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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

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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).

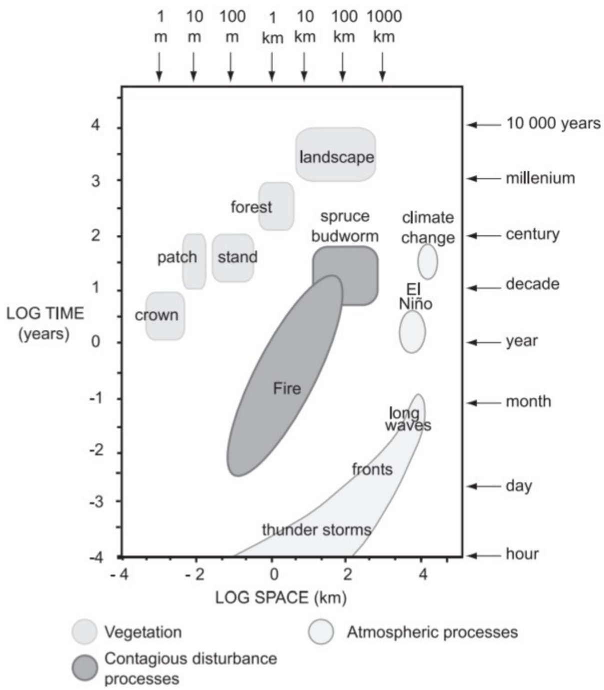

Figure 1. The time-size relationship between disturbances that effect boreal forests (Drever *et al.*, 2006).

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.

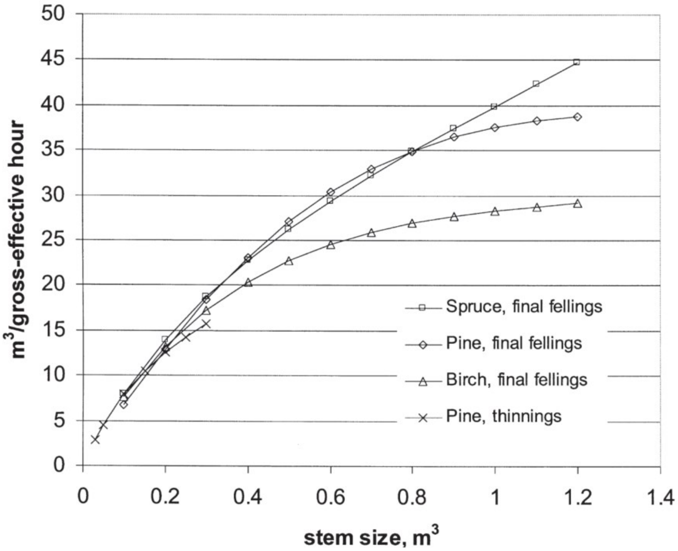

Figure 2. Relationship between time consumption and average tree size in final felling and thinning of coniferous trees. The number of assortments is two for pine, spruce and birch in final felling and one for pine in thinning (Nurminen et al., 2006).

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 $\geq$ 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.

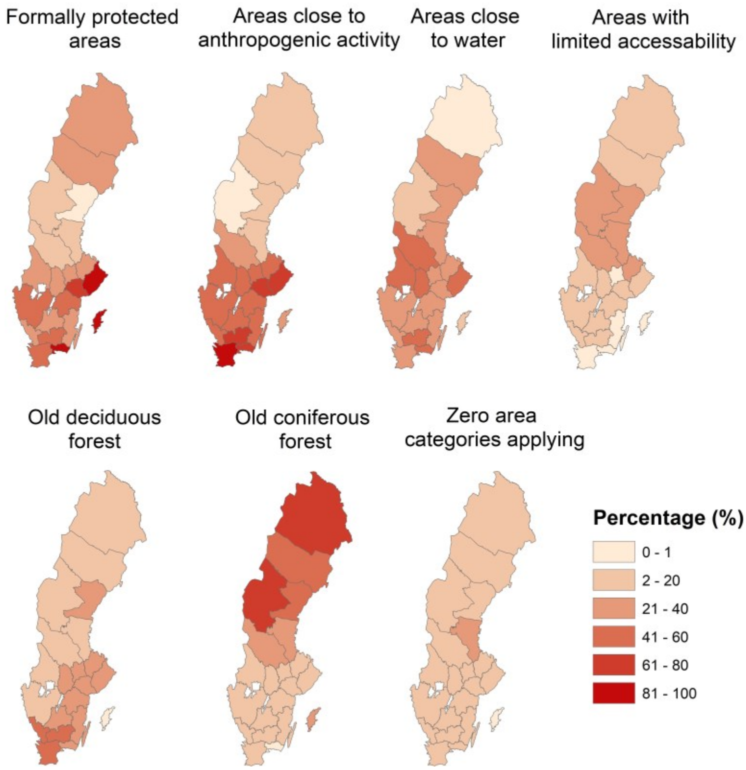

Figure 3. Percentage of the total NCM area within each county meeting the criteria of various numbers of area categories, i.e. at different complexity levels (Grönlund *et al.*, 2019).

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).

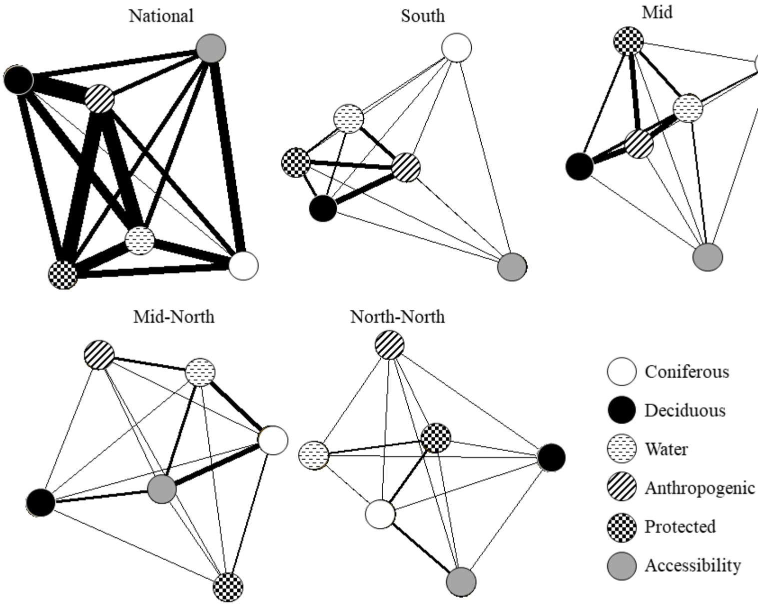

Figure 4. Affiliation network plots of all area categories, shown by region. Thicker lines indicate that the two area categories in the nodes connected by the line appear more frequently than pairs along thinner lines. Positioning and distance between nodes shown have no significance. Coniferous=Old 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, $\chi 2$ (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:
    - o 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.
    - o 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.
    - o 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:
    - o 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.
    - o Forwarding distance was significantly longer, and restrictions when planning the road network meant increased risk of soil damage.
    - o Costs were higher than in final felling, but the effect on net revenues in operations was small.
    - o 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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Multifunctional forestry is forest management intentionally promoting several ecosystem services. The objective of this thesis is to increase knowledge about, and improve implementation of, multifunctional forest operations in Sweden. This is addressed through four studies of how forest operations can be implemented in multifunctional forestry. 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.

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