,672 ha, comprising 1.7% of the companies' holdings, were intended for NCM. No analysis was done at company level, i.e. it was assumed that there are no systematic differences between companies' implementation of NCM. The data covers almost 27,000 stands with an average and median area of 5 and 2.4 ha, respectively. The data was divided into four regions, from south to north (Table 1, Figure 1).

Along with spatial data, companies also provided data on stand characteristics collected through field inventories. Since the analysed data was retrieved from several forest companies, the availability of attributes varied. Information on current standing volume, age, mix of tree species, and the main reason for conservation measures was available for most stands (Table 2).

Creation of NCM area categories and subsequent criteria

A set of 40 forest types with their own separate identifiers and goals (more detailed description in Table A1, Appendix A) was devised after combining information about the care demanding habitats (Andersson et al., 2016) with publicly available forest company VSA guidelines (Aulén 2012; Skellefteå Kraft 2013; Grönlund 2014; Sveaskog 2016; Holmen skog 2017; SCA skog 2017; The Church of Sweden n.d.). Of the 40, 31 forest types were described as requiring NCM, at least under certain conditions, to attain or maintain intended values. These forest types vary in extent and characteristics. Aim of the consideration included e.g. biodiversity, small-scale environmental considerations, management of cultural historical sites and adaptions of forestry to improve recreational values. Some forest types included quantitative indicators, while all contained qualitative attributes for identification and a brief description of what could be considered suitable management of the areas.

A set of six NCM area categories were created based on these 31 forest types, by grouping them according to their main attributes. The six area categories were complemented by a "category" for stands that met none of the listed criteria (Table 3). The forest types in each area category had common denominators in terms of aims and management strategies or stand characteristics. Each area category included criteria deemed identifiable given the available data, and chosen so that there was no overlaps between area categories. The forest type "Lime soils with herbaceous plants on dry soils" (no. 38 in Table A1, Appendix A) was identified as having a possible need for conservation management. However, it was not included in any of the six area categories or placed in a separate seventh category. This because the main identifier of this category is the bedrock and the data provided by the landowners contained no bedrock data and according to the Geological Survey of Sweden (SGU 2017) the official national mapping of Sweden's bedrock, even at the highest resolution, is not detailed enough to describe the bedrock at stand level. All area categories and their criteria are summarised (Table 3) and presented below.

Areas with high degree of formal protection (Protected)

NCM stands containing areas with a high degree of formal protection were categorised as "Areas with high degree of formal protection" (designated Protection in this text). Data on

Table 1. General description of analysed stand data divided into the four regions illustrated in Figure 1. Numbers in parentheses are standard deviation values.

Region	Number of stands	Total area (ha)	Average polygon area (ha)	Median polygon area (ha)	Average standing volume (m^3 ha^{-1})	Age[a] (year)
South	5645	16,853	3.0 (3.9)	1.8	205 (123)	76 (39)
Mid	6981	32,651	4.7 (6.8)	2.7	225 (126)	76 (42)
North-mid	8905	37,594	4.2 (7.8)	2.1	196 (105)	109 (45)
North-North	5404	49,552	9.2 (13.1)	4.2	155 (82)	117 (49)
Total	26,953	1,36,672	5.0 (8.6)	2.4	197 (114)	95 (48)

[a]Average age of highest trees.

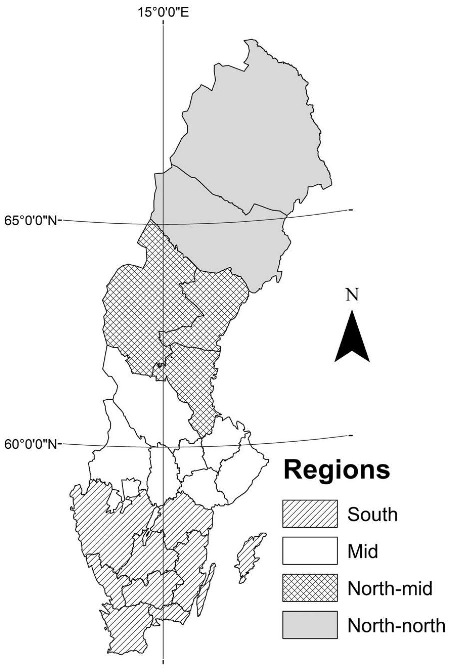

Figure 1. Map of Sweden and the four geographical regions used in presentation of analyses and results. Solid lines within regions indicate county borders.

locations of nature reserves and national parks were retrieved from WDPA (UNEP-WCMC 2017). Data on other types of formal protection that will affect the management to a lesser extent, such as Natura 2000 areas and the several Swedish concepts for protection of forest land were retrieved from a database created by The Swedish Forest Agency (2017a).

Areas close to anthropogenic activity (Anthropogenic)

Stands in the area category "Areas close to anthropogenic activity" (Anthropogenic) could meet either of two criteria:

Table 2. Proportion of stands containing the different attributes as supplied by the forest companies

Attribute	Data availability (% of total number of stands)
Standing volume (m^3 ha^{-1})	100
Age, average age of highest trees (years)	100
Species mixture, proportion of standing volume divided into pine, spruce, deciduous	98
Reason for conservation (varying greatly in level of detail)	92
Site index, expected height at age 100 (a proxy for increment)	58
Basal area (m^2 ha^{-1})	57
Tree height (m), average of thickest trees	57
Average breast height diameter (cm)	57
Tree density (n ha^{-1})	57
Accessibility (slope, roughness, bearing capacity)	57
Latest applied and/or suggested silvicultural measure	41

Table 3. Names, titles and a brief description of the criteria for identification of each category. More detailed descriptions can be found in Table A1, Appendix A.

Area category	Designation in text	Criteria
Areas with high degree of formal protection	Protected	Areas overlapping nature reserves, national parks or some other formally protected forest
Areas close to anthropogenic activity	Anthropogenic	Stands within 300 metres of residential buildings and stands overlapping areas or within 20 metres of lines and points identified as being sites with cultural heritage value
Areas close to water	Water	Stands within a 30-metre buffer zone of water surfaces
Areas with limited accessibility	Accessibility	Areas with limited accessibility due to low bearing capacity, high ground roughness, or steep slopes
Old coniferous forests	Coniferous	Stands where ≥ 70% of standing volume is coniferous species and stand age ≥ 120 years
Old deciduous forests	Deciduous	Areas where ≥ 25% of standing volume is deciduous species and stand age ≥ 60 years
Zero-category stands	Zero	Stands meeting none of the above criteria

they are close to urban areas and/or close to sites of cultural historical importance. Closeness to urban areas was defined as areas within 300 metres of residential buildings, as identified by a land use map with 25-metre square pixels (The Swedish Environmental Protection Agency 2000) and the land use area categories for residential areas. Andersson et al. (2016) defined the distance of 300 metres from buildings as being the maximum distance citizens normally venture into forests.

Using data from the Swedish National Heritage Board (2017), points, lines and areas identified being of importance for cultural heritage were identified. Stands containing areas of cultural heritage or being within 20 metres of lines or points identified as cultural heritage were categorized accordingly.

Areas close to water (Water)

Areas within a buffer zone of 30 metres from water were categorised as "Areas close to water" (Water). The general recommendation for final felling sites in Swedish forestry is to leave a buffer zone of forest along water edges of no less than 10 metres, which has been identified as insufficient when aiming to avoid negative impact on mosses (Hylander et al. 2002) and land snails (Hylander et al. 2004). Few studies have been made of wider zones but Hågvar et al. (2004) also concluded that a 30-metre buffer zone to water in clearcuttings was too small to avoid negative effects on bird life. Water areas were identified using the Swedish terrain map (The Swedish Mapping Cadastral and Land Registration Authority 2017) containing spatial data on all lakes and streams in Sweden wider than 6 metres.

Areas with limited accessibility (Accessibility)

Limited accessibility was defined using forest owner data containing information on terrain classification according to Berg (1992) on bearing capacity, ground roughness and slope. This category was called "Areas with limited accessibility" (Accessibility). The criteria for in-field classification involved a scale from 1 (easy conditions) to 5 (very difficult conditions). Each of the attributes were estimated individually and all combinations were possible. Stands classified as level 4 or 5 on any of the three attributes were categorised as areas with limited accessibility.

For 18% of the analysed area, there was no data on bearing capacity but information on soil type, as presented in Berg (1992). Soil type is one of the main components when estimating bearing capacity, and stands containing three soil types (peat, mud and silt) were categorised as limited accessibility by bearing capacity. Another 41% of the analysed area contained no information on either of the three attributes (bearing capacity, ground roughness and slope). Since there was no national data available on ground roughness or bearing capacity or any reliable method to estimate them from remote sensing data, these attributes were not estimated for this share of the data set. Slope was estimated using a national high resolution (2 by 2-metre pixels) digital terrain model (The Swedish Forest Agency, 2017b). Slopes were averaged over areas of 1 ha (100 by 100-metre pixels) to prevent results being skewed by steep, but small, slopes. The pixel with the highest value inside or within 100 metres from the stand edge was assumed to be the "limiting" slope for the whole stand.

Old coniferous forests (Coniferous)

Using stand data provided by the forest owner, stands where more than 70% of the standing volume comprised domestic coniferous species (Pinus sylvestris or Picea abies), and the stand age was older than 120 years, were categorised as "Old coniferous forest" (Coniferous). The thresholds used were consistent with the Swedish Forest Agency definition of old coniferous forests (Andersson et al. 2016).

Old deciduous forests (Deciduous)

Using stand data provided by the forest owner, stands where more than 25% of the standing volume comprised deciduous trees, and the stand age was older than 60 years, were categorised as "Old deciduous forest" (Deciduous). Since no thresholds were presented by the Swedish Forest Agency (Andersson et al. 2016), the thresholds applied were retrieved from the Swedish Environmental Protection Agency, as described in the national standards for environmental goals (The Environmental Objectives Portal 2017).

Zero area categories applying (Zero)

Stands meeting none of the categorisation criteria above (Zero).

Application of category criteria on areas intended for NCM

The purpose of the categorisation was to group and thereby attempt to explain the reasons why the forest companies chose to assign the analysed stands/areas to NCM. Each category was identified applying the different criteria for each category on each polygon in the dataset. If a stand or parts of it met the criteria for a category, the entire stand was classified as being intended for NCM on these grounds. Accordingly, some stands met the criteria of no area categories and were classified as "zero-category stands" while others could meet the criteria of several area categories. The number of category criteria met by a stand was interpreted as proxy for conservation complexity in the stand. Stands were accordingly assigned a NCM complexity value, ranging from 0 to 6, the value not considering the combination of NCM area categories present in each stand.

Data processing and statistics

Results are presented in absolute and relative areas, in hectares. This is supplemented in a few instances with the number of stands meeting the criteria of area categories.

To illustrate the relationships between the six area categories, affiliation network analyses were performed using the igraph package in R (R core team 2017). The analyses were performed at national as well as regional level. All spatial analyses were performed in ArcMap 10.1 (ESRI 2012) and ArcMap 10.5 (ESRI 2016) using mainly the Buffer, Clip and Intersect tools in the Analysis toolbox. Remaining statistical calculations, e.g. averages and standard deviations, were performed in SAS Enterprise Guide 6.1 (SAS 2014).

A total of 18 stands, representing 66.4 ha of the analysed stands (0.07% of the stands and 0.05% of the area), were considered outliers and removed from the dataset; their database attribute values were deemed to be probably results of typing errors. Fifteen stands, representing a total of 57.8 ha, were considered outliers because of high standing volume (>700 $m^3\ ha^{-1}$) when the average in the dataset was 197 $m^3\ ha^{-1}$. Three stands, representing a total of 8.6 ha, were considered outliers because their stated age was greater than 300 years when the average in the dataset was 95 years.

Results

Eighty-six percent of the analysed area met the criteria for one or more NCM area categories. The most common category observed was Coniferous, whose criteria were met in 43% of the analysed area (Table 4).

Some spatial patterns were observed in the abundance of areas meeting the distinct area categories (Figure 2). Most notable was that Coniferous was strongly represented in the northern counties while all other area categories, except Accessibility, were more abundant in the southern part of the country.

Most commonly, stands met one or two area categories (41 and 32% of the area) while no stands met the criteria of all six area categories (Figure 3, Tables 4 and 6). NCM complexity, i.e. the number of area categories occurring within each stand, followed a south–north gradient with lower complexity being more common in northern Sweden; this area mostly comprised Coniferous stands (Table 5, Figure 3).

The category that is most frequent in complexity level 1 is also one of the most frequent combinations at higher complexity levels. This also applies to all other complexity levels, e.g. the "added" category in complexity level 2 is also part

Table 4. Areas, number of stands and proportions of the analysed dataset meeting the criteria of each category. Protected = Areas with high degree of formal protection, Anthropogenic = Close to anthropogenic activity, Water = Close to water, Accessibility = Areas with limited accessibility, Deciduous = Old deciduous forest, Coniferous = Old coniferous forest and Zero = Zero area categories applying.

Category	Area meeting criteria (ha)	Percentage of total area (%)[a]	Number of stands	Percentage of total number of stands (%)[a]
Protected	36,135	26	6038	22
Anthropogenic	34,175	25	7 961	30
Water	33,116	24	6 104	23
Accessibility	19,358	14	4 247	16
Deciduous	22,537	16	6 322	23
Coniferous	58,553	43	8 168	30
Zero	19,163	14	4 569	17
Total	136,672		26 953	

[a]Totals exceed 100% since stands could meet the criteria of several of the area categories simultaneously.

of the most frequent combinations at higher complexity level. The North-Mid region slightly deviates from this pattern and it is not apparent on a national level (Table 5).

Fifty percent of the Coniferous area was at complexity level 1, while all other area categories were most frequent in stands with complexity level 2, meaning that two NCM area categories were observed in the stand (Figures 4 and 5).

In the regions South and Mid, Anthropogenic is a core category, both at low and high complexity. In higher complexity it appears along with either Deciduous, Water or Protected. In Regions North-Mid and North-North, Coniferous is the core category, mainly appearing with Protected and Accessibility (Figure 6).

Three general trends in occurrence of different combinations in geographical regions (Table 6) can be identified: (1) category combinations increasing or decreasing along a south–north gradient, e.g. Anthropogenic, Anthropogenic + Deciduous or Anthropogenic + Deciduous + Water decrease from South to North, while Coniferous increases from South to North; (2) category combinations unaffected by the latitude, e.g. Protected + Water or Deciduous; (3) category combinations appearing predominantly in the central regions, e.g. Water or Coniferous + Water.

Discussion

This comprehensive analysis of Swedish forests intended for NCM provides new insights into Swedish NCM forests. As has been found for VSA in northern Sweden (Simonsson et al. 2016), the analysis found that the most common type of forest company NCM forest is old coniferous forests. In the northern region, the stands most commonly comprise

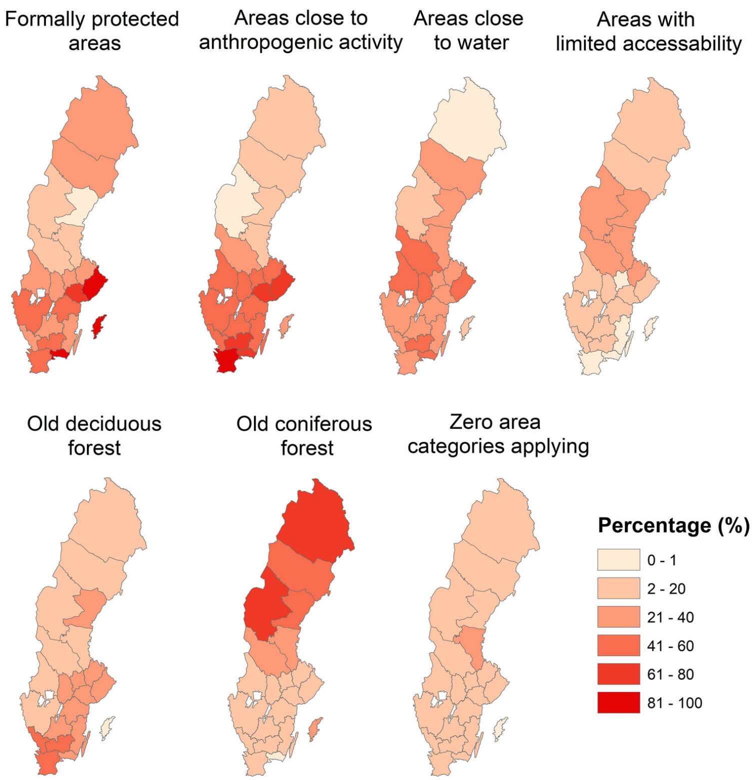

Figure 2. Percentage of the total NCM area within each county meeting the criteria of each category.

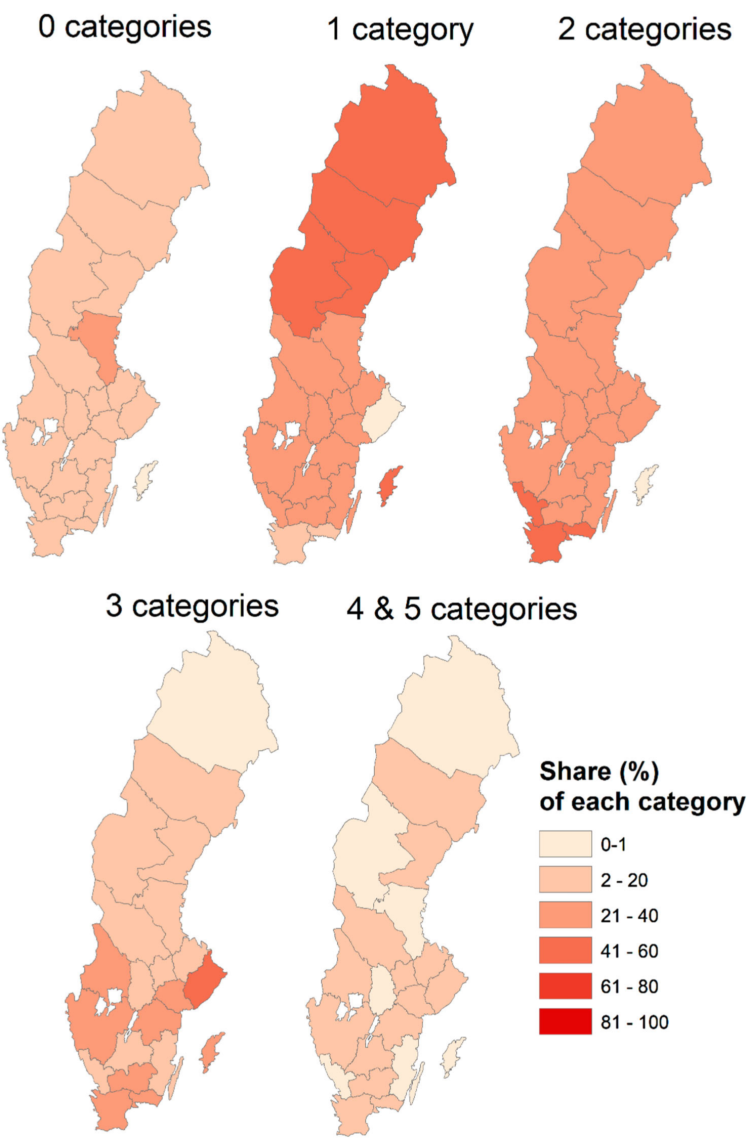

Figure 3. Percentage of the total NCM area within each county meeting the criteria of various numbers of area categories, i.e. at different complexity levels.

only this category but when another category does occur, it is most commonly areas with a high degree of formal protection. This is in supported by findings from Claesson and Eriksson (2017), indicating that VSA and formal protection more often overlap in northern Sweden than in the south.

In the southern regions, four area categories are most common: old deciduous forest, areas close to water, areas with a high degree of formal protection and areas close to anthropogenic activities. Stands most often meet the criteria of two or three of these four. That stands belongs to multiple area categories indicates that more complex considerations are required in the actual management. NCM stand complexity is, in general, low in the north and increases along a north–south gradient. The area categories were able to describe NCM values in 86% of the analysed dataset, but the method used in the study will not be able to detect values that are not recorded in these registers and do not appear explicitly in stand descriptions.

Previous attempts to quantify NCM areas in Sweden have involved surveys (The Swedish Forest Agency 1998, 2002, 2008; Stål et al. 2012; Claesson and Eriksson 2017). The latest survey indicates that an estimated 40% of VSAs in

Table 5. Percentage of complexity levels appearing in each region along with the most frequent combination appearing at each level in each region. Coniferous = Old coniferous forest, Deciduous = Old deciduous forest, Water = Close to water, Anthropogenic = Close to anthropogenic activity, Protected = Areas with high degree of formal protection, and Accessibility = Areas with limited accessibility

	Complexity level					
	0	1	2	3	4	5
South						
Percentage of region NCM area (%)	12	31	36	18	3.1	0.2
Most frequent combination	-	Anthropogenic	Anthropogenic Deciduous	Anthropogenic Deciduous Water	Anthropogenic Deciduous Water Protected	Anthropogenic Deciduous Water Protected Accessibility
Mid						
Percentage of region NCM area (%)	12	31	33	20	3.6	0.4
Most frequent combination	-	Anthropogenic	Anthropogenic Water	Anthropogenic Water Protected	Anthropogenic Water Protected Deciduous	Anthropogenic Water Protected Deciduous Accessibility
North-Mid						
Percentage of region NCM area (%)	15	45	30	8.3	1.3	0.2
Most frequent combination	-	Coniferous	Coniferous Accessibility	Coniferous Anthropogenic Water	Anthropogenic Water Deciduous Accessibility	Anthropogenic Water Deciduous Accessibility Protected
North-North						
Percentage of region NCM area (%)	13	49	31	6.3	1.7	0.1
Most frequent combination	-	Coniferous	Coniferous Protected	Coniferous Protected Water	Coniferous Protected Water Anthropogenic	Coniferous Protected Water Anthropogenic Accessibility
Total						
Percentage of NCM area (%)	13	43	32	12	2.2	0.2
Most frequent combination	-	Coniferous	Coniferous Protected	Anthropogenic Protected Water	Anthropogenic Deciduous Protected Water	Accessibility Anthropogenic Deciduous Protected Water

southern Sweden and 20% in northern Sweden were intended for NCM. This roughly translates to the conclusion that 1.2–2.4% of Swedish forest land is VSA NCM forests. The data in the present study found 1.7% of the participating companies' holdings being set aside for NCM, however, these holdings represents a larger share of the forest land in northern part of the country than in the southern.

Many of the patterns for the different area categories are in line with what could be expected. For example, NCM stands close to anthropogenic activities were common in regions South and Mid, which are also more densely populated areas (Statistics Sweden 2012) and where cultural heritage findings are more abundant (the Swedish National Heritage Board 2017). Along a south–north gradient, NCM areas, on

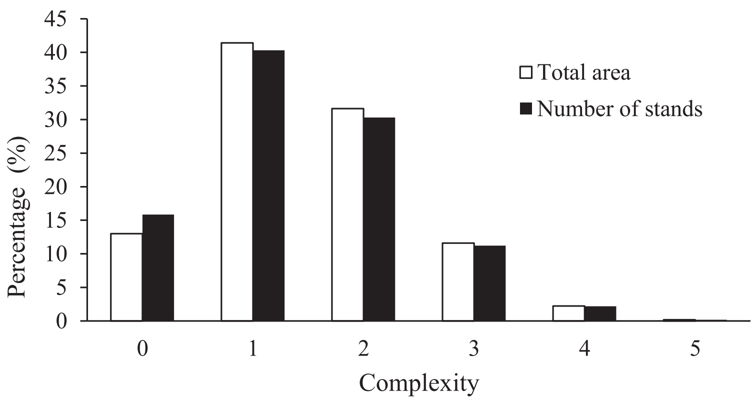

Figure 4. Percentage of total area and number of stands per complexity level.

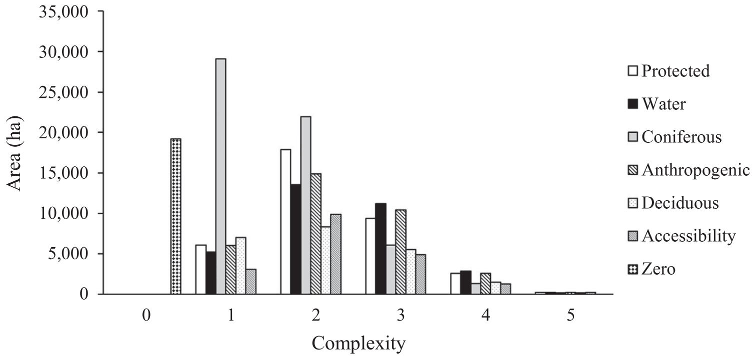

Figure 5. Occurrence of area categories at each level of NCM complexity level (i.e. complexity is the number of area categories within each stand). Protected = Areas with high degree of formal protection, Water = Close to water, Coniferous = Old coniferous forest, Anthropogenic = Close to anthropogenic activity, Deciduous = Old deciduous forest, Accessibility = Areas with limited accessibility, and Zero = Zero area categories applying.

average, increased in size while the proportion of areas with mainly coniferous trees increased and the average standing volume per hectare decreased, all themes that can be observed in conventional production forests (Nilsson et al. 2017; The Swedish Forest Agency 2017a). Furthermore, as has been observed within formal reserves (Götmark and Nilsson 1992; Borgström et al. 2013), the complexity in the analysed NCM areas was higher closer to urban areas in the South and Mid regions. The results from the present analysis of NCM areas indicate no differences in terms of standing volumes and tree age distributions compared with previous investigations of VSA areas in Sweden (Fridman and Walheim 2000; Finnström and Tranberg 2014; Simonsson et al. 2016).

There were, however, some unexpected findings. The Deciduous category was not as clearly clustered in the southern regions as is the case in the general Swedish forest land (Nilsson et al. 2017). This might be a result of efforts to increase the amount of deciduous trees, e.g. as expressed by the certification schemes (FSC 2010; PEFC 2012). Furthermore, stands categorised as being close to water were more common in the Mid region, even though

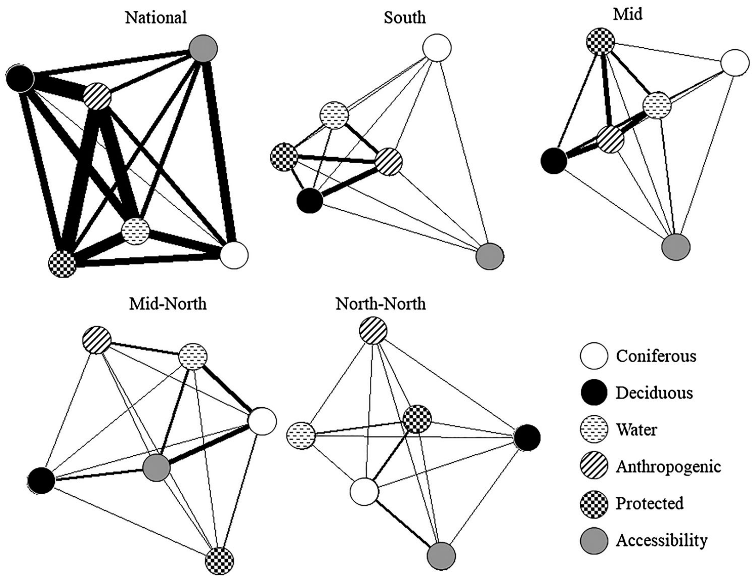

Figure 6. Affiliation network plots of all categoriesarea categories, shown by region. Thicker lines indicate that the two categoriesarea categories in the nodes connected by the line appear more frequently than pairs along thinner lines. Positioning and distance between nodes shown have no significance. Coniferous = Old coniferous forest, Deciduous = Old deciduous forest, Water = Close to water, Anthropogenic = Close to anthropogenic activity, Protected = Areas with high degree of formal protection, and Accessibility = Areas with limited accessibility.

Table 6. Most frequent combinations of area categories nationally and in the four regions (% of analysed area) presented by order of magnitude at country level. Coniferous = Old coniferous forest, Deciduous = Old deciduous forest, Water = Close to water, Anthropogenic = Close to anthropogenic activity, Protected = Areas with high degree of formal protection, Accessibility = Areas with limited accessibility, and Zero = zero area categories applying.

	Total	South	Mid	North-Mid	North-North
Coniferous	21.3	3.8	5.4	28.5	32.2
Zero	13.0	11.6	11.6	15.3	12.6
Coniferous + Protected	6.0	2.1	1.0	2.8	13.0
Deciduous	5.1	5.3	2.1	4.6	7.5
Protected	4.5	8.5	5.2	1.6	4.7
Anthropogenic	4.4	10.1	9.1	1.9	1.3
Accessibility + Coniferous	4.1	0.3	0.9	7.3	5.2
Water	3.8	3.4	7.6	4.2	1.2
Coniferous + Water	3.6	1.2	5.1	7.1	0.9
Anthropogenic + Protected	2.9	8.3	6.1	0.8	0.7
Anthropogenic + Deciduous	2.9	11.1	5.2	0.8	0.3
Anthropogenic + Water	2.4	3.2	5.7	1.4	0.7
Protected + Water	2.3	3.9	3.2	0.9	2.2
Accessibility	2.3	0.1	1.8	4.2	1.8
Anthropogenic + Coniferous	2.2	1.4	0.7	2.1	3.6
Anthropogenic + Protected + Water	2.1	4.8	5.0	0.3	0.6
Anthropogenic + Deciduous + Water	1.7	4.4	4.2	0.5	0.1
Deciduous + Protected	1.2	1.8	0.7	0.5	1.9
Anthropogenic + Deciduous + Protected	1.1	4.3	2.1	0.1	0.2
Accessibility + Deciduous	1.1	0.0	0.6	2.4	0.8
Accessibility + Coniferous + Water	1.1	0.1	2.0	2.0	0.2
Other[1]	10.8	10.4	14.6	10.9	8.3

[1]Summarised percentage of the 39 remaining combinations of area categories that occur, all of which appear in less than 1% of the total analysed area.

there is no general clustering of lakes and rivers in these, or any, parts of the country (Statistics Sweden 2012). This could be a result of the Mid region being more densely populated than other regions. There are general recommendations to consider closeness to water when establishing recreation forests close to urban areas (Hannertz et al. 2016) and e.g. stress recovery benefits of visiting a forest is higher in forests close to water (Sonntag-Östström et al. 2011). Accordingly NCM areas in the Mid region could be chosen considering recreation, and closeness to water, to a larger extent than in other regions.

The dataset represents a majority of the forest land owned by forest companies in Sweden and could therefore be considered reliable and generalisable to, at least, all forest land owned by forest companies in Sweden. The forest land not included in the study was mainly privately owned non-industrial forest, which is about 50% of the forest land in Sweden (Nilsson et al. 2017). There is a wide variety in management strategies among the approximately 330,000 private forest owners in Sweden (Ingemarson et al. 2006) and it can be assumed that there are differences as to why and how private forest owners set aside NCM areas. Caution should therefore be applying when attempting to generalise the study results onto these areas.

Claesson & Eriksson (2017) noted that VSAs are generally sited on low productivity soils, possibly to reduce costs. These areas may also be VSAs because they have been less affected by harvesting operations than other areas, due to lower profitability in general. This could imply longer continuity and higher conservation values. In the present study, the category of limited accessibility is a proxy for areas where forest operations may be costlier than average. The results do not indicate that areas meeting the criteria for limited accessibility, regardless of conservation values, have been systematically set aside for NCM. Limited accessibility was the least frequent among the NCM area categories and it was no more common than the other area categories as level 1 complexity stands. However, for a significant proportion of the dataset, the data for analysis of accessibility was indirectly described through geospatial information for some of the data, so the occurrence of this type of stand may have been underestimated.

The North-Mid region deviates slightly from the pattern of increasing average stand size along a south–north gradient. This is affected by one of the datasets in this region containing many stands with small areas (24% of stands in the region were <0.5 ha, compared to 4–14% in the other regions). After detailed analysis of a sample of these stands, some were identified as being parts of larger stands. These stands appeared to have been split into several polygons, e.g. by roads or drawing errors, but were not separate management units. Interpreting the data on total area rather than number of stands is one way to account for this but since these small areas appeared to only partly be the result of unintentional division, no measures were taken to address this.

In the 14% of the area meeting the "criteria" for the Zero category, it should not be assumed that there are no conservation values. The interpretation should be that area categories based on stands and spatial data cannot account for all the values that can be found in NCM areas. As an example, parts of this could be the "Lime-soils with herbaceous plants on dry soils" biotope described by Andersson et al. (2016) that was not included in a category. Limestone bedrock and subsequent lime soils occur in many parts of Sweden (SGU 2017) and the error caused by not being able to include these soils in the categorisation is difficult to evaluate.

Identifying conservation values and deciding on management needs for VSA stands is a complex process. Attempts have been made to use remote sensing technology to identify explicit conservation values (Ørka et al. 2012; Eldegard et al. 2014; Lindberg et al. 2015). The alternative approach is to consider remote sensing as a resource during the more costly field inventories (Wikberg et al. 2009). Aligning with the second approach, this study reported has devised a simple method for description of conservation values using basic stand data, routinely collected by all forest owners, and data freely available for the whole of Sweden (e.g. The Swedish Environmental Protection Agency 2000; The Swedish Forest Agency 2017a; The Swedish Forest Agency, 2017b; SGU 2017).

The results are therefore intended to (1) increase the understanding of NCM areas in Sweden, and (2) form the basis of further research into identifying areas possibly containing conservation values, values that inevitably must be described through field inventories. However, this knowledge is only one of the stages in reaching a position where NCM is the intention in areas with the highest values. If biodiversity is to be increased in Swedish forests, NCM must actually be implemented, but evaluations have indicated this is currently not the case (The Swedish Government Office 2001; The Swedish Environmental Protection Agency 2012); the reasons for this have not yet been fully investigated. This study also increases awareness of factors characterising the NCM stands but that may hinder the management needed.

In conclusion, basic stand data and freely available data can be used to describe NCM values in Swedish forests. Forest areas owned by Swedish forest companies intended for NCM largely followed expected patterns in terms of tree composition and conservation complexity, although some deviations were noted. NCM complexity was higher in southern than in northern Sweden, implicating a need for more complex management of NCM areas in southern Sweden. The description of NCM areas is the first step in a process where efforts now should be directed towards understanding practices and drivers behind any decision to carry out NCM.

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Appendix A

Table A1. Biotopes described in the source material, along with more detailed properties for identification in the cases where it was expressed, grouped according to the NCM area categories created within the project. The table also shows whether the source material recommended NCM. When management is indicated as “Yes/No” there is need for management in some cases while free development is preferred in others.

	Forest type identifiers	Management required
Category: Close to anthropogenic activity		
1	Old forest pasture with no dominant tree species	Yes
2	Forest “islands” in farming land	Yes
3	Forest containing a spot (with or without buildings) where people enjoy going, even if far from cities	Yes
4	Overgrown old pastures and meadows managed to replicate historical management	Yes
5	Overgrown pastures and meadows managed for “natural” forest development	No
6	Close to urban area forests, within 300 metres of buildings	Yes/No
7	Forests used for recreation, but not the ones closest to urban areas	Yes/No
8	Forests with paths and trails	Yes/No
9	Old stone hedges and stone piles deriving from the establishment of farmland	Yes/No
10	Old huts and pits from historical charring	Yes/No
11	Various spatially small types of indicators of former reindeer herding	Yes/No
12	Remains of historical buildings	Yes/No
13	Old roads and paths	Yes/No
14	Mire meadows	Yes/No
15	Tar production sites	Yes/No
16	Edges of forests bordering farmland with a mix of tree species	Yes/No
Category: Areas close to water		
17	Forests along streams and similar “small” watercourses	Yes
18	Areas with herbaceous plants along water with > 70% herbaceous plants ground cover	Yes
19	Beach and seasonally submerged forests	No
20	Forests affected by natural springs, generally only on small areas	No
21	Forests in or adjacent to marshes and small water areas	No
Category: Areas with limited accessibility		
22	Steep slopes, not necessarily long	Yes/No
23	Vertical surface, minimum 5 metres long and 2.5 metres high	Yes/No
24	Chasms, minimum depth 2.5 metres	Yes/No
25	Gorges, minimum depth 5–10 metres	Yes/No
26	Areas with boulders of size large enough and frequent enough to affect conventional forestry	Yes/No
27	Old forests on islands and headlands	No
28	Old low productive forest with rocky ground	No
29	Wetland forests	No
Category: Old deciduous forest		
30	Stands dominated by deciduous trees with many bushes and dead wood	Yes
31	Open deciduous forest with many old trees	Yes
32	Beech forest with gaps and dead wood	Yes
33	Hazel groves	Yes/No
Category: Old coniferous forest		
34	Predominately old pine on sandy-gravel soils	Yes
35	Long continuous forest cover of coniferous species	Yes
36	Old multi-layered coniferous stands	Yes
37	Long continuous cover of conifers with many hanging lichens	Yes/No
Uncategorised		
38	Lime soils with herbaceous plants on dry soils	Yes/No
39	Areas with traces of recent fires	No
40	High value individual trees, already there or with high potential	No

II

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Nature conservation management in voluntary set-aside forests in Sweden: practices, incentives and barriers

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ABSTRACT

In Sweden, there is a lack of knowledge about nature conservation management (NCM) practices in voluntary set-aside forests. Estimates indicate that, for unknown reasons, only a small proportion of the NCM needed is carried out. The aims of this study are to (1) describe current practices for NCM of voluntary set-aside areas in Sweden and (2) identify factors affecting whether NCM of these areas is carried out. Twenty-seven semi-structured interviews were held with professional forestry practitioners and the responses analysed applying thematic analysis. NCM in Sweden generally has two main aims: (1) creation of dead wood and (2) promotion of domestic broadleaf tree species. Simplified, these aims are attained through removal of Norway spruce (*Picea abies* (L.) H. Karst.). The decision to implement NCM is influenced by few incentives and many barriers. Incentives include certification scheme obligations and commitment from dedicated individuals, while barriers include weak internal company incentives, the experienced or anticipated risk of high costs, and experienced or anticipated criticism from internal company experts or public actors. Based on the results, a set of managerial implications was drawn up, aimed at increasing the extent of NCM.

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Introduction

Sixty-three per cent of Sweden's land area is covered by forest (Nilsson et al. 2017). These 28.1 million hectares (Mha) account for only 0.7% of the global forest land, yet Sweden was, for example, the 10th largest producer of wood in the world in 2011 (FAO 2015). Sweden was also the source of 8.5% of the coniferous pulpwood consumed globally in 2016 (FAOSTAT 2017).

Industrial harvest of wood for sawmills and the pulp and paper industry has been one of the cornerstones of the Swedish economy since the late nineteenth century. This exploitation of the natural resource eventually led to legislation to ensure sustainable land use and the 1903 Forestry Act obliged forest owners to secure reforestation (Nylund 2009). However, the early versions of forestry legislation were solely aimed at securing long-term timber production, and it was not until the revision of the Forestry Act in 1993 that other forest benefits (e.g. biodiversity, recreation and reindeer husbandry) were highlighted, and environmental/conservation objectives were given equal weight to production objectives (SFS 1979:429).

In Sweden, forest land is conserved through a combination of formal preserves, voluntary set-asides and retention forestry required in all forest management. From the 28.1 Mha forest, 2.3 Mha is formally protected within national parks and nature reserves (The Swedish Forest Agency 2019). Out of these, ~1.0 Mha is situated in productive forest land (annual increment >1 m^3 ha^{-1}) (Statistics Sweden 2017). Landowners certified through FSC and/or PEFC are committed to voluntary set-aside, among stands larger than 0.5 ha, at least 5% of their holdings of productive forest land (FSC 2010; PEFC 2012). In Sweden, voluntary set-asides have been estimated to 1.2 Mha (Claesson and Eriksson 2017). The Forestry Act (SFS 1979:429) also requires landowners to adapt forest management to local conditions and ensure that high-value biotopes are preserved. This generally involves retention of individual trees or smaller areas, totalling an average of 3–5% of the area treated (Gustafsson et al. 2012), currently adding up to ~0.4 Mha (The Swedish Forest Agency 2019).

Originating in a nomenclature applied when making forest management plans, two general management strategies are employed to attain/maintain the desired complexity in private-owned preserved areas: free development areas and nature conservation management (NCM) areas. NCM intend to maintain a desired forest structure or simulate natural disturbances such as wildfires, storms, flooding, snow breakage, insects and fungal outbreaks and grazing (Pickett and White 1985; Attiwill 1994). Human efforts to limit the effects of two of the main disturbances, wildfires and insect outbreaks, have been increasingly effective (Eidmann 1992; Linder and Östlund 1998), while the use of meadows and extensive grazing has decreased with the mechanisation of farming (Eriksson et al. 2002). Although these changes have been beneficial for the society in many ways, the absence of disturbances have negative effects on biodiversity (Nilsson et al. 2013; Hunter, 2009).

Among the large state and private forest companies, accounting for ~40% of the Swedish forest land, 1.7% of the

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holdings is intended for NCM (Grönlund et al. 2019), while among small-scale private forest owners, the proportion is estimated to be slightly higher (Claesson and Eriksson 2017). To what extent these areas are being managed according to plan is not known in detail. A rough estimate made by the Swedish Environmental Protection Agency (2012) is that <20% of the areas in formal preserves needing NCM is being actively managed, and the corresponding number in voluntary set-asides is <10%.

There is currently little knowledge about the more explicit need for management procedures and what type of operations are actually being performed in managed NCM areas. There is also little published knowledge on how to actually perform NCM operations in practice. The existing literature on NCM comprises either theoretical frameworks (cf. Angelstam and Kuuluvainen 2004; Drever et al. 2006; Lindenmayer 2006; Kuuluvainen et al. 2012; Kuuluvainen and Grenfell 2012), general descriptions of desired biological states (cf. Nitare et al. 2014; Bengtsson et al. 2015; Andersson et al. 2016) or specific guides developed by forest companies for management of voluntary set-aside areas (cf. Aulén 2012; Grönlund 2014; Holmen Skog 2017; The Church of Sweden n.d.; SCA Skog 2017; Skellefteå Kraft 2013; Sveaskog 2016).

NCM in voluntary set-asides is being carried out, even though to a smaller proportion than what would be desirable. Consequently, there should be undocumented experiences among the practitioners of NCM operations in Sweden. Given that this is management practices landowners have committed to, it is also relevant to investigate the reasons for the failure to meet set goals, i.e. why NCM is not carried out.

The aim of this paper is twofold: (1) to describe current practices for NCM in voluntary set-aside areas in Sweden and (2) to identify factors in current forestry affecting whether NCM in these areas is carried out or not.

Materials and methods

Data regarding current practices and factors influencing the decision to carry out NCM were collected by qualitative interviews, a method suitable for the mapping of less investigated fields of research (Brinkmann 2015).

Interviewee selection

When selecting interviewees, the following three selection criteria were considered:

(1) For the reliability of data, only interviewees with NCM work experience were recruited.
(2) The data needed to cover various aspects of NCM. As noted, for example, by Jensen (2003) and Erlandsson et al. (2017), practitioners' perspectives vary with the profession. Therefore, a set of interviewee profession groups was defined prior to selection.
(3) The descriptions of NCM ideals in Sweden presented by Nitare et al. (2014) identify differences in expected measures and outcomes following the natural climate borders. In Sweden, this is mainly a division between the southern broad-leaved nemoral forests and the northern boreal forests. Accordingly, interviewees' geographical area of operations had to be considered.

After summarising the criteria, eight interviewee cohorts were defined (Table 1). Interviewees were either: (a) machine operators employed by forest companies or contractor companies, the machine operators could also be contractor company owners, (b) forest managers employed at forest companies, responsible for the contact with machine operators, (c) nature conservation experts within forestry companies or (d) officials within the Swedish Forest Agency (SFA).

The initial challenge when sampling interviewees was to identify the population and the sub-populations, i.e. identifying and getting in touch with the people in each cohort involved in NCM operations in voluntary set-asides in Sweden. While profession groups c and d consist of practitioners whose professional role focus on nature conservation, practitioners in profession groups a and b could be expected to consider NCM as one among many work tasks. The entire population within profession groups c and d is smaller, a rough estimate is that they comprise 50–100 people each. Due to criteria 1 in establishing cohorts and the fact that forest organisations are not structured from nature conservation perspectives, estimating the size of profession groups a and b is complicated.

In order to gain wide representation from populations not known, a group of interviewees included in the analysis were sampled through purposive sampling (Robinson 2014). They were recruited through an advertisement posted on 25 August 2016 on the Facebook page of the Swedish Forestry Research Institute (Skogforsk), asking people with experience of NCM to contact the project leader. According to Facebook statistics, the advertisement had been viewed 15,984 times by 15 June 2018. This resulted in 23 people contacting the project leader. Applying the criteria stated above (mapping of prior work experience, professional role and geographical area of operations), 14 interviewees were recruited.

After these interviews, two methodological conclusions were drawn that led to a need for additional interviews: (1) interviewee profession groups b and c were defined differently in different companies, causing the groups to partly overlap – nature conservation experts at some companies were, for example, doing much of the NCM fieldwork and (2) more data collection was considered necessary to reach desired representation within all interviewee cohorts (selection criteria 2 and 3). Thirteen additional interviewees were therefore recruited through snowball sampling (Robinson

Table 1. Sampling matrix including the final number of interviews within each cohort of interviewee profession and climate region where she or he is operating.

	Operator	Forest manager	Nature conservation expert	Swedish Forest Agency officials	Σ
Nemoral forests	4	5	2	5	16
Boreal forests	2	1	4	4	11
Σ	6	6	6	9	27

2014). After 27 interviews, no new data were collected and data saturation (Glaser and Strauss 1967) was attained.

Interview process

Interviews were semi-structured and contained three parts: (1) a general introduction concerning the interviewee's background, current work and experiences with NCM, (2) an in-depth description of the interviewee's process regarding decisions for NCM planning/preparations, execution and follow-up/evaluation and (3) visions and ideas for future development of NCM. An interview guide (provided in the Appendix) was prepared with sets of open-ended questions for each part. The guide was mailed beforehand to most interviewees, but in two cases, the interviewee had not provided an address.

In the beginning of each interview, interviewees were promised anonymity and asked for permission to record the interview. During each interview, the interviewee was given freedom to elaborate and, if subjects particularly relevant to the aims of this study arose, these were probed more thoroughly even if they were not included in the prepared interview guide.

Interviews lasted 60–150 min. Sixteen interviews were held face-to-face and 11 were held by telephone, when requested by the interviewee. The interviewee was invited to select the interview location. Six interviews were held outdoors while walking in forests and were therefore not recorded. During these interviews, detailed notes were taken instead. Detailed notes were also taken during one telephone interview that could not be recorded due to a technical malfunction. In three interviews with machine operators and two interviews with forest managers, a colleague of the intended interviewee was present. These interviews were not treated differently, but all questions were asked to both interviewees and presented as one interview in the study.

Notes from the interviews not recorded were processed within 24 h and supplemented with remembered details to form a complete record. The recorded interviews were processed within one week. Prior to publishing the results, all interviewees were given the opportunity to read the report and check that they were not misquoted or that their anonymity had been compromised.

Analysis

The analysis of current practices (aim 1) involved entering the responses from all interviewees in an Excel worksheet divided into interviewee cohorts (Table 1). Generalisations and trends were identified and mostly presented as intervals. Due to the small number of interviewees in each cohort, groupings were done and no quantitative analysis (nor conclusions) was done.

A thematic analysis of the data, as described by Braun and Clarke (2006), was carried out to identify key factors affecting decisions regarding NCM (aim 2). This analysis was done in four steps: (1) initial coding, (2) searching for themes, (3) reviewing themes and (4) defining and naming themes. All interviewee responses were initially coded (step 1), where codes were used to accommodate that the same thing can be said using different phrasings.

After this initial coding, all codes were grouped into factors which in turn were sorted under generic themes (step 2). This process enabled patterns and general trends to be identified, thereby pinpointing the key factors affecting decisions regarding NCM. The process was iterative and, as recommended by Braun and Clarke (2006), both the coding and grouping into factors and themes were revisited (step 3). Finally, patterns in the data were identified and themes representing the entire data set were defined (step 4).

Results

All interviewees had NCM experiences from at least the past 5 years and up to 30 years, and the number of NCM activities they estimated they had been involved in over the past 12 months ranged from 0 to "a couple of hundred hectares". Even though they themselves had the experience of NCM, interviewees' assessment was that NCM currently is a marginal activity in Swedish forestry. The interviewees confirmed the assumptions in interviewee selection criteria 2 and 3, by providing information on different aspects of NCM largely based on their role in the management and their main geographical area of operations.

NCM in voluntary set-aside areas in Sweden

What is NCM in Swedish forestry?

Although the terminology varied, all interviewees clearly distinguished between two types of NCM: restoration NCM and preservation NCM. Restoration NCM was described as taking place in areas that have needed NCM for a long time, and where the conservation values are suffering from lack of NCM. A common example mentioned by interviewees was former farmland in southern Sweden where Norway spruce (*Picea abies (L.) H. Karst.*) spontaneously established when farming stopped in the 1950–1970s. The resulting increased competition for light was detrimental for the old oaks (*Quercus robur L.*) and ground flora that had been growing in these open fields, thus making removal of, the large volumes of, spruce trees urgent. Preservation NCM measures are implemented in areas where (1) there has been sufficient disturbance to maintain conservation values or (2) the original conservation values can be increased by management. Using the example above, preservation NCM would take place if grazing had ended in the 2000s, and operations would consist of removal of smaller Norway spruce and other trees in time to avoid fading vitality in the oaks and to maintain high flora biodiversity.

The interviewees did not define any explicit time frames distinguishing the two types, but the interviewed SFA officials, in accordance with agency policy, aimed to evaluate the need for management at least every 8–12 years in all preserves managed by the agency. This evaluation is to avoid preservation NCM areas deteriorating to a restoration NCM forest state. However, the evaluation frequency was not necessarily equivalent to the management frequency. One interviewee had worked under a company policy stating that NCM forests, in general, should be managed every 30 years. There was a common view among interviewees that restoration NCM, in general, should be carried out in several stages at intervals of 3–10 years depending on local conditions to minimise the risk of light shock on the remaining trees. Interviewees described removal as being less intense in preservation NCM.

In NCM carried out by the SFA, the interviewees expressed minor concerns about the costs associated with the activities. Interviewees from this group also expressed a desire to achieve a state of preservation NCM forest and maintaining this state. In forestry companies, i.e. professional groups of forest managers and nature conservation experts, the interviewees acknowledged the idea that NCM should be frequent enough to achieve a continuous preservation NCM state but admitted that this was seldom the case. The stated reason for not achieving this was the, relative to conventional management, small scale of NCM. This makes a priority of restoration NCM, where the urgency was felt to be greater and the NCM, in many cases, is also economically profitable, thanks to the removal of larger volumes of trees with commercial value.

What NCM operations are carried out?

When asked about what NCM operations are carried out, all interviewees described the same two, often concurrent, measures as making up by far the most NCM in Sweden: (1) creation of dead wood and (2) removal of Norway spruce to secure the survival of light-demanding species. This may seem an oversimplification but the interviewees generally agreed that removal of spruce is the most common measure. They also considered this activity to be sufficient, at least at the current stage when NCM is carried out to such a small extent and activities need to be prioritised.

Some interviewees acknowledged that NCM activities involved more than the creation of dead wood and removal of spruce. Apart from specific measures, e.g. felling of deciduous trees to improve conditions for a locally endangered bee species, the only other well-defined NCM measure described by the interviewees was prescribed burning.

The difference within NCM operations is basically where, when and why spruce is removed. In the nemoral region of southern Sweden, spruce is mainly removed from forested old farmland. The aim is to promote naturally occurring deciduous light-demanding trees and ground flora species, including Dutch elm (*Ulmus glabra Huds.*), European Ash (*Fraxinus excelsior L.*), linden (*Tilia cordata Mill.*), Norway maple (*Acer platanoides L.*) and oak (*Quercus robur L.*). In the boreal region (northern Sweden), spruce is removed to ensure the survival of old Scots pine (*Pinus sylvestris L.*) and naturally occurring deciduous species, mainly alder (*Alnus* spp.), aspen (*Populus tremula L.*), birches (*Betula* spp.) and willow (*Salix caprea L.*).

All interviewees were asked which NCM operations were typically not carried out. Only nature conservation experts and SFA officials expressed clear views on this matter, which can be summarized into three operational measures: (1) prescribed burning, (2) very light thinning requiring removal of only a few trees and (3) preservation NCM (as previously described) as it is not being considered as urgent as restoration NCM. However, the interviewees did acknowledge that practitioners learn how to identify and perform certain types of NCM, leading to a self-perpetuating cycle of a favoured NCM activity being the one carried out, while other measures are not.

How is NCM done?

According to the interviewees, NCM forestry in Sweden generally follows the same procedure, regardless of the measure to be carried out and location in the country. This procedure is similar to that in conventional timber production thinnings. Before the NCM activity, a forest manager from a forestry company or wood buying organisation plans the measures in the field. The planning results in both written instructions with maps and in-field markings of the important items to consider during operations that may not be evident to the machine operators.

The major difference between conventional thinning and NCM, apart from the inherent different purposes, is the level of detail in the planning of the measures and written instructions to the operators. Both machine operators and in-field forest managers stressed the need for correct instructions with sufficient detail to attain the desired results. Forest managers and operators shared the view that it is challenging to find a balance between providing specific instructions while providing leeway for the operator to, for example, select strip roads and which trees to remove. Production of an overly detailed instruction document was considered very time-consuming and its benefits questionable, since machine operators see the results of the ongoing operation and can adapt it accordingly, while a forest manager could fail to notice certain details.

When using current systems for the planning of logging operations, forest managers mark areas of interest where special attention is needed. In NCM, this kind of consideration is generally needed on much of the logging site, making planning and writing of instructions more time-consuming and detailed, if the same structure was followed. An alternative approach is to give less detailed instructions and leave more decisions to (the highly trained) operators. Achieving high quality in the operation then means that the operator requires a detailed understanding of NCM goals and practices, which increases the complexity of their already demanding task. Most forest managers preferred a less detailed instruction document and expressed that overly detailed written instructions were pointless except for in some, more complex cases. The operators, on the other hand, generally expressed a preference for more detailed in-field instructions because it lowered the complexity of their work and reduced the risk of being accused of doing something in the wrong way. Both operators and forest managers considered inconsistent levels of detail in instructions a risk leading to misunderstandings.

All interviewees agreed on the need for written instructions and, especially where less experienced operators were concerned, an in-field briefing at the start of the operation. In the cases of experienced operators and a high level of trust between forest managers and harvesting crew, the in-field visits were considered less necessary but were still frequent. The completion of 5–10 NCM operations was considered sufficient to establish an understanding for the other party's way of handling the task.

Interviewees described three typical machine systems used in NCM felling operations: (1) motor manual work with a clearing saw, (2) motor manual chainsaw work complemented by a forwarder when necessary and (3) a conventional cut-to-length harvester complemented by a forwarder. The latter is the dominating logging system in Swedish forestry. The three systems are used to varying degrees, but combinations of two or all three occur in NCM operations. In the boreal region, fully mechanised harvester systems were preferred both by operators, forest managers and nature conservation experts. In the nemoral region, a combination was preferred by several interviewees, mainly operators and SFA officials. Mainly among SFA officials, the exclusive use of clearing saw was considered desirable. In this group, an NCM stand needing harvester felling was almost considered a failure, implying that it was preservation NCM that had deteriorated into a restoration forest state. The logic in this thinking was acknowledged by all nature conservation experts but none of them worked to manage NCM stands with such a frequency that clearing saw would be the primary felling tool.

In fully mechanised NCM, all interviewees preferred large harvesters (typically 20–25-tonne machines with, ~200 kW engine and 9–11 m crane reach) over smaller ones, since there often is a need to fell large trees. However, the forwarder should not exceed mid-size (typical loading capacity 12–15 tonnes), in order to minimise strip road width, risk of damage to remaining trees and to reduce the risk of soil damage through machine weight. Especially in southern Sweden, interviewees were accustomed to felling by chainsaw to some extent. This was applied when trees were too large for the harvester or where trees could be damaged due to either being located on areas of low bearing capacity or too close to other trees.

Landowners with large holdings certified by either FSC or PEFC are obliged to annually perform prescribed burning on certain areas. Prior to burning, certification schemes allow, and under certain conditions recommend, removal of biomass to attain the desired development of the fire and also to partly finance the costly measure. The certification aims for prescribed burning are seldom met. The interviewees involved in these tasks, mainly nature conservation experts and SFA officials, agreed this was an unsatisfactory situation but considered it difficult to solve, since controlled, i.e. safe and purposeful, burning is heavily dependent on specific weather conditions and is therefore difficult to plan.

Three different payment models to contractor companies for NCM services were defined by interviewees: a pre-negotiated fixed sum for a specific NCM measure, an agreed hourly rate or a piece-work rate. The latter was normally a sum paid per cubic metre harvested or area thinned with a clearing saw. SFA officials exclusively relied on the fixed-sum model, while 16 of the 18 remaining interviewees applied the hourly rate. Only two interviewees were accustomed to piece-work rates, which is otherwise the most common payment model for contractor services in conventional forestry operations.

Who executes NCM?

The interviewees reported that a key challenge is that NCM operations differ from conventional forestry and require slightly different skills, so the selection of operators for NCM activities is important. Forest managers and nature conservation experts, who are responsible for deciding on which operators to assign, described two approaches for handling this issue, but none were satisfied with their current solution. Half of them relied on dedicated NCM operators, arguing that not all operators are suited for and interested in this kind of work. This strategy is intended to promote high quality in NCM operations but was considered to increase costs, mainly due to the risks for increased relocation costs, decreased flexibility and reduced capacity to perform NCM operations. The other half wanted almost all operators to perform NCM, arguing that it increases flexibility and reduces costs, since NCM stands are often managed in conjunction with conventional thinning operations in neighbouring stands. For the latter solution, a balance was needed between the risk of reducing the quality of NCM operations and increasing the costs associated with ensuring that all operators attain the required skills. All respondents agreed on two points: for the most complicated operations they tended to rely on the most experienced operators, and they did not consider all operators to be suitable for NCM. Even in companies where the intention was to include every operator, some operators were not used for NCM operations.

When is NCM carried out?

In mechanised NCM, i.e. operations involving harvesters and forwarders, the interviewees preferred the activities to be carried out in late summer, commonly August–September, and to some extent during winters when there are good ground conditions with little snow cover and frozen soil, mainly January–March. The reason for this short time period is that there are many restrictions for when NCM is best carried out or even allowed.

Firstly, forest certification schemes state that NCM is not allowed during bird nesting, which occurs at different times for different species and different regions, but generally covers all the spring period between March and June. Secondly, the soil must not be damaged during NCM, which all interviewees but one nature conservation expert considered to be the most important aspect in NCM operations. The expert with a deviating view argued that a small disturbance to the topmost soil layer could be beneficial for biodiversity. Regardless of the level of assigned importance, the risk for soil damage fully disqualifies seasons when the general bearing capacity is low due to thaw or heavy rainfall, i.e. early spring and autumn. The exact times for this vary greatly between regions and years, but affect large parts of the periods February–April and September–December. The interviewees all pointed out that temporary rains during dry seasons are also a reason to halt operations requiring heavy machinery. Thirdly, some interviewees regarded snow-covered ground as a limiting factor for NCM, since objects on the ground, e.g. creeks or sites of cultural heritage, might not be noticed and subsequently risk being damaged. Three interviewees (one operator and two SFA officials) preferred winter over late summer, seeing of it as the best way to avoid ground damage. As July is normally the vacation period in Sweden, August and early September was generally considered the ideal season for NCM.

Factors affecting NCM decisions

The interview data helped identify several factors affecting whether NCM operations are implemented. When the factors were sorted into themes, and divided into barriers vs. incentives for NCM activities, there were substantially more barriers, and these were also mentioned more frequently (Figure 1).

Barriers to NCM

Physical conditions. The physical condition of a stand has a large influence on when NCM can be carried out. As previously developed, the best and, in many cases, only possible time of the year for NCM involving heavy machinery is August–September. This coincides with a season when forest industries depend on a large and reliable inflow of roundwood. This demand is difficult to meet in NCM stands where machine productivity is normally lower than in conventional operations. This situation was mostly emphasised by interviewees with timber supply commitments, i.e. forest managers and operators who also owned contractor companies.

Personal incentives. Performing NCM was considered to require a slightly separate set of skills than conventional forest management. Most operators and forest managers have theoretical knowledge on the aims of NCM and often a general understanding of what measures are needed to fulfil the aims. What distinguished the skilled forest managers was understanding, attained through own experience, of how to design NCM operations. The forest managers lacking practical NCM experience are accordingly stuck in the dilemma that performing NCM requires them to previously have performed NCM.

NCM operations were also considered to require more work time per unit (area or per harvested cubic metre), which are the most common key indicators in monitoring performance of operators and forest managers in Swedish forestry. The interviewed forest managers estimated that the pre-operational planning of a typical NCM operation requires three to five times more time per unit compared to a conventional thinning operation. Operators estimated that time consumption in NCM operations is between 10 and 50% higher than conventional operations. In all forest companies, there were individual NCM goals for all employed operators and forest managers. These goals were expressed either in total area, number of stands or harvested timber volumes associated with NCM. Exceeding goals was not rewarded in any way in any of the represented forest companies. Since NCM is time-consuming, the interviewees considered both reaching and exceeding NCM goals a risk of lowering their ability to reach other goals, e.g. productivity or profitability. In the case of contractors, i.e. most operators, high productivity was also considered a crucial metric in negotiations for extended contracts. Consequently, the general opinion among both operators and forest managers was that the existing pricing models do not provide an incentive for operators to develop their NCM skills. However, two of the operators considered themselves highly specialised, by having the skills and the trust of the customer company to perform high-quality NCM operations; these interviewees, therefore, perceived some freedom to prioritise NCM quality over productivity.

Costs and revenues. Many interviewees, mainly forest managers and nature conservation experts but also some SFA officials, perceived the costs and revenues for NCM difficult to estimate, and felt restrained by this uncertainty due to the risk of costly operations returning a negative net profit. Where interviewees had actual experience of this uncertainty, or merely anticipated it, many of them considered this a limiting factor. Some considered they had performed certain kinds of NCM operations often enough to be able to better estimate the profitability in similar operations. However, this was not thought to improve their ability to estimate the profitability of other kinds of NCM operations.

Criticism. All interviewees were familiar with the effect of forest certification on NCM. Both FSC and PEFC certification schemes require a management plan for all forest stands, both conventional and NCM stands. This plan is established and reviewed regularly. The plan contains general descriptions of what NCM activities are to be carried out, leaving the details of exactly when and how the management is carried out to later stages. Considering that effects on biodiversity are mostly long term and thereby cannot be captured in a conventional short-term follow-up, interviewees said that it was difficult to prove that the NCM would have the targeted effect. This causes a situation where the interviewees considered themselves less motivated to perform NCM because the risk of being criticised for not having chosen the right/optimal NCM measures, due to either earlier experience of criticism or simply anticipation of criticism. The criticism, experienced or anticipated, could be received both from internal actors such as nature conservation experts in companies or from external actors, such as private landowners or environmental NGOs.

Incentives for NCM

The personal commitment was considered the most crucial factor for NCM. All interviewees reported that successful NCM requires at least one person to be deeply committed to NCM in the management chain, from strategic decisions to the operative activities being carried out. The common view was that this person could be situated anywhere in the chain, but there were no examples of machine operators being the driving force. The dedicated person spreads knowledge about NCM operations to others in the chain. With time, this can potentially extend even further, as many of the interviewees had learnt about NCM from one such committed individual and had themselves later taken the driving role to promote NCM. In the rare instance that an NCM chain contained two such committed individuals, the experience was that the magnitude and quality of NCM was increased.

Figure 1. Factors and overarching themes presented by interviewees affecting decisions on whether or not to perform NCM.

All forest managers and nature conservation experts had experiences where NCM operations had been economically profitable, such as when performing restoration NCM operations and where large volumes, mainly spruce, had been harvested. Government subsidies are available for NCM (SFS 2010:1879), administered by the SFA. These subsidies are intended to promote NCM operations in areas containing high conservational values. The forest managers and nature conservation experts were the professional groups with first-hand experience of the subsidy process. Only one of them considered the subsidies as substantial incentives for NCM. The others considered the application process overly time-consuming, and that it was difficult to predict whether a certain NCM operation would be granted a subsidy. The subsidies therefore only have a minor incentivising effect on the decision to perform NCM activities.

Both the FSC and PEFC certification standards state that management must be applied in accordance with the adopted management plans. Certificate holders' compliance with the standards is audited, and failure to perform NCM operations could be considered a deviation from the commitment. None of the interviewed forest managers, who make the final decision on which NCM operation to perform, had experience of criticism from the certification organisations for lack of NCM. However, among nature conservation experts, there were experiences of this kind of criticism from the certification organisations.

Discussion

The interview data suggest that NCM of voluntary set-asides is a small part of Swedish forestry practices but a large part of the industry's contribution to the conservation of biodiversity. According to the interviewees, NCM in Sweden aims to create dead wood and promote old, domestic deciduous trees and pine trees through the removal of spruce trees. The removal of spruce is a way to return to a historically more common forest state (Lindbladh et al. 2014), e.g. beneficial for ground-level biodiversity (Brunet et al. 2011). The procedure for NCM is similar to conventional thinnings in cut-to-length forestry, but requires more time spent in planning by forest managers and during execution by operators. Decisions on implementing NCM activities are surrounded by few incentives and many barriers. Incentives comprise requirements from certification standards and the dedication of individuals. Barriers can be attributed to the combination of four themes: (1) the short time span in each year suitable for the tasks, (2) the lack of incentives to invest the resources needed, (3) experienced or anticipated risk for costly operations and (4) experienced or anticipated criticism.

The aim of the study was to perform an initial mapping of practices and reasoning among practitioners. Both interviewee sampling and interview design were adapted accordingly. The choice of a purposive sampling (i.e. non-random sampling) has been found suitable for recruitment of knowledgeable interviewees (Patton 2005). Sampling through advertisement was used to attain wide representation in an unknown population. Semi-structured interviews with much freedom for the interviewee to elaborate are helpful to collect a broad span of data (Brinkmann 2015). Enabling the experts to elaborate, using their own words, reduced the risk of the data becoming only the interviewer's interpretation, a risk identified by Braun and Clarke (2006). Data saturation as defined by Saunders et al. (2018) was attained and it is thereby reasonable to assume that the study has identified most practices and decision themes. The weakness in both sampling and interview design, as is the inherent risk in qualitative study designs, is regarding validity (Kvale 1989) and reliability (Miles and Huberman 1994). The variations in setup between interviews added an element of uncertainty, a type of uncertainty mainly hindering quantifications of interviewee answers, and comparisons between cohorts. The main objective of the study was, however, not to perform quantifications and this loss was considered less important than the risk of not capturing certain practices or themes, which might have happened if the design had been more rigid. Furthermore, the fact that interviewee populations were largely unknown once more highlights the issue of reliability. It could be that the predefined cohorts are lacking, and other cohorts would be preferable. While the use of profession and geographical area of operation cohorts has been used in interview studies of forestry (cf. Jensen 2003; Raymond et al. 2009; Keskitalo and Liljenfeldt 2014; Erlandsson et al. 2017), no prior studies were found with an aim sufficiently similar to the present study to provide guidance regarding cohort design. The presented results are therefore not to be seen as complete mappings but rather descriptions of common themes regarding practices and reasoning in NCM operations. The recommendation for further investigations of NCM operations is to focus on certain themes and adapt the methodology accordingly.

Earlier studies have reviewed the reasoning behind decisions made by forestry professionals (cf. Hugosson and Ingemarson 2004; Erlandsson 2013; Erlandsson et al. 2017; Young et al. 2018) and descriptions of conservation forestry activities (cf. Götmark 1992, 2013), respectively. The contribution of this study is to expand the studies of forestry professionals reasoning into the field of nature conservation. The results were obtained using thematic analysis, a method not commonly used in the field of forestry but common in other fields, e.g. the article presenting the analytic framework by Braun and Clarke (2006) had according to a search on Scopus by 2 September 2019 been cited 28,045 times. The choice of a data-driven analysis was considered suitable in a less investigated field. The use of a more rigid method risks to limit the analysis and causing important aspects to be overlooked.

It was not clear whether the general and simplified task of removing spruce is a generalisation applicable to all available NCM or if it was limited to the areas that were treated. It could be that the interviewees had slightly confounded the need for NCM with what is actually being carried out, which in many instances is the removal of spruce. On the other hand, there is a reason for this emphasis on spruce. Spruce is a late-successional species that has become more frequent in Sweden over a long time period (Lindbladh et al. 2014). Subsequently, there is a need to remove late-successional species in certain areas, while in areas containing values associated with late-successional tree species, there is often no need for management (Pickett and White 1985; Attiwill 1994). In Sweden, there are several naturally occurring late-successional tree species but the most common is spruce, and in the northern parts of the country, it is the only one (Nilsson et al. 2017).

Interviewees' division of task into restoration NCM and preservation NCM can both be considered rehabilitation of forested areas, using the terminology presented by Stanturf et al. (2014). This indicates that even though management may be needed, it is still on the end of the scale where it is possible to attain forests with high conservation values within a reasonable time frame and at relatively low costs.

Primmer and Karppinen (2010) found that forest professionals' decision to engage in biodiversity conservation was determined by the individual's habits and professional norms. This kind of reasoning was found also in the present study, being one among the many factors presented by the interviewees.

Interviewees refrained from NCM due to anticipated or experienced high costs while payment for services in most cases was based on hourly rates. This payment model places the economic uncertainty on the buyer of services rather than on the contractor company. The stated reason for preferring this payment model was that no contractor should be pressured to reduce conservation ambitions due to economic restrictions. It could be the case that the subsequent uncertainty on the buyers' side is part of the uncertainty contributing to decisions not to implement NCM. For conventional thinnings, there is much research on the costs of operations (cf. Brunberg 1997, 2004; Nurminen et al. 2006), and annual statistics of average costs (Christiansen and Eliasson 2018). There are fewer studies on non-conventional operations (cf. Niemistö et al. 2012; Grönlund and Eliasson 2019) and purely conservational treatments (cf. Santaniello et al. 2016). Costs of NCM operations have not been examined in this study, but the interviewees indicated that costs vary widely, where complex NCM requires more resources and skills while some NCM is straightforward and costs are easily estimated.

In the large forest companies represented among the interviewees, the costs associated with NCM were handled locally. As for ordinary treatments, all units must bear the costs of NCM. The short-term (local) profitability of NCM is in many cases small or possibly negative. It could be argued that the costs should be accounted at the same organisation level as the revenues. NCM is a requisite for the production of certified wood products, which enables the increased value of company end-products. NCM, along with certification could be argued, mainly is intended to increase the value of the company trademark (Johansson 2013). Referring the costs to departments gaining from NCM (i.e. marketing or sales departments) might create better incentives and possibly increase the extent of NCM.

The interviewees highlighted the lack of resources (sorted into the theme "time and effort") as a barrier to NCM. This could also be a result of the low priority given to NCM operations. Forest managers are generalists with broad responsibilities, requiring knowledge about silviculture, forest technology, wood supply, logistics, business management and ecology. If a forest manager has special knowledge and commitment in one topic, they will probably invest more energy into that part of the management, with the risk of lower quality in other aspects if resources are limited (Pregernig 2001). Operators and contractor companies also face this type of balancing. As seen in similar conditions by Erlandsson et al. (2017), contractor companies are likely to specialise in areas that are appreciated by the customer. The interviewed operators were committed to NCM, and admitted that this interest might have a negative effect on their productivity in conventional timber-focused operations.

The combination of weak incentives for reaching NCM goals with no bonus for those exceeding them will inevitably create a situation where company goals are not reached. Since forest managers have different preferences, many of them will underachieve on NCM goals.

Interviewees in the present study did not consider applying for NCM subsidies worth the time. An evaluation of the SFA subsidy (Roth et al. 2015) supports this finding. The analysis, however, found that only one-fifth of the operations would have been carried out had the subsidies not existed. This conclusion differs from the present study, possibly since Roth et al. (2015) sampled among those who had applied for subsidies while interviewees in the present study in many cases refrained from applying. Even though it is not stated, the subsidies appear to mainly target small-scale forest owners, at least in practice. Small-scale private forest owners received 79% of the subsidies and the median amount in 2012–2015 was SEK 3640 (roughly €350), an amount possibly considered insufficient to incentivise efforts in applying from forest managers.

The criticism that interviewees anticipated or had experience of was, in many instances, related to performing what by someone might be considered the "wrong" NCM operations. This is difficult to avoid, since it is rarely only one conservation value that is considered in NCM operations and there is no "correct" design of NCM operations (Lindenmayer and Franklin 2002). Addressing this kind of criticism is also a problem, since effects of the measures may not be seen until long after the operations have been carried out; the criticism is often directed years before a fair evaluation of the operations can be made. This reinforces the need for an open debate regarding NCM, a debate refraining from "blame games" and instead striving for high-quality NCM operations that balance the various aims involved.

Even though the interviewees considered NCM operations as being a small part of Swedish forestry, no data were presented as to the actual extent of current NCM efforts. The best estimates are that there are 1.2 Mha voluntary set-asides in forests, of which 0.4–0.5 Mha are intended for NCM (Claesson and Eriksson 2017; Grönlund et al. 2019). In addition, formal preserves constitute ~1.0 Mha productive forest land (Statistics Sweden 2017) and retained areas are 0.4 Mha (The Swedish Forest Agency 2019), of both which an unknown proportion is intended for NCM. Assuming the same proportion as in voluntary set-asides, 0.4 Mha of formal preserves and 0.15 Mha retained areas could, therefore, be intended for NCM. Based on rules of thumb presented by the interviewees, each stand intended for NCM need treatment, on average, every 20–30 years. Consequently, a conservative estimate is that NCM operations are needed on 30,000–35,000 ha in Sweden every year. As a point of reference, ~400,000 ha are commercially thinned and 200,000 ha clearcut in Sweden every year (Nilsson et al. 2017).

The scope of the study has been voluntary set-aside areas aimed for NCM in Sweden, both among large state and industrial forest owners as well as non-industrial private forest owners (respectively accounting for ~40 and 50% of the Swedish forest land). Though there are differences, the results have applicability both in formal preserves aimed for NCM and in countries with forest types and natural disturbance regimes similar to Swedish conditions.

Conclusions

This study indicates that, in Sweden, the most common NCM operation in voluntary set-asides is the removal of spruce, carried out in a process similar to conventional thinning. Such operations are performed by dedicated individuals through their own commitment, but this can be restricted by the uncertainty created when their organisation prioritise other goals. The study was on NCM in voluntary set-asides in Sweden, the results do, however, have applicability in other areas aimed for NCM (e.g. retained areas and formal preserves) and countries with forest conditions similar to Sweden. Based on the findings, a set of managerial implications for NCM operations can be identified: (1) There must be incentives to carry out NCM operations if they are to be increased; (2) NCM operations that are not carried out in late summer will probably be deferred until a year later if they involve heavy machinery; (3) basic NCM operations are easily carried out, if adequate instructions are given; (4) NCM operations could be increased if there was a separate, not necessarily larger, budget for these tasks; and (5) identified key actors knowledgeable about NCM sharing their expertise with a relatively small group could contribute to a substantial increase in NCM operations.

This study indicates that NCM operations must be promoted if Swedish conservation targets are to be met. The results presented suggest that future work aimed at increasing the extent of NCM in Sweden should focus on three topics: (1) development of organisational incentives promoting NCM in voluntary set-asides, (2) increase knowledge about costs and revenues in NCM and (3) investigate the actual causes and extent of criticism directed toward those involved in NCM.

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Appendix. The interview guide used during the interviews. The original guide was in Swedish and included a cover sheet explaining the purpose of the project.

1. PRESENTATION OF THE INTERVIEWEE AND IT'S ORGANIZATION

What is your role within the organization and how do you work with NCM?

How many in your organization/company/district work with NCM?

How large is the NCM areas you treat annually?

What type of NCM do you perform? Is it possible to generalize stands and measures, where it is carried out?

Are there key figures in your follow-up of NCM measures?

How much information is exchanged between actors engaged in NCM?

Do you refrain from any type of NCM?

2. THE NCM PROCESS – WHAT IS DONE, AND HOW?

2.a. Planning

Who plans NCM measures and how is the planning done?

What level of detail is used in planning? Are generalisations applied?

What goals/aims are set for the execution of NCM?

2.b. Procedure

How is the procedure for execution of NCM decided? And how are operators/operation teams/contractors chosen?

How is time of the year for operations chosen? Who decides when to halt/pause operations?

What technical solutions (motor manual and mechanized) are applied and what advantages and disadvantages do you see with them?

How is it decided whether operations are to be mechanised or carried out motor manually?

Do you balance nature conservation benefits and the operation economics in NCM?

What are the major operational challenges in NCM?

2.c. Follow-up procedures

How is the follow-up of the measures done?

What performance metrics are used, if any?

How are entrepreneurs being paid, is this a satisfactory payment model?

3. FUTURE – WHAT SHOULD THE FUTURE NCM COMPRISE?

What development potential do you see in planning NCM measures?

Based on today's execution, what are the major challenges, and can you think of technical solutions that handle/reduce this problem?

Does the current follow-up capture the quality of the measures?

III

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Birch shelterwood removal – harvester and forwarder time consumption, damage to understory spruce and net revenues

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ABSTRACT

To improve the micro climate for Norway spruce (*Picea abies* (L.) Karst.) regeneration and achieve higher growth, a system of birch shelterwoods with naturally regenerated birch (*Betula* spp.) creating an overstory sheltering planted spruce is implemented in southern Sweden. Even though the primary objective is to establish a new spruce stand, the economic viability depends on efficient birch overstory harvest with little damage to spruce regeneration. This study aimed to analyze time consumption and net revenues for harvester and forwarder work when removing the birch overstory, and to describe the frequency of logging damage in the residual spruce stand. Time consumption data was collected through time studies of harvesting and forwarding of 10 study plots. Sample plots were inventoried after harvesting and forwarding operations to identify damage on the residual spruce. Average harvester productivity was 2.8 oven dry ton per efficient work hour. The variation in time consumption was up to 94%, explained by a positive correlation with the number of trees harvested per hectare and a negative relationship with removed volume per hectare. Forwarder loading time correlated with forwarded volume along the strip road and the number of birch trees per ha prior to logging. Approximately 7–17% of the residual trees were damaged, and the harvester caused 83% of the damage. Due to high harvesting costs and low revenues, only plots with large removals provided positive net revenues. Birch shelterwoods can therefore not be expected to increase net revenues but are best seen as a regeneration method for addressing stand re-establishment challenges.

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Introduction

Final felling in even aged stands is the starting point of a new forest generation and subsequent reforestation. In Sweden, planting was the reforestation method of choice on 73% of the area felled during 2003–2009 (Fries et al. 2013), and the second largest reforestation method is natural regeneration through seed trees, shelterwoods or existing seedlings (22%) (Nilsson et al. 2017). Of the planted area, 49.8% was planted using Norway spruce (*Picea abies* (L.) Karst.) seedlings and 45.6% using Scots pine (*Pinus sylvestris* L.) seedlings (The Swedish Forest Agency 2017).

In spruce stands, an alternative to the conventional practice of removing all birch (*Betula* spp.) plants in the pre-commercial thinning stage, is to reduce their numbers and exploit the fast growth of the birch trees to establish an even-aged two-storey shelterwood stand. Shelterwoods reduce spruce mortality e.g. by reducing competing ground vegetation (Johansson 1990), reducing the risk for frost damage (Ottosson Löfvenius 1993) and reducing pine weevil (*Hylobius abietis*) damage on seedlings (von Sydow and Örlander 1994). Furthermore, two-story spruce-birch stands have a higher volume production compared to spruce monocultures (Tham 1988; Mård 1996; Fridley 2001).

Birch shelterwoods have been introduced mainly to address the challenges posed by reforestation in frost prone areas, but also to exploit the apparent qualities of shelterwoods. Johansson (1992) presents the general concepts that have been implemented in Sweden:

(1) Simultaneous establishment of birch (through natural regeneration) and planting of 2000–2500 spruce ha^{-1};
(2) Pre-commercial thinning of birch to attain 3500 stems ha^{-1} at 3–4 meters of height;
(3) Pre-commercial thinning of birch to attain 1100–1600 stems ha^{-1} at 6–9 meters height; and
(4) Removal of the birch shelterwood when it reaches 8–12 meters height to establish a single-story spruce stand.

There are several challenges in birch shelterwood management, both economical and operational. Firstly, the added pre-commercial thinnings and the early thinning in which the birch shelterwood is removed are both time consuming and expensive. Secondly, operations must be carried out within a short timespan to minimize growth losses in the spruce understory, caused by overstory light competition (Johansson 1990) and whipping of spruce top shoots (Frivold 1982). Thirdly, the removal of the birch trees should preferably produce sufficient profits to justify the costs of the pre-commercial thinning operations. Fourthly, damage to the residual trees caused by the logging operation must be minimized so as not to impair future growth and revenues.

However, there are few studies of harvester and forwarder productivity when removing the birch overstory or the economic outcome of this logging operation.

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Niemistö et al. (2012) investigated the impact on harvester and forwarder productivity for removals of birch overstories where the understory was retained to different degrees. However, there have also been studies of felling of high shelterwoods (Fjeld and Granhus 1998; Eliasson et al. 1999; Sikström and Glöde 2000; Granhus and Fjeld 2001; Surakka et al. 2011), thinning from above (Jäghagen and Lageson 1996; Lageson 1997) and energy removals in early thinning (Laitila et al. 2016) that all provide some knowledge of relevance also for birch shelterwood harvesting operations.

From a forest management standpoint there is a need for better knowledge on harvester and forwarder productivity, logging costs, and logging damage to the residual spruce stand to improve the decisions of when and where it is justified to use the birch shelterwood method.

This study aims to increase the knowledge on the removal of the birch overstory by analyzing time consumption and subsequent net revenues for harvester and forwarder work and assessing the frequency of logging damage in the residual spruce stand.

Materials and methods

Studies of harvesting and forwarding were carried out on 10 study plots in six forest stands in Southern Sweden. The time studies were made during daylight conditions in May and June 2014 (six study plots), May 2016 (two study plots) and November 2017 (two study plots). In all operations, medium-sized harvesters and forwarders were used but there were different machines and operators in different years (Table 1).

All study plots had been planted with spruce and contained an equally old overstory of naturally regenerated birch. Harvester operators were instructed to remove all birch trees except in spots without understory spruce. In patches with dense spruce, the crop was thinned in accordance with conventional instructions, i.e. to achieve a stand with 1300–1600 spruce trees ha^{-1} post thinning. Due to differences in market conditions and stand characteristics, both whole tree bioenergy and pulpwood assortments were produced on study plots treated in 2014 while only pulpwood assortments were produced on the study plots treated in 2016 and 2017. The harvester sorted the assortments in piles and forwarding was done for one assortment at a time.

Prior to harvest, 50–123 meters (m) strip roads in homogenous birch shelterwood areas were marked in the field. The harvested area along each strip road was regarded as a study plot. The width of the plot equalled the working width of the harvester, on average 17.3 m. This resulted in study plots ranging between 0.08 and .23 ha. To describe the stands, 4–6 sample plots covering 23–49% of the study plots were placed systematically using a random starting point. In these 100 m^2 sample plots, diameter at breast height (dbh) and tree species was recorded for all trees with dbh ≥ 4 cm, i.e. all trees viable for whole-tree harvest. The number of trees with dbh < 4 cm on each sample plot was recorded. In each sample plot, height was registered on 5–10 sample trees per species, covering all occurring diameter classes. Birch height sample trees were selected in all sample plots, but spruce heights were sampled only in study areas where a commercial removal of spruce would be done. In the remaining study plots, average spruce height was estimated. The observed diameter-height relationship from all sampled trees was used to estimate heights of remaining trees in the sample plots (Table 1).

In 2014, damage to residual trees were inventoried on six 50 m^2 sample plots in each study plot (Figure 1) both after harvesting and forwarding. In the sample plots, dbh, species, height and damage were recorded for all trees. Damage was classified into "broken top" and "other." Damage observed after harvest was marked to avoid being counted again after forwarding. In 2016–2017, rows of 2 by 2 m plots perpendicular to the strip road were inventoried at every 8 m alternating between the sides of the strip road (Figure 1). Dbh, species, height, distance to nearest cut tree, distance to strip road and vitality was recorded for all trees. The cause, type and magnitude of all damage was registered according to Table 2, which is a modification of the thinning damage classification scheme presented by Granhus and Fjeld (2001).

Continuous time studies of harvesting and forwarding were done using an Allegro hand-held computer running SDI Skogforsks time study software. At all study occasions, harvester work was split into seven work elements (Table 3) and forwarder work was split into 11 (Table 4). If more than one work element was performed simultaneously, the work element with the highest priority was recorded. All elements were measured as effective times (E_o). In the analysis of harvester work elements, boom out, felling, boom in and processing are summed to boom cycle time. In the analysis of forwarder work elements, boom out, gripping, rearrangement on ground, boom in, release and rearrangement in bunk and movement while loading were summed to loading time. Delay times were recorded but not included in the analysis. Due to disturbances caused by the scaling of the loaded forwarder, no analysis was done of driving with and without load or time consumption in unloading.

The harvested biomass was scaled while unloading the forwarder at the landing. On plots harvested in 2014 this was done using a strain gauge crane tip scale (Intermercato WX 70 BS) while on plots harvested in 2016–2017, mobile truck scales (Palmenco EVOCAR-2000) were used to weigh both the loaded and tare weight of the forwarder for each load. Moisture content (M) was calculated through 12 representative biomass samples per species and stand studied. The samples were dried in 104ºC until constant mass in accordance with ISO 18134–1:2015 (Swedish Standards Institute 2015) whereafter dry mass was calculated as scaled weight of the harvested biomass multiplied by (1-M). The average moisture contents from the samples were considered valid for the volumes harvested in each stand.

Data analysis

Time consumption per oven dry tonne were analyzed with an ANCOVA model using proc GLM in SAS. In all analyses, removal method (R) was used as a factor with two levels (pulpwood operation and combined operation). As plot mean values were used in the analyses total degrees of freedom is limited, which in turn limits the possible number of fixed factors and covariates. Covariates were selected based

Table 1. Characteristics of study plots before harvest and harvest data for the study plots. Denotation d_a = arithmetic mean diameter and d_{ba} = basal area weighted mean diameter.

Characteristic		Study plot 2014.1	2014.2	2014.3	2014.4	2014.5	2014.6	2016.1	2016.2	2017.1	2017.2
Stand age	Years	25	25	25	14	14	14	16	16	N/A	N/A
Prior pre-commercial thinnings	N	0	0	0	1	1	1	1	2	3	3
Birch											
Trees*	n ha^{-1}	2325	2125	2225	2475	1925	2775	1350	1650	880	450
d_a	cm	10.5	8.6	7.8	7.1	7.3	7.3	12.0	10.1	9.3	9.4
d_{ba}	cm	12.7	10.2	9.5	7.0	7.8	6.9	12.8	10.9	9.8	9.9
Average height	m	12.6	12.0	11.7	9.1	9.4	8.9	12.9	12.3	10.0	10.0
Standing volume	m^3 ha^{-1}	133	84	74	51	46	61	94	90	32	17
Spruce											
Trees[a]	n ha^{-1}	3525	3000	4450	2050	1725	1500	1533	1350	2640	2575
Average diameter	cm	6.2	7.2	7.6	4.8	4.1	4.2	5.7	6.1	8.9	8.7
Average height	m	6.8	8.1	7.6	4.5	4.2	4.3	5.2	6.3	8.8	8.8
Operations											
Harvester		Valmet 901.4	Valmet 901.4	Valmet 901.4	Valmet 901.4	Valmet 901.4	Valmet 901.4	John Deere 1070	John Deere 1070	Gremo 1050h	Gremo 1050h
Harvesting head		SP 250	SP 250	SP 250	SP 250	SP 250	SP 250	H754	H754	SP 561	SP 561
Forwarder		John Deere 810	John Deere 810	John Deere 810	John Deere 810	John Deere 810	John Deere 810	Ponsse Elk	Ponsse Elk	Gremo 1050f	Gremo 1050f
Removal											
Trees harvested[b]	n ha^{-1}	5126	3447	4789	3403	2960	2886	1547	1735	1950	2108
Pulpwood removal	odt ha^{-1}	47.55	20.50	14.58	8.95	13.61	5.37	47.28	44.07	8.10	9.14
Energywood removal	odt ha^{-1}	19.49	9.20	11.87	13.33	13.03	14.06	-	-	-	-
Trees harvested per crane cycle	n	1.79	1.82	2.33	2.78	2.59	2.73	1.23	1.26	1.42	1.45
Gross revenues	€ ha^{-1}	4314	2069	1732	1219	1549	987	3473	3238	595	672
Logging costs	€ ha^{-1}	3586	2353	2622	2299	2017	1880	1822	1790	1282	1413

[b]All diameters.
[a]Diameter breast height ≥ 4 cm.

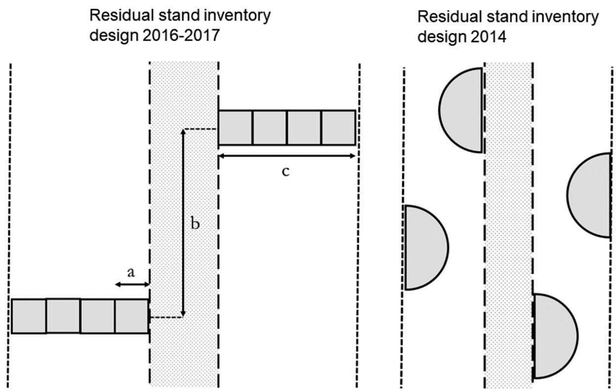

Figure 1. Residual stand and damage inventory design. Darker grey areas represent sample plots, bright grey areas represent strip road while the outer lines are study area edges. a = 2 m, b = 10 m and c = 8 m.

Table 2. Vitality and damage classification scheme used in the 2016 and 2017 damage inventories.

1. Damage type	**Damage severity**
1.1. No damage	Uninjured
1.2. Stem damage, bark injury	
a. 5– 20 cm^2	Damaged
b. > 20 cm^2	Severely damaged
1.3. Broken top	
a. Mainly top broken	Severely damaged
b. Top shoot broken but new top visible	Severely damaged
c. Top shoot broken and no top visible	Severely damaged
d. Stem broken lower than 50% of the height	Severely damaged
1.4. Crown reduction	
a. 10–30% of branches missing	Damaged
b. > 30% of branches missing	Severely damaged
1.5. Partial uprooting/leaning	
a. > 10 degrees leaning	Severely damaged
2. Damage cause	
2.1. Machine movement (mainly tires)	
2.2. Felling damage caused by crane or felling head	
2.3. Collision by tree/dragging of felled trees	
2.4. Unknown/miscellaneous	

Table 3. Harvester work elements used in the study. The time for the highest prioritized work element was recorded if multiple work elements were performed simultaneously.

Work element	Priority	Definition
Boom out	2	Starts when the harvest head is moved towards a tree, ends when an element with higher priority starts or the movement stops.
Felling	1	Starts when the harvest head is within 1 m of the first tree to be cut and ends when the last tree in the crane cycle has been cut.
Boom in	2	Starts when the harvest head, while holding a tree(s), is moved towards the machine and ends when an element with higher priority starts or the harvest head is opened and let go of the tree(s).
Processing	1	Starts when tilting of the harvest head is initiated and ends when last log is cross-cut.
Movement	3	When the harvester wheels are moving
Miscellaneous	4	Productive work elements that do not belong to any of the elements above specified.
Delay		Non-productive time, not included in the analysis.

on earlier studies on harvesting and forwarding (e.g. Brunberg et al. 1989; Kuitto et al. 1994). For analyses of

Table 4. Forwarder work elements used in the study. The time for the highest prioritized work element was recorded if multiple work elements were performed simultaneously.

Work element	Priority	Definition
Boom out	2	Starts when the crane is set in motion towards the pile about to be collected.
Gripping	1	Starts when the grapple is within 1 m of the pile, ends when the grapple is closed.
Rearrangement on ground	1	Starts when grapple is initially closed, ends when crane movement towards the machine is initiated.
Boom in	2	Starts when crane is set in motion towards machine, ends when the grapple is above the load carrier.
Release and rearrangement in bunk	1	Starts when the grapple is above the load carrier, ends when an element with higher priority starts or the crane no longer moves.
Movement while loading	3	When the forwarder wheels are moving during loading.
Movement when loaded	3	When loading is completed, i.e. there is no more crane movement prior to unloading, and the forwarder wheels are moving.
Un-loading	2	Starts when the loaded forwarder is on landing and the crane is moving to unload.
Movement empty	3	When the forwarder is moving towards the stand, the load carrier is empty and there is no crane movement.
Miscellaneous	4	Productive work elements that do not belong to any of the elements above specified.
Delay		Non-productive time, not included in the analysis.

harvester time consumption (T_H), harvested biomass ha^{-1} (B) and harvested number of trees ha^{-1} (N) were used as covariates resulting in the following statistical model:

$$T_H = b_0 + R + b_1 \times B + b_2 \times N + \varepsilon \quad (1)$$

where b_x are constants and ε the error term. For analyses of time consumption for pulpwood loading during forwarding (T_{FP}), harvested pulpwood biomass per 100 m of strip road (B_p) and harvested number of birch trees ha^{-1} (N_b) were used as covariates resulting in the following statistical model:

$$T_{FP} = b_0 + O + b_1 \times B_p + b_2 \times N + \varepsilon \qquad (2)$$

Analyses of time consumption in biomass forwarding (T_{FE}) was made using a similar regression model with the influencing variables harvested energy biomass per 100 m of strip road (B_e) and N_b.

Analysis of damage was done in two stages. Firstly, chi-square goodness of fit tests were done to assess damage frequency in relation to distance to strip road. For the 2014 data distance classes were "bordering strip road" and "bordering plot edge." In the 2016/2017 data, distance classes were: 0–1.99 m, 2–3.99 m, 4–5.99 m and 6–7.99 m from strip road edge. Further analysis of the 2016/2017 data was done using an ANOVA with average damage frequency in sample plots (I) as response and distance to the nearest harvested tree (D_h), height of the tree (H) and distance of the sample plot to the strip road (D_s) as factors:

$$I = b_0 + D_h \times b_1 + H \times b_2 + D_s \times b_3 + \varepsilon \qquad (3)$$

All statistical analyses were done using SAS Enterprise guide 7.1 and results were considered significant if $p < 0.05$.

Net revenue

In the calculations of the economic data an exchange rate of 1 € = 10 SEK was used, harvester cost was set to 110 € $E_{15}h^{-1}$ and forwarder cost 90 € $E_{15}h^{-1}$. Relations between study time and $E_{15}h$ according to Kuitto et al. (1994) were applied. Assuming a fixed transport distance of 250 m, load size 14 m^3 and easy ground conditions, forwarder transport time was calculated to 0.538 min m^{-3} based on Brunberg (2004). An unloading time of 0.564 min m^{-3} was used based on Nurminen et al. (2006). Birch pulpwood price was set to 36 € m^{-3} solid and bioenergy price of 20 € m^{-3} solid, in accordance with published prices in the study areas's region (Södra 2018a, 2018b). Conversion from odt to m^3 was done based on Lehtikangas (1999). For birch, 1 oven dry tonnes (odt) was assumed equivalent to 2.04 m^3 solid pulpwood or 2.10 m^3 solid energy wood. For spruce, 1 odt was assumed equivalent to 2.50 m^3 solid pulpwood or 2.60 m^3 solid energy wood.

Results

Harvesting

Average time consumption was 1300 s odt^{-1} (2.77 odt E_0h^{-1}), at removal of 3000 stems ha^{-1} and 30 odt ha^{-1}. Harvester operators used multi-tree felling in 23–83% of the crane cycles, and the average number of trees per crane cycle in each study plot ranged from 1.23 to 2.78 (Table 1). Total boom cycle times were almost identical between removal methods, although the shares of work element within the boom cycle differed (Table 5). Total harvesting time per odt was significantly affected by the covariates "harvested number of trees ha^{-1}" and "harvested biomass ha^{-1}" while there was no significant effect of removal method (Tables 6 and 7 and Figures 2 and 3).

Table 5. Predicted least square mean harvester time consumption (s odt^{-1}) for removal of 30 odt ha^{-1} and 3,000 stems ha^{-1} for the two removal methods studied.

Work element	Combined	Pulp
Boom out	175	276
Felling	547	414
Boom in	128	229
Processing	385	310
∑ Boom cycle time	**1236**	**1230**
Movement	52	109
Miscellaneous	13	11
∑ Efficient time	**1301**	**1340**

Table 6. ANCOVA-table for harvester time consumption (s*odt^{-1}). Total SS = 5,088,601, r^2 = 0.942.

Source	DF	Type III SS	Mean square	F-value	Pr > F
Removal method	1	3275	3275	0.07	0.804
Harvest, odt ha^{-1}	1	4,342,512	4,342,512	89.37	<0.0001
Trees harvested, n ha^{-1}	1	539,267	539 267	11.1	0.016

Table 7. Parameter estimate for the ANCOVA models of total harvester time consumption (s odt^{-1}), and pulpwood loading time (s odt^{-1}). Covariates used are harvested biomass per ha (B), harvested pulpwood biomass per 100 m of strip road (B_p), birch trees ha^{-1} prior to operations (N), and number of harvested birch trees ha^{-1} (N_b).

Parameter	Total time harvester	Pulpwood loading forwarder
Constant	1442	1171
Removal method		
Combined	39.2	333
Pulpwood	0	0
B (odt ha^{-1})	−25.82	–
B_P (odt $100m^{-1}$)	–	−92
N (harvested trees ha^{-1})	224	–
N_b (harvested birch trees ha^{-1})	–	−332

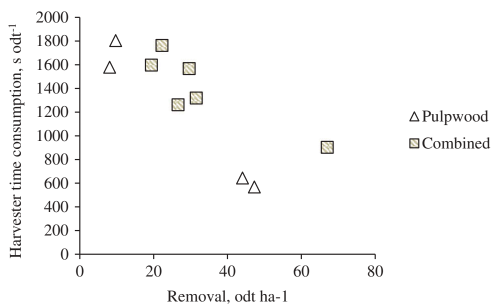

Figure 2. Plot of observed relationship between harvester time consumption (s odt^{-1}) and removal (stems ha^{-1}).

Forwarding

Of the 22 forwarder loads studied, 16 were pulpwood loads and six whole-tree energy wood loads. Time consumption for pulpwood loading was significantly affected by the parameter harvested biomass per 100 m of strip road, but not by the number of birch trees harvested ha^{-1} (p = 0.899) or removal method (p = 0.193) (Table 8, Figures 4 and 5). However, there was a significant correlation between removal method and number of birch trees ha^{-1} prior to logging (p = 0.0001).

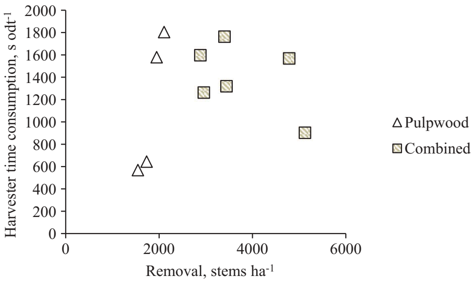

Figure 3. Plot of observed relationship between harvester time consumption (s odt^{-1}) and number of stems removed (stems ha^{-1}) for the two methods of removal studied.

Table 8. ANCOVA-table for forwarder loading time consumption when forwarding pulpwood. Total SS = 1,597,913, r^2 = 0.66.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Removal method	1	85,219	85,219	1.9	0.193
Biomass density	1	585,827	585,827	13.08	0.004
Birch trees harvested, n ha^{-1}	1	152,381	152,381	3.4	0.090

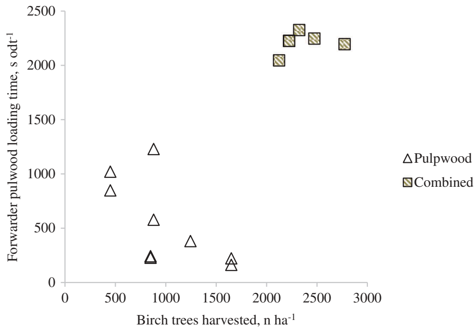

Figure 4. Plot of observed relationship between forwarder loading time consumption (s odt^{-1}) and number of birch trees harvested (stems ha^{-1}) in forwarding of pulpwood, for the two methods of removal studied.

No significant correlations were identified for time consumption in forwarding of energy assortments although there are tendencies that harvested energy biomass density 100 m^{-1} strip road and number of birch trees harvested ha^{-1} affected time consumption (Table 9). The predicted model (Equation 4) accounted for 89% of the observed variation in time consumption.

$$T_{FE} = 1,082 + 93 \times B_e - 0.26 \times N_b \quad (4)$$

Damage to residual trees

On study plots harvested in 2014, the residual stand had, on average, 2030 trees ha^{-1}, out of which 8.5% of them were damaged. On plots harvested in 2016/2017 there were 2235 trees ha^{-1} post-harvest, out of which 14.5% were damaged (Table 10).

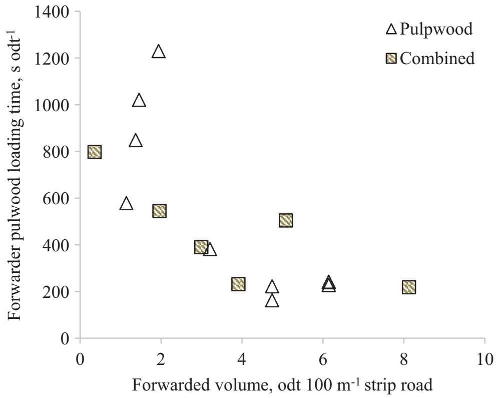

Figure 5. Plot of observed relationship between forwarder loading time consumption (s odt^{-1}) and forwarded volume (odt 100 m^{-1} strip road) in forwarding of pulpwood, separated by the two methods of removal studied.

Table 9. ANCOVA-table for forwarder loading time consumption (s odt-1) of energy wood. Total SS = 55,040, r^2 = 0.73.

Source	DF	Type III SS	Mean square	F-value	Pr > F
Harvested biomass density, odt 100 m^{-1} strip road	1	38,507	38,507	7.73	0.069
Birch trees harvested, n ha^{-1}	1	28,068	28,068	5.63	0.098

Table 10. Inventoried trees and damage frequency after operations.

3Distance to strip road	Trees registered (n)	Total damage (%)	Severe damage (%)
Plots harvested 2016/17			
0–1.99 m	43	14.0	7.0
2–3.99 m	34	14.7	8.8
4–5.99 m	18	16.7	11.1
6–7.99 m	7	14.3	14.3
Plots harvested 2014			
Bordering strip road	213	10.8	-
Bordering plot edge	260	6.5	-

On plots harvested in 2014, there was a tendency that damage frequency was higher in plots bordering the plot edge than in plots bordering the strip road, χ^2 (1) = 2.74, $p < 0.10$. On plots harvested in 2016/2017 there was no significant difference in damage frequency between distance to strip road classes, χ^2 (3) = 0.89, $0.50 > p > 0.10$. None of the analyzed variables in the ANOVA had a significant effect on damage frequency but tendencies of a negative relationship existed between damage frequency and distance to nearest harvested tree (p = 0.16) while there was a positive relationship between average height of trees in the plot and damage frequency (p = 0.15).

Out of the 54 damaged trees observed, 19% were damaged in both operations while 69% were damaged only by the harvester and 13% were damaged only by the forwarder.

Net revenues

With total cost ranging from 1282 to 3586 € ha^{-1} and revenues ranging from 595 to 4314 € ha^{-1} (Table 1), only the largest removals per ha resulted in profitable operations (Figure 6). Harvester costs, on average, made up for 61% (ranging from 47 to 71%) of logging costs in pulpwood removal while in combined removals the corresponding number was 80% (ranging from 77 to 83%).

Discussion

The birch shelterwoods silvicultural system has been applied to varying degrees for more than 50 years, but often in some parts of stands where reforestation has been challenging. As such, stand registries have been lacking information on these areas and thus inefficient for identification of birch shelterwood stands. As more than 500,000 hectares in Southern Sweden comprise mixed spruce and birch stands (Drössler 2010), the difficulty of finding birch shelterwood areas in stand registers was surprising. This is a main contributor to this study being carried out over several years, it was in fact hard to find stands suitable for the study. Often the parts of stands managed as birch shelterwood that were visited visited during selection of stands for the study were too small or irregular for establishment of research plots. This was also a factor limiting plot size in those stands selected for the study. The long data collection phase enabled development of the methodology, mainly of the damage inventory in order to better determine the causes for damage.

Harvesting

The observed harvester time consumption was more than double that observed by Niemistö et al. (2012) in felling of birch shelterwood. This is an effect of the considerably larger birch trees harvested in the Finnish study. However, the current results are similar to what has been found in studies which reported the results of harvesting of small trees for biomass (cf. Belbo 2010; Laitila and Väätäinen 2013).

Conventional models for harvester time consumption are based on average stem volume in felling (cf. Brunberg et al. 1989; Kuitto et al. 1994). These older models do not account for the effects of multi-tree handling, which has a significant effect on harvester performance. The benefits of multi-tree handling increase with decreasing size of trees harvested (Brunberg and Iwarsson Wide 2013; Laitila et al. 2016). As

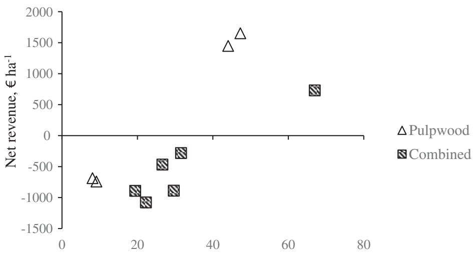

Figure 6. Plot of observed relationship between the net revenue from the logging operation (€ ha^{-1}) and removal (odt ha^{-1}) for the two methods of removal studied.

multi-tree handling makes accurate observation of individual tree size difficult, the harvester time consumption model was based on total harvested biomass (odt ha^{-1}) and number of stems removed (n ha^{-1}). These could be seen as proxies for the parameter often having the greatest influence on harvester performance, the average volume of harvested trees.

When modelling small tree harvesting, Laitila and Väätäinen (2013) found a significant effect on productivity by the number of stems removed and Belbo (2010) explained productivity variation by the average stem volume in combination with the number of trees accumulated in each crane-cycle.

A shelterwood removal could be considered as an extreme thinning from above with the aim to convert a two storied stand to a single story spruce stand, making consideration of the residual stand a crucial part of the felling. In some plots, the height difference between the two species was on average quite small. Laitila et al. (2016) and Niemistö et al. (2012) both examined the effects on harvester performance when either performing thinning of a shelterwood or making expressed efforts to spare the residual stand. In both studies, considering the residual stand had a significant effect on harvester performance even though other parameters, i.e. average harvested stem volume and number of trees removed, were of greater importance.

Forwarding

Harvested biomass density per 100 m of strip road was found to significantly influence forwarder loading time consumption while there was also a strong correlation between the time consumption and the number of birch trees harvested. Prior investigations of forwarding have identified forwarded volume expressed as removal ha^{-1} (Brunberg 2004) or removal m^{-1} of strip road (Kuitto et al. 1994; Nurminen et al. 2006) and load size (Proto et al. 2018) being the main determinants in loading time consumption. The former was supported by the reported study while the latter could not be analyzed since only mid-size forwarders were studied. In all models, forwarding distance had a large effect on driving with and without load, and thus total time consumption. In this study, only loading time was included in the analysis, due to the interference of the scaling process on driving loaded and unloading.

Damage to residual trees

Between 6.5 and 16.7% of the trees examined were damaged, the damage frequency being mostly affected by the height of the damaged tree and distance from the damaged tree to nearest tree being harvested. However, as in studies of high shelterwood removals (Sikström and Glöde 2000) sufficiently undamaged spruce trees remained to create a viable spruce stand. Both Fjeld and Granhus (1998) and Siren et al. (2015) found a relationship between damage frequency and distance to the nearest harvested tree in felling in multi-story spruce stands.

Niemistö et al. (2012) reported damage frequencies between 14 and 44% after felling of birch shelterwoods depending on stand characteristics before harvest and whether special consideration was taken in the residual stand or not. Investigations of damage frequency among residual trees in felling of uneven-aged stands have found damage frequencies ranging from 1 to 5% (Sirén 2000), 4–7% (Modig et al. 2012), 11% (Fjeld and Granhus 1998), 19–25% (Siren et al. 2015), 18–61% (Surakka et al. 2011) and 17–76% (Granhus and Fjeld 2001). It should be noted that all damage frequency investigations in uneven-aged stands were done after removal of much larger trees than in the present study.

The overall damage inventory observed a large number of trees, but the more detailed damage inventory of areas treated in 2016–2017 examined a relatively small number of trees. Since only a fraction of these were damaged, the sample of damaged trees is accordingly not large enough to make detailed conclusions regarding e.g. the cause of damage and types of damage.

As the operators selected which trees to cut, there is always a possibility that they remove trees that have been damaged rather than leave a damaged tree in the residual stand, thus reducing the rate of damaged trees in the residual stand. Sirén (2001) found this being the case for 12% of the trees removed in thinning. Avoiding this situation could be done by pre-determining which trees to remove, which would be another deviation from normal operating conditions that both affect productivity and the operators' possibility of reducing the risk for stand damage (cf. Lageson 1997).

Net revenues

The results presented in this paper indicate that the harvester time consumption and, thus, the economic result in the removal of birch shelterwoods, as for most harvester operations, is strongly affected by the average stem volume of the trees harvested and the density of the removal. The observed logging costs ranged from 39 to 158 € odt^{-1} and are in line with or considerably higher than the average for thinning in southern Sweden in 2017, 51 € odt^{-1} (Eliasson 2018). The average tree size harvested in the current study was considerably smaller (0.015–0.06 m^3) than the average size reported (0.095 m^3) in the national statistics for southern Sweden, which to a large extent can explain these cost differences. The harvesting operation is not the only action that determines the net revenue outcome and the suitability of the birch shelterwood system. The study plots had not been managed in accordance with instructions for birch shelterwood management (Johansson 1992), e.g. most plots had only been pre-commercially thinned once while it is recommended to perform two or three pre-commercial thinnings. Nevertheless, in all cases a satisfactory spruce regeneration had been attained.

The results presented will be applicable in operational forestry when estimating operational costs in shelterwood removal and since the differences to conventional thinning are relatively small, harvest of dense shelterwoods with subsequent low average tree volume will prove unprofitable. There is an ongoing development of technology adapted for small tree harvest, e.g. through geometrical thinning and/or bundling (cf. Belbo 2011; Bergström 2009), that could prove useful also in shelterwood felling.

In conclusion, time consumption in harvesting and forwarding of overstory birch are, as is the case in conventional single-story thinnings, strongly influenced by number of trees and biomass harvested per hectare. Damage frequency among understory spruce was notable but the density of undamaged residual trees was high enough to ensure a viable single-story spruce stand. The silvicultural method could accordingly be a viable option in areas where re-forestation is challenging or in areas considered suitable for higher shares of broad leaf tree species. However, birch shelterwood management is demanding and as such requires engagement of committed forest managers for plausible results.

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IV

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Harvester and forwarder productivity and net revenues in patch cutting

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ABSTRACT
Patch cutting is beneficial for many ecosystem services, but the effects of the management system on operations have not been analyzed. A two-machine system with harvester and forwarder is often used in mechanized cut-to-length operations. The aim of this study was to analyze differences in harvester and forwarder productivity in final felling and patch cutting, and estimate their effects on net revenues per harvested m3. Harvester time consumption was studied using automatic data collection from the machine computer. The data set comprised approximately 18,150 trees harvested during 48 shifts. Analyzes were based on shift level averages. In the observed interval of 0.30–0.60 m3 average tree volume, patch cutting productivity was 20–15% lower compared to final felling. Forwarding was analyzed in three steps. First, a GIS analysis of terrain transport distance found that patch cutting increased forwarding distance by 29%. Secondly, a time study found that loading and unloading times were 16% greater in patch cutting than in final felling. Thirdly, a theoretical analysis found that total forwarder time consumption was 16% higher in patch cuts than in final felling areas. Operational costs in patch cutting were 18% higher than in final felling, thereby reducing net revenues from harvesting operations by 4%. While operational costs were found to be higher in patch cutting than final felling, they are lower than the costs expected for other continuous cover forest management systems. Investigations of later stages of patch cutting are needed before full conclusions regarding the management system can be drawn.

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Introduction

Simultaneous production of multiple ecosystem services is a prerequisite for sustainable forest management (United Nations 1992). Historically, there has been an emphasis on timber production, but demand for other ecosystem services is increasing and implied e.g. in the UN SDG agenda (Sachs et al. 2019). Traditions, practices, and legislation vary, but biomass production goals are attained through even-aged forestry in much of the world (Sands 2013). Even-aged forest management in boreal forests results in higher growth (Lundqvist 2017; Hynynen et al. 2019) and enables lower operational costs (Jonsson 2015) than un-even-aged forest management systems. Even-aged forest management does however result in loss of habitats for species associated with old forests (Lindenmayer and Franklin 2002; Kuuluvainen et al. 2012), loss of landscape biodiversity (Schall et al. 2018), nitrogen leaching (Gundersen et al. 2006), and the visual impression of clearcuts is generally disfavored (Gundersen and Frivold 2008). These disadvantages have led to restrictions in even-aged forest management, e.g. in several European countries (Bürgi and Schuler 2003; Pommerening and Murphy 2004).

Alternatives to even-aged forestry is a range of methods and systems within the concept of continuous cover forestry. This is a diverse term referring to forest management without large clearcuts (Pommerening and Murphy 2004). Patch cutting is a continuous cover forest management system that partly emulates the partial and small-scale disturbances suggested to be the most common disturbance regime in natural Fennoscandian forests (Kuuluvainen and Aakala 2011). Small clearcuts, patches and gaps are suggested to be vital parts in an approach to emulate natural forest disturbance and succession cycles in managed forest, and thereby maintain structural and compositional heterogeneity characteristics of the natural forest (Kuuluvainen and Siitonen 2013).

In Sweden, there is currently a trend toward a more diversified forestry in terms of silvicultural and management systems. National policy goals for increased variability in forest management are set by the Swedish Forest Agency, and the new FSC standard (valid from 2020) states that 5% of the forest holding should be managed with alternative methods, to meet environmental and social goals (FSC 2020).

Erefur (2010) described a patch cutting forest management system where the stand is treated as rectangular patches in a checkerboard pattern. In each treatment, half the patches are cut. Erefur (2010) examined patches measuring 30 by 45 meters, the longer diagonal oriented north-south, enabling high light radiation and successful regeneration, while the patch size was deemed suitable for mechanized harvesting operations.

Most of the harvesting in Sweden, both in thinning and final felling, is made using mechanized cut-to-length operations. Mechanized cut-to-length operations are cost efficient (Eliasson et al. 2019) and decrease the risk of work-related accidents (Axelsson 1998). Mechanized cut-to-length machinery can be used with high productivity under many conditions (Spinelli et al. 2011). The system does, however, rely on highly trained operators and investment costs are high (Malinen et al. 2016).

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There are many parameters determining productivity and cost for harvesters and forwarders in cut-to-length operations. For harvesters, the dominating effect is size of the trees harvested (Kuitto et al. 1994; Nurminen et al. 2006; Brunberg 2007). However, in all kinds of harvesting operations, trees left after felling (i.e. a residual stand) can be expected to decrease harvester productivity, due to greater restriction of machine and boom movements (Eliasson 1998). Harvester productivity in selective thinning operations has been found to be about 30% lower than final felling of trees of the same size (cf. Kuitto et al. 1994; Brunberg 1995, 1997; Jonsson 2015).

In different forms of cuttings and thinning of shelterwoods, the difference compared to final felling has been found to be smaller (Eliasson et al. 1999; Eliasson 2000; Grönlund and Eliasson 2019), due to fewer residual trees restricting the operations. Studies of patch cutting in Norway found that harvester productivity was 10–15% lower in single-tree selection than in patch cutting (Suadicani and Fjeld 2001). However, this difference decreases with decreasing patch size and increasing harvesting intensity in the single-tree selection treatment. On the other hand, no differences in harvester productivity were found between single-tree selection and clustered selection in a study in the Italian Alps (Spinelli and Magagnotti 2013).

There are no previous studies of wood extraction in patch cutting using forwarders, but as the most influential factors on forwarder time consumption are wood concentration and loaded and unloaded travel distance (c.f. Bergstrand 1985; Kuitto et al. 1994), it is possible that there are no or only small differences in the loading work in patch cutting compared to final felling. However, the more restricted possibilities for strip road layout in patch cutting compared to final felling may increase traveling distances and cause longer travel times for the forwarder. The differences in the road network may also affect the distribution of the logs which i.e. Manner et al. (2013) found influenced forwarder loading time consumption.

Patch cutting as an alternative to thinning has been found less costly in the context of southern Europe (Mercurio and Spinelli 2012), western Canada (Phillips 1996) and Norway (Suadicani and Fjeld 2001), but costlier than final felling (Phillips 1996). Operations in patch cutting using a regular pattern such as the checkerboards studied by Erefur (2010) have not been studied, and there is a knowledge gap regarding operational costs and revenues. Based on the literature, both harvester and forwarder productivity should be lower than in ordinary final felling, increasing operational costs per cubic meter.

The aim of this study was to analyze differences in harvester and forwarder productivity in final felling and patch cutting, and estimate their effects on net revenues per harvested m^3.

Materials and methods

Study areas

The study was carried out during January and February 2018 in the provinces of Västmanland and Uppsala in central Sweden. Patch cutting was studied in one harvesting site on 9–24 January. As a reference, final felling was studied at three sites during the period 29 January to 16 February. All operations were carried out using the same single-grip harvester and forwarder and the same machine operators. During these periods, harvester data were gathered in the form of time-stamped hpr-files, and time studies were performed of the forwarding work. This resulted in a data set consisting of 48 harvester shifts, 27 in normal final felling and 21 in patch cutting, and 44 forwarder loads. The harvester was operated by two operators, both with at least 10 years of experience as harvester operators, each operating the machine for 24 shifts. The forwarder was studied with its normal full-time operator. The trees in one of the final felling sites were smaller than in the other sites, so the variation in average stem volume per shift is larger in final felling than in the patch cutting (Table 1).

Prior to logging, undergrowth cleaning had been performed in all stands. In all stands, Norway spruce was the predominant species (Table 2).

The landowner had decided on patch cutting, removing 50% of the area in the patch cutting site. However, after deduction of unproductive areas, partial areas on the site boundary and voluntary set aside areas for nature conservation, a net area of 10.8 ha was selected for cutting, made up of 80 30 × 45 m plots in a checkerboard pattern.

As the property containing the patch cutting site was privately owned, and the owner had already selected the contractor for the cutting, the researchers had no influence on the choice of machines and had to negotiate with the contractor to carry out the studies and to provide access to machine data. The agreement with the contractor prevented the publishing of any time consumption or productivity figures for the two treatments, so the results are presented as time differences between treatments and relative productivity for patch cutting compared to final felling.

Analyses of harvester productivity

Harvesting involved a Ponsse Scorpion harvester and extraction of the logs involved a Ponsse Buffalo forwarder. On both machines, bogie tracks were used to increase flotation and reduce the risk of rutting. For safety reasons, all data on harvester time consumption per tree, species, volume and

Table 1. Average stem volume (m^3 under bark) per shift in final felling and patch cutting.

Stem volume	Final felling	Patch cutting
Average	0.37	0.49
Minimum	0.16	0.29
Median	0.38	0.49
Maximum	0.64	0.60

Table 2. Characteristics of the stands studied.

	Patch cutting	Final felling 1	Final felling 2	Final felling 3
Removal, m^3 ha^{-1} *	310	290	285	305
Average tree volume, m^3	0.49	0.30	0.52	0.36
Composition of species **	22/72/6	41/56/3	18/78/4	26/48/27

*In the area treated
**Percentage of trees (pine/spruce/deciduous)

number of assortments for each tree were gathered from the machine computer. Data were collected in the StanForD 2010-standard (Möller et al. 2013; Arlinger 2020) as time-stamped hpr-files. This data set comprised approximately 18,150 trees, 11,500 in final felling and 6,650 in patch cutting.

For each tree, the machine computer recorded the total time (s) as the time between the end of processing of the previous tree and the end of the processing of the current tree. This necessitated filtering the data to remove trees harvested after a longer break or when a delay had occurred during the harvest; here, this filtering involved removing all trees with a processing time equal to or longer than 600 s. The average processing time per tree during a shift was then calculated as an arithmetic mean of all trees with a time less than 600 s, and shift level averages for both stem volume and number of logs per tree were calculated.

Statistical analyses of the harvester work were based on general linear models and mixed linear models in SAS 9.4. The following linear model (Eq. 1) was tested:

$$\bar{t} = \mu + T + O + T \times O + b_1 \times \bar{v} + b_2 \times T \times \bar{v} + \varepsilon \quad (1)$$

where mean time per tree ($\bar{t}$) was used as response, Treatment (T) and Operator (O) as factors, average stem volume ($\bar{v}$) as covariate, b_x are constants, μ the expected value, and ε is the error term.

The mixed models used the same variables but with operator as a random factor. In both cases, effects or interactions that were clearly non-significant ($p > 0.15$) were removed from the final model.

The relative productivity (P_r) in patch cutting at a given mean stem volume is calculated as the quota between productivity in patch cutting and productivity in final felling at that stem volume.

The dependencies between relative harvester productivity and average stem volume (Eq. 2) were modeled using the following polynomial regression:

$$P_r = b_0 + b_1 \times \bar{v} + b_2 \times \bar{v}^2 + \ \ldots \ + b_p \times \bar{v}^x \quad (2)$$

The regression includes relative productivity (P_r), average stem volume ($\bar{v}$), and effects (b_p). Effects that were clearly non-significant ($p > 0.15$) were removed from the final model.

Analyses of terrain transport

Terrain transport was analyzed in three steps: 1) an analysis of how the studied patch cutting affected the terrain transport distance compared to final felling of the same site, 2) a time study of the forwarding work, and 3) a theoretical analysis comparing total time consumption and costs for forwarding in patch cutting and final felling.

Terrain transport distance analysis

As the transport distance is heavily dependent on site conditions, transport distance in the two treatments was analyzed using the Skogforsk BestWay software (Willén et al. 2017) to minimize transport distance in the site. In both treatments, “no go” areas, i.e. nature conservation areas and nonproductive forest areas, were defined where strip roads were not permitted. The software also minimized traffic in and over wet areas. For the patch cutting treatment, strip roads were not permitted in uncut patches. Based on these restrictions, the shortest route for forwarding all harvested wood to the landing was calculated, and recalculated to an average transport distance for each treatment.

Forwarder time study

Terrain transport was carried out using a Ponsse Buffalo forwarder, which was studied on the patch cutting sites and on one of the final felling sites. In the patch cutting, 37 forwarder loads were time studied, but only seven loads were studied in final felling. The reason for this imbalance is that the forwarder operator ended his employment at the end of January 2018 and, since the entire patch-cut area had been forwarded, the benefits of studying the operator’s replacement were considered small. The time study of the forwarding work was done using a hand-held computer equipped with Skogforsk SDI software, and was carried out as a comparative time study with snap back timing (Bergstrand 1987). In addition to time, surface structure, slope and travel distances were measured for each load.

Loading and unloading forwarding work was split into three work elements that were recorded during the study. Delays were recorded, but only effective times were included in the analyses. The productive work elements were *loading, driving while loading*, and *unloading* but, for most analyses, *loading* and *driving while loading* were summarized into *total loading*. All measured times for each load were summarized per work element and divided by load size in m^3 to obtain times in s per m^3 before the analysis.

Statistical analyses of the forwarder work were performed using a general linear model in SAS 9.4 (Eq. 3):

$$\bar{t} = \mu + T + A + T \times A + \varepsilon \quad (3)$$

where mean time per m^3 ($\bar{t}$) for each work element was used as response and treatment (T), number of assortments in the load (A) as factors. The model also includes expected value (μ) and an error term (ε). In all cases effects or interactions that were clearly non-significant were removed from the final model.

Theoretical analysis of forwarder productivity

The theoretical analysis is based on Brunberg’s productivity standard for forwarding (Brunberg 2004). Using this standard, time consumption for forwarding in final felling and patch cutting was compared for a harvesting site with a harvested volume of 250 m^3 per ha, transport distances according to the distance analysis, a flat terrain with few stones, and assuming the use of a large forwarder. Terminal time (*loading, driving while loading*, and *unloading)* in the patch cutting treatment was increased by the relative difference observed in the time studies.

Net revenues from harvesting operations

The average costs for final felling in southern Sweden 2018 (Eliasson 2019) were used as a basis for calculating the differences in operational costs. Average harvested stem volume in the patch cut areas was similar to averages for southern Sweden in 2018, 0.44 m^3, while the harvested volume per hectare was higher than the average for southern Sweden (216 m^3 ha^{-1}) (Eliasson 2019). As the national statistics indicate only a minor difference for indirect costs between thinning and final felling, it was assumed that these costs do not differ between patch cutting and final felling. Using the national statistics, the total cost difference between treatments was calculated through the productivity ratio previously observed.

Net revenues were calculated assuming wood prices in the national statistics (Eliasson 2019) and volumes harvested for each assortment as indicated in the analyzed hpr-files.

Swedish kronor (SEK) was converted to US dollars (USD) using the average exchange rate for February 2018, 1 USD = 8.03 SEK (Riksbanken 2018).

Results

Harvester productivity

Cutting treatment and average stem volume had significant effects on mean time per tree (Table 3). There was also a weak tendency toward an operator effect and an operator by treatment interaction, which is understandable given the mean times in Table 4. The weak operator effect motivated use of the operator as a random factor in the mixed analysis (Table 5), which showed a significant treatment effect corresponding to a 9.2 s per tree increase in the mean time per tree in patch cutting compared to ordinary final felling. The relative productivity (P_r) for patch cutting as a percentage (Figure 1) can be estimated by a polynomial regression line (Eq. 4), valid for stands with an average tree volume ($\bar{v}$) between 0.30 and 0.60 m^3 under bark.

$$P_r = 69.0 + 44.1\bar{v} - 25.0\bar{v}^2 \quad (4)$$

Table 3. ANOVA table for the GLM model explaining harvester time consumption per tree. The model explains 75.6% of the variation.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Operator (O)	1	96.8	96.8	2.53	0.1187
Treatment (T)	1	747.7	747.6	19.57	<.0001
O × T	1	90.7	90.7	2.38	0.1306
Tree volume (v)	1	1994.6	1994.6	52.22	<.0001

Table 4. Deviation in mean time per tree (s) from the average for final felling, divided into operator and treatment.

	Operator	
Treatment	A	B
Final felling	−0.3	0.3
Patch cutting	6.3	12.0

Table 5. Fixed effect model table for the mixed model explaining harvester time consumption per tree.

Type 3 Tests of Fixed Effects				
Effect	Num DF	Den DF	F Value	Pr > F
Treatment (T)	1	44	19.20	<.0001
Tree volume (v)	1	44	51.70	<.0001

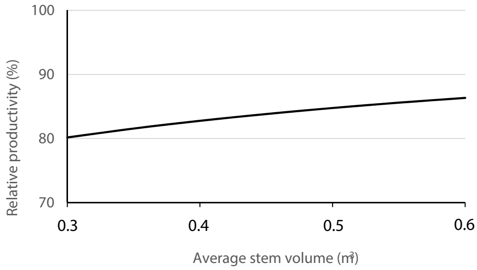

Figure 1. Harvester productivity in patch cutting relative to final felling.

Terrain transport

Terrain transport distance analysis

The results from the BestWay analysis found that patch cutting increased transport distance by 28.6% compared to final felling. Considering the no go areas due to wet ground and environmental restrictions, the optimal average forwarding distance for the harvested stand would have been 274 m if the whole stand had been harvested in a final felling operation; for the patch cutting, the optimal average forwarding distance was 352 m.

Forwarder time study

Of the 44 forwarder loads in the time study data set, 22 consisted of only one assortment, 17 of two assortments and 5 of more than two assortments. The loads with more than two assortments were not included in the statistical analysis. However, as all of them occurred in the patch cutting treatment, unloading and total loading time in that treatment might be somewhat underestimated (cf. Table 6).

Total loading time per m^3 increased significantly (Table 6, Table 7), from 58 s for forwarding after conventional final felling to 73 seconds in the patch cut areas. However, this was partly affected by the slightly more difficult terrain in the patch cutting stand. Loads with two assortments took, on average, 13 s per m^3 longer to load compared to when the load consisted of only one assortment.

There was a small difference in unloading time per m^3 between patch cutting (26 s) and final felling (31 s). This difference was probably an effect of the landing in the area

Table 6. Observed forwarder mean total loading times (s m^{-3}) divided into treatment and number of assortments.

	Treatment	
No. of assortments*	Patch cutting	Final felling
1	66	57
2	81	61
3	86	
4	95	

*Loads with more than two assortments were not included in the statistical analysis.

Table 7. ANOVA table for the GLM model explaining total forwarder loading time (s m^{-3}). The model explains 20.6% of the variation.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Treatment (T)	1	1231.4	1231.4	4.45	0.0420
Number of assortments (A)	1	1678.8	1678.8	6.06	0.0187

patch cut site allowing unloading on both sides of the machine, while the landing in the final felling site only allowed single-sided unloading. Loads with two assortments required, on average, 3 s longer per m^3 to unload compared to when the load consisted of only one assortment. Assuming there was no difference in unloading time between treatments, loading and unloading required 16.8% longer after patch cutting than after final felling.

Theoretical analysis of forwarder productivity

Using Brunberg's productivity standards (2004) for forwarding, the time for *loading and unloading* and *driving* were calculated for the two treatments (Table 8). Loading and unloading times for patch cutting were reduced by 4 s to recalculate them to the same terrain conditions as for the final felling stand. This gave a 12% increase in loading and unloading time for patch cutting compared to final felling, with figures in Brunberg's equations used to calculate the loading and unloading time. Total forwarding times were estimated as 117 s m^{-3} after final felling and 139 s m^{-3} after patch cutting, equating to a forwarder productivity of 30.8 m^3 PMH^{-1} and 26.0 m^3 PMH^{-1} respectively. This corresponds to forwarder productivity being 16% lower in patch cutting compared to final felling.

Net revenues from harvesting operations

Compared to the USD 11.57 m^{-3} that is the average cost for final felling operations in southern Sweden, patch cutting increased the costs for harvesting and forwarding by USD 2.13 m^{-3} (Table 9), or 18%. The average wood value at the landing in the patch cutting site was USD 61.21 m^{-3} and the observed increase in operational costs corresponded to a 4.3% reduction in net revenues after patch cutting compared to final felling in the site.

Discussion

This study found that both harvester and forwarder productivity in patch cutting was 15–20% lower than in final felling, assuming equal tree size in both treatments. This was not unexpected, since harvester work is more restricted in the patch cutting treatment. There were fewer restrictions to felling in untreated patches than could be expected in later treatments, where there will be saplings (or at least small trees) in adjacent patches. Earlier studies show that harvester productivity decreases when saplings and young trees must be considered (Glöde 1999; Glöde and Sikström 2001).

Most of the earlier studies on harvester productivity are traditional time studies, while in this study all data on harvester time consumption per tree, species, volume and number of assortments for each tree were gathered from the machine computer in the form of time-stamped hpr-files. Harvester data have been found suitable for analysis of harvester time consumption (cf. Palander et al. 2012; Strandgard et al. 2013), as well as Big Data approaches (Rossit et al. 2019). Although models based on harvester data are of high quality (Brewer et al. 2018), in many ways their resolution is closer to a shift level study than a time study, as less information is available on causes of individual disturbances (Bergstrand 1987; Olsen et al. 1998). In many cases, such as the current study, gathering of harvester data is safer for study personnel, less likely to disturb the operator, and can be done at a comparatively low cost, enabling a large data set covering a much longer time period than would have been possible using time studies. It should however be noted that the study only includes two harvester operators. The quite large number of observations for each operator could indicate that their individual productivity in each treatment has been mapped, but it is known that differences between operators can be large (c.f. Purfürst and Erler 2011).

In this study, tree processing times exceeding 600 s were excluded from the harvester data set. This threshold was chosen mainly to include most of the trees harvested, while excluding long breaks (lunches and the stops between shifts) and other nonproductive time as the harvester computer did not separate productive and nonproductive time. It was also chosen so the remaining time should not be confused with productive machine hours (PMH), which includes delays larger than 15 minutes (900 s). Observe that it is the sum of productive and nonproductive time for accepted trees that must be less than or equal to 600 s. This threshold of 600 s removed 136 of roughly 18,000 trees in the entire data set, i.e. less than three trees per shift. A reasonable altering of the filtering threshold has only a small effect, e.g. a removal of processing times exceeding 200 s would exclude 497 trees. However, it is reasonable to assume that, with a 200-s threshold, some trees would have been excluded where no delays had occurred.

The forwarder data set is based on time studies with detailed observations on each load. The biggest limitation is that only seven of the 44 loads studied were in final felling areas, due to the decision of the forwarder operator to change their employer. As the difference between operators can be large, especially between an experienced operator and one that is getting used to a new machine, no further time studies of forwarding in the final felled sites were carried out.

Time study data were used to analyze the loading and unloading phases, while an analytical approach based on the productivity standards developed by Brunberg (2004) was used to analyze the time for traveling empty and with a load. This approach was chosen to avoid differences caused by a disparity in terrain conditions between the studied sites. However, the effects of different terrain conditions were not totally

Table 9. Harvesting operations costs (USD m^{-3}) for the two treatments.

Costs	Final felling	Patch cutting
Harvester	5.85	7.03
Forwarder	4.98	5.93
Indirect	0.74	0.74
Total	11.57	13.70

Table 8. Calculated forwarder productivity (s m^{-3}) for the two treatments.

	Treatment	
Work element	Patch cutting	Final felling
Loading and unloading	100	89
Driving with and without load	39	28
Total time	139	117

eliminated, so they also may influence the time consumption for loading and driving while loading.

The most important factors influencing forwarding loading time in the present study were wood concentration, in m^3 per m of strip road or m^3 per ha, and number of assortments in the load. These are factors observed by previous studies (c.f. Bergstrand 1985; Kuitto et al. 1994; Brunberg 2004; Manner et al. 2013; Eriksson and Lindroos 2014; Cadei 2020). While the number of assortments should not be affected by the cutting treatment, the wood concentration per m of strip road can be affected even though the wood concentration per ha treated is unaffected. If the harvester manages to concentrate all wood in a patch to a single strip road running diagonally through the rectangular patch, wood concentration would be higher than in a final felling with about 12–14 m between strip roads. On the other hand, if two strip roads are needed through each patch, strip road length would likely be longer per harvested ha than in an ordinary final felling. As the BestWay analysis found, the overall road distance will be higher in patch cutting, as the roads must pass through the corners of the patch to continue to the next patch. Unfortunately, this also limits the opportunity to select strip road locations that reduce the risk of rutting (cf. Mohtashami et al. 2012, 2017).

Few, if any, studies have been made of the later stages of patch cutting, which involves some obvious differences in conditions compared to the first cutting. The main risk is damage to remaining trees (i.e. damage to trees that have grown in the patches cut in the first stage). Previous studies have found a negative relationship between risk of damage to a tree and several factors; distance to nearest tree cut (Granhus and Fjeld 2001; Sirén et al. 2015), size of the residual tree (Granhus and Fjeld 2001; Sirén et al. 2015) and distance to strip road (Grönlund and Eliasson 2019). While saplings have been found to be exposed to a high probability of damage in felling of large trees (Sikström and Glöde 2000), the residual trees in subsequent treatments cannot be considered saplings. The aim of the forest owner was a continuous cover of mature trees, in which case the next felling would not be within the next 20 years. Although there are mitigating factors, there is a risk of damage to the residual stand in future operations, and the considerations needed will inevitably affect harvester productivity negatively.

A further risk in patch cutting is challenges relating to maintaining orientation in the field, i.e. the risk of getting lost, acknowledged by Roach (1974). This risk increases with the number of stages in cutting and the more complex mosaic created in the treatment area. The challenge can be overcome by modern machines equipped with high-resolution GPS systems. Overall, many factors will influence time consumption and subsequent productivity in the later patch cutting, but not all will be disadvantageous to productivity, e.g. the trees cut may be larger than the ones in the present study.

Patch cutting is one of many continuous cover forest management systems. While the areas treated in this study were for timber production, there are similarities between patch cutting and natural disturbances caused by storms in boreal forests (Drever et al. 2006; Kuuluvainen and Grenfell 2012). Practices vary but, in Sweden, nature conservation management is the aim of management on large areas (Eriksson 2019; Grönlund et al. 2019). While selective cutting is suitable for meeting the aims on most of these areas (Grönlund et al. 2020), adapted patch cutting might prove resourceful in other areas.

This study is one of several investigations of the first stage in patch cutting. The outcome of later treatments must be considered before a comprehensive evaluation of the management system can be carried out. These investigations should also consider the option of cutting less than half of the area in each treatment. The implications for operations if cutting is done in three, four or five steps, while maintaining the structure of rectangular patches, present challenges that are difficult to anticipate at this stage.

In conclusion, the study found that for a spruce stand in central Sweden, harvester and forwarder productivity in patch cutting 15–20% lower than in final felling. However, the costs are lower than what could be expected in thinning, indicating that patch cutting could be a viable option in areas where final felling is to be avoided. The observed difference in costs can mainly be attributed to the increased harvester time consumption caused by the need to consider residual trees. Difference in forwarder time consumption is the result of longer forwarding distances and more time-consuming loading. The net effect is that operational costs increased by 18%, which is equivalent to a decrease in net revenues from harvesting operations of 4%. Note that the current study only covers the first cutting and that a full evaluation of the patch cutting management system requires further investigation of the later fellings as well as studies of regeneration, growth and yield.

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Disclosure statement

No potential conflicts of interest are reported by the authors.

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