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A window into forest landscapes

Studying the relationship between forests, ownership, ecosystem services, and biodiversity in landscapes

Bakx, Tristan

2024

Document Version:
Publisher's PDF, also known as Version of record

Link to publication

Citation for published version (APA):
Bakx, T. (2024). *A window into forest landscapes: Studying the relationship between forests, ownership, ecosystem services, and biodiversity in landscapes*. [Doctoral Thesis (compilation), Dept of Physical Geography and Ecosystem Science]. Lund University (Media-Tryck).

Total number of authors:
1

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DEPARTMENT OF PHYSICAL GEOGRAPHY AND ECOSYSTEM SCIENCE | LUND UNIVERSITY

A window into forest landscapes

Studying the relationship between forests, ownership, ecosystem services, and biodiversity in landscapes

Tristan Bakx

DOCTORAL DISSERTATION

Doctoral dissertation for the degree of Doctor of Philosophy (PhD) at the Faculty of Science at Lund University to be publicly defended on the 19th of January at 10.00 in Pangea Hall, Department of Physical Geography and Ecosystem Science, Sölvegatan 12, Lund

Faculty opponent
Dr. Kyle Eyvindson, Associate Professor

Organization
LUND UNIVERSITY

Document name: Doctoral dissertation

Date of issue 2024-01-19

Author(s): Tristan Bakx

Sponsoring organization

Title and subtitle: A window into forest landscapes - Studying the relationship between forests, ownership, ecosystem services, and biodiversity in landscapes

Abstract

Production forests are faced with the challenge of adapting to environmental change and simultaneously helping mitigate it and host rich biodiversity. This leads to new conflicts and trade-offs for forest management. Many management options have been proposed to achieve these goals while minimizing the loss of timber production. In this thesis, I explore the status and future of forest landscapes through multiple disciplines including physical geography, ecology, and forestry. Across landscapes, solutions for increased sustainability can be limited by the distribution and size of non-industrial privately-owned forest (NIPF) properties. At the national scale, it is important to prioritize the parts of the country where environmental measures should be focused. In my thesis, I studied different aspects of the relation between Swedish forests and spatial and temporal scale within the context of forest sustainability. I studied how NIPF properties could be classified by the characteristics of the forest within them. I also investigated how this characterization related to characteristics of the owner such as gender and age. Many forest properties were still significantly shaped by storm damage from over 15 years earlier. The diversity of forests that NIPF owners have presents each owner with a different challenge to adapt to a changing environment. This landscape diversity can affect the possibility of NIPF owners to implement environmental considerations in management. To illustrate this, I showed that forest owners with large properties can store more carbon in their forest at a lower cost than owners with little forest. Additionally, introducing carbon sequestration targets in forestry to aid mid-century climate mitigation efforts could be particularly costly for forest owners. Furthermore, the distribution of streams in a forest landscape will affect the amount of forest land that owners have to set-aside to protect those streams. I showed that the cost of implementing those buffer zones is unequally distributed among forest owners and that this inequality is largest among owners with small forests. The benefits of economies of scale can be explained by the positive relationship between spatial scale and landscape heterogeneity. Future policies should take this relationship into account to effectively persuade forest owners to increase the sustainability of their forests. Finally, I evaluated whether a proposed prioritization of Swedish landscapes for future conservation measures can target specialist and threatened forest birds. The proposed scheme mainly covered specialist forest birds in Northern Sweden and appropriate conservation measures could benefit those species. In other parts of Sweden, additional prioritizations are needed to provide sufficient opportunities to protect forest biodiversity. Overall, this thesis shows how the heterogeneity within and between forest landscapes influences the potential to increase sustainability for different environmental targets in forest management in Sweden. The understanding of the spatial distribution of forest properties, the spatiotemporal scale of management, and interactions between forestry objectives are all essential for solving the environmental puzzle that 21st-century forestry faces.

Key words: Forest, landscape, space, spatial scale, ownership, sustainability, trade-offs, biodiversity, conservation, forestry

Classification system and/or index terms (if any)

Supplementary bibliographical information

Language English

ISSN and key title

ISBN
978-91-89187-33-7 (print)
978-91-89187-34-4 (PDF)

Recipient's notes

Number of pages 85

Price

Security classification

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Date 2023-11-17

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Cover art by Anja van Waard

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Faculty of Science
Department of Physical Geography and Ecosystem Science

ISBN (print): 978-91-89187-33-7
ISBN (PDF): 978-91-89187-34-4

Printed in Sweden by Media-Tryck, Lund University
Lund 2024

Printed matter
3041 0903

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Table of Contents

Abstract

Production forests are faced with the challenge of adapting to environmental change and simultaneously helping mitigate it and host rich biodiversity. This leads to new conflicts and trade-offs for forest management. Many management options have been proposed to achieve these goals while minimizing the loss of timber production. In this thesis, I explore the status and future of forest landscapes through multiple disciplines including physical geography, ecology, and forestry. Across landscapes, solutions for increased sustainability can be limited by the distribution and size of non-industrial privately-owned forest (NIPF) properties. At the national scale, it is important to prioritize the parts of the country where environmental measures should be focused. In my thesis, I studied different aspects of the relation between Swedish forests and spatial and temporal scale within the context of forest sustainability. I studied how NIPF properties could be classified by the characteristics of the forest within them. I also investigated how this characterization related to characteristics of the owner such as gender and age. Many forest properties were still significantly shaped by storm damage from over 15 years earlier. The diversity of forests that NIPF owners have presents each owner with a different challenge to adapt to a changing environment. This landscape diversity can affect the possibility of NIPF owners to implement environmental considerations in management. To illustrate this, I showed that forest owners with large properties can store more carbon in their forest at a lower cost than owners with little forest. Additionally, introducing carbon sequestration targets in forestry to aid mid-century climate mitigation efforts could be particularly costly for forest owners. Furthermore, the distribution of streams in a forest landscape will affect the amount of forest land that owners have to set-aside to protect those streams. I showed that the cost of implementing those buffer zones is unequally distributed among forest owners and that this inequality is largest among owners with small forests. The benefits of economies of scale can be explained by the positive relationship between spatial scale and landscape heterogeneity. Future policies should take this relationship into account to effectively persuade forest owners to increase the sustainability of their forests. Finally, I evaluated whether a proposed prioritization of Swedish landscapes for future conservation measures can target specialist and threatened forest birds. The proposed scheme mainly covered specialist forest birds in Northern Sweden and appropriate conservation measures could benefit those species. In other parts of Sweden, additional prioritizations are needed to provide sufficient opportunities to protect forest biodiversity. Overall, this thesis shows how the heterogeneity within and between forest landscapes influences the potential to increase sustainability for different environmental targets in forest management in Sweden. The understanding of the spatial distribution of forest properties, the spatiotemporal scale of management, and interactions between forestry objectives are all essential for solving the environmental puzzle that 21st-century forestry faces.

Popular Summary

Forests are often managed to produce wood-based products for people to use. In light of today's climate, biodiversity, and other environmental crises, forests need to adapt to survive. At the same time, we can use forests to help solve these same environmental crises. These challenges and opportunities require us to better understand how forests can be managed to achieve those goals.

Different solutions have been proposed for more environmentally friendly forests while minimizing the cost of such changes in terms of timber needed for society. Scientists have mainly created these solutions across large forest landscapes. However, most European forest landscapes are owned by many forest owners with each a unique piece of forest. This means that making proposed solutions a reality might be complicated because of all the different forest owners involved. Problems that can arise have to do with who carries the cost of more environmentally friendly forest management and with limitations in terms of what is actually possible to achieve when dealing with many forest owners. On a bigger scale, like all of Sweden or Europe, it is important to find the most important areas for sustainable forestry and nature protection. This is a way to minimize potential conflicts with other land use goals.

In my thesis, I studied Swedish forest landscapes and the ownership of those landscapes in relation to efforts to make forests in Sweden more sustainable. The research was divided into four papers:

To successfully make forestry more sustainable, it is important to recognize that forest owners own very different kinds of forest properties. Different kinds of forests present different opportunities for sustainable management. So, we showed that properties owned by private individuals could be characterised by which forest you find in them. We could distinguish forest properties with old coniferous forests, with coniferous forests of average ages, with unprotected and protected broadleaved forests, and finally with a lot of young mixed forests. These differences aligned with differences in distance to lakes (coniferous or broadleaved), differences in owner gender (more women in the protected broadleaved properties), and the severity of storm damage (highest in the properties with young mixed forest).

Second, we studied what would happen to the financial value of forest properties if forest owners were asked to store more carbon in their forests to mitigate climate change. Forests take up carbon-dioxide from the air and store it in trees and other plants. Normally, forest owners cut the forest down to sell the wood but they can be asked to leave their forest standing longer or to cut less to increase the carbon storage. Our results showed that people with small forest properties cannot store as much carbon as those with larger forest properties because it is costlier for them. This is so because they have less forest to make decisions about and are thus less flexible to adapt. Furthermore, if we ask forest owners to store carbon more rapidly to meet emission reduction targets in the next few decades, it will be much more expensive.

Third, we studied how much it costs for forest owners to keep the forest areas around all streams in their properties forests instead of clear-cutting them and selling the wood. This is important to do because these forests provide many benefits such as protection of the water from pollution, high carbon storage, and distinct biodiversity. We found that the costs of this varied widely among forest owners. Owners with small properties face larger cost disparities than people with a lot of forest. The reason for this is that, at a small scale, the alignment between stream locations and forest properties is not good. In future policies, efforts should be made to reduce this inequality so that protecting streamside forests feels fairer for all forest owners.

Finally, we studied if a plan to better protect a network of forest landscapes could be beneficial to forest bird species in Sweden. The plan focused on areas where there are already many protected forests but did not consider if important forest birds also use those areas. We found that the network mainly overlaps with the location of specialist forest birds in Northern Sweden and that the network could be used to improve their protection. However, in other parts of Sweden, the plan aligned less strongly with forest birds, so expansions of the current plan or new plans might be needed to protect forest biodiversity.

Overall, my thesis highlights significant variations within and between forest landscapes that affect the possibilities to increase sustainability for different environmental targets in forest management in Sweden. Understanding where different kinds of forests are in a landscape, the size of areas managed, and how this relates to different sustainability targets is vital for addressing the environmental challenges that forests face in the 21st century.

Populair-wetenschappelijke samenvatting

Bossen worden vaak beheerd met als doel houtproducten te produceren voor verschillende doeleinden zoals de bouw en energieproductie. In het kader van klimaatverandering, biodiversiteitsverlies en andere milieucrises moet het bos zich aanpassen om te overleven. Tegelijkertijd geven bossen ons kansen om dezelfde milieuproblemen op te lossen. Bossen leggen bijvoorbeeld koolstofdioxide vast en helpen zo klimaatverandering tegen te gaan en gezonde bossen zorgen voor goede waterkwaliteit. Deze uitdagingen en kansen vereisen een beter begrip van hoe bossen duurzaam kunnen worden beheerd.

Er zijn veel verschillende oplossingen voorgesteld om bosbouw milieuvriendelijker te maken met een zo klein mogelijk economisch verlies. Dit is belangrijk omdat bossen economisch belangrijk zijn en hout een bouwmateriaal is met een kleine klimaatvoetafdruk. Wetenschappers hebben voornamelijk deze oplossingen ontwikkeld voor grote bosgebieden. De meeste Europese boslandschappen worden echter beheerd door veel verschillende eigenaren, elk met een eigen uniek stukje bos. Dit betekent dat het ingewikkeld kan zijn om voorgestelde oplossingen in de praktijk te brengen, omdat veel verschillende bosbezitters betrokken zijn. Problemen die kunnen ontstaan, hebben te maken met wie de kosten draagt voor milieuvriendelijker bosbeheer en met de beperkte mogelijkheden voor individuele boseigenaren om bij te dragen aan grootschalige oplossingen.

Op een grotere schaal, zoals in heel Zweden of heel Europa, is het belangrijk om de meest belangrijke gebieden te vinden voor duurzaam bosbeheer en natuurbescherming. Het ene gebied is het andere niet. Zo komen diersoorten die bescherming nodig hebben niet overal evenveel voor. Door te focussen op de belangrijkste gebieden kunnen mogelijke conflicten met andere landgebruiksdoelen geminimaliseerd worden.

In mijn proefschrift heb ik inspanningen om Zweedse boslandschappen duurzamer te maken bestudeerd in relatie tot de variatie die bestaat in en tussen landschappen. Een belangrijk thema was om te kijken naar het effect van de hoeveelheid bos in iemands bezit op de mogelijkheden om duurzamer bosgebruik toe te passen. Mijn proefschrift was verdeeld in vier onderzoeksprojecten:

Eerst toonden we aan dat privé-eigendommen kunnen worden gekenmerkt op basis van de eigenschappen van het bos. We konden eigendommen onderscheiden met oud naaldbos, met naaldbos van gemiddelde leeftijd, met onbeschermde en met beschermde loofbossen, en met jong gemengd bos. Deze verschillen kwamen overeen met verschillen in de afstand tot meren (naald- of loofbossen), verschillen in geslacht van de eigenaren (meer vrouwen in de beschermde loofbosgebieden) en de ernst van stormschade (dit was het hoogst in de gebieden met jong gemengd bos). Dit betekent dat om bosbeheer succesvol te verduurzamen, het belangrijk is om te erkennen dat bosbezitters zeer uiteenlopende percelen bezitten.

Ten tweede onderzochten we wat er zou gebeuren met de financiële waarde van bosgebieden als bosbezitters werden gevraagd om meer koolstof in hun bossen op te slaan om klimaatverandering tegen te gaan. Normaal gesproken kappen bosbezitters het bos om het hout te verkopen, maar ze kunnen worden gevraagd om hun bos langer te laten staan of minder te kappen om de koolstofopslag te vergroten. Onze resultaten toonden aan dat mensen met kleine bosgebieden niet zoveel koolstof kunnen opslaan als degenen met grotere bosgebieden, omdat het duurder voor hen is. Dit komt doordat ze minder bos hebben om beslissingen over te nemen en dus minder flexibel zijn om zich aan te passen. Bovendien, als we bosbezitters vragen om koolstof sneller op te slaan om de emissiereductiedoelen in de komende decennia te halen, zal het veel duurder zijn.

Ten derde onderzochten we wat het kost voor bosbezitters om de bossen rondom alle waterwegen (beken, sloten, rivieren) op hun land in stand te houden in plaats van ze volledig te kappen. Dit is belangrijk omdat deze bossen vele voordelen bieden zoals bijvoorbeeld bescherming van het water beschermen tegen vervuiling. We ontdekten dat de kosten hiervan sterk varieerden onder bosbezitters. Eigenaren van kleine percelen worden geconfronteerd met grotere kostenverschillen dan mensen met veel bos. De reden hiervoor is dat op kleine schaal de afstemming tussen de locatie van waterwegen en bosgebieden niet goed is. In toekomstig beleid zouden inspanningen moeten worden geleverd om deze ongelijkheid te verminderen, zodat het behoud van beekbossen eerlijker is voor alle bosbezitters.

Tot slot hebben we onderzocht of een plan om een netwerk van beschermde boslandschappen te maken, gunstig zou kunnen zijn voor vogels in de Zweedse bossen. Het plan richtte zich op gebieden waar al veel beschermde bossen zijn, maar hield geen rekening met het voorkomen van belangrijke bosvogels in die gebieden. Het was dus belangrijk om te onderzoeken of die soorten ook daadwerkelijk voorkomen in de gebieden in het netwerk. We ontdekten dat het netwerk voornamelijk overeenkomt met de locaties van gespecialiseerde bosvogels in Noord-Zweden en dat het netwerk kan worden gebruikt om hun bescherming te verbeteren. In andere delen van Zweden komt het plan minder overeen met de habitats van bosvogels, dus uitbreiding van het huidige plan of nieuwe plannen zijn wellicht nodig om de biodiversiteit van de bossen te beschermen.

Kortom, mijn proefschrift benadrukt aanzienlijke variatie binnen en tussen boslandschappen die van invloed zijn op de mogelijkheden om bosbeheer duurzamer te maken voor verschillende milieu-doelen in Zweden. Zo draagt het bij aan ons begrip van de verscheidenheid aan bospercelen in een landschap, van de invloed van de grootte van de bospercelen op de kosten van verduurzaming voor eigenaren en waar de belangrijkste bossen om te beschermen zijn. Dit begrip is belangrijk om het aantrekkelijker voor boseigenaren te maken om bij te dragen aan het oplossen van de milieuproblemen waarmee we worden geconfronteerd in de 21e eeuw.

List of Papers

Paper I

Bakx, T.R.M., Akselsson, C., Trubins R., *Exploring the diversity of non-industrial private forest properties in Southern Sweden*. Under review at Scandinavian Journal of Forest Research

Paper II

Bakx, T.R.M., Trubins, R., Eggers, J., Akselsson C. (2023), *The effect of spatial and temporal planning scale on the trade-off between the financial value and carbon storage in production forests*. Land Use Policy, 127, 106583.

Paper III

Bakx, T.R.M., Trubins, R., Droste, N., Lidberg, W., Akselsson, C., *Riparian Buffer Zones in production forests create unequal costs among forest owners*. Under review at European Journal of Forest Research

Paper IV

Bakx, T.R.M., Green, M., Akselsson, C., Lindström, Å., Opedal, Ø., Smith, H.G. (2023), *Areas of High Conservation Value support specialist forest birds*. Ecosphere, 14:6, e4559.

Author’s contribution to the papers

Paper I

RT conceptualized the study. **TB**, RT, and CA further developed the study and methodology. **TB** and RT collected the data. **TB** designed and executed the analysis with feedback from RT and CA. **TB** wrote the first draft and all authors contributed to revisions of the manuscript.

Paper II

TB, CA, and RT conceptualized and developed the study. **TB** and RT designed the methodology. JE contributed data and refinements to the methodology. **TB** executed the modelling, analysis, and visualizations. **TB** wrote the first draft and all authors contributed to revisions of the manuscript.

Paper III

TB, CA, and RT conceptualized and developed the study. **TB** and RT designed the methodology. WL executed the hydrological modelling. All authors contributed with refinements of the methodology. **TB** executed the modelling, analysis and visualizations. **TB** wrote the first draft and all authors contributed to revisions of the manuscript.

Paper IV

MG and ÅL conceptualized the study. All authors further developed the study and methodology. ÅL and MG provided the bird data. **TB**, ØO, and HS designed the analysis. **TB** collected data from other sources and executed the analysis and visualizations. **TB** wrote the first draft and all authors contributed to revisions of the manuscript.

Abbreviations

AHCV	Area of High Conservation Value
C	Carbon
DSS	Decision Support System
DTM	Digital Terrain Model
DTW	Depth-To-Water index
ES	Ecosystem Services
EU	European Union
HCVF	High Conservation Value Forest
jSDM	joint Species Distribution Model
NFI	National Forest Inventory
NIPF	Non-Industrial Private Forest
NPV	Net Present Value
RBZ	Riparian Buffer Zone

Glossary

Areas of High Conservation Value

Areas of High Conservation Value (AHCV) are forest landscapes in Sweden that encompass areas with a high density of protected and for biodiversity deemed valuable forest (Bovin et al. 2017a; 2017b). They were based on the existing distribution of protected and deemed valuable forests. The deemed valuable forests include the so-called "woodland key habitats" (Swedish: nyckelbiotoper) and unprotected eco-parks and biodiversity-parks from state-owned and private large forestry companies.

Biodiversity

According to the Intergovernmental Panel on Biodiversity and Ecosystem Services: "The variability among living organisms from all sources including terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are a part. This includes variation in genetic, phenotypic, phylogenetic, and functional attributes, as well as changes in abundance and distribution over time and space within and among species, biological communities and ecosystems."

Continuous Cover Forestry

Continuous Cover Forestry (CCF) is a forestry approach in which single or small patches of forest (usually <0.25 ha) are harvested so that no large clear-cut areas are created. This often creates forests with mixed-age classes of trees.

Ecosystem services

The ecosystem services (ES) framework describes a cascade of processes from biophysical structures to distinct goods, benefits, and values for humanity (Turner and Daily 2008; Potschin and Haines-Young 2016). The biophysical structures of an ecosystem generate a set of ecosystem functions that together shape the ecosystem. In the ES framework, these functions are also called supporting or intermediate services. These supporting services generate the final ecosystem services that can be classified into three categories: Provisioning (providing goods used by people), Regulation and Maintenance (regulating and maintaining the functioning of the environment, henceforth "regulating"), and Cultural (concerning the cultural and spiritual benefits of nature to humans).

Even-aged forest management

Even-aged forest management, also called rotation forestry or clear-cut forestry, is a forestry method in which stands of even-aged trees, usually of a single species, are (self-)sown or planted, thinned and clear-cut throughout a multi-decadal cycle. These stands are generally 1 to 10 ha in size but this distribution is biased towards the smaller sizes.

Landscape

Generally speaking, the word landscape can mean “a large area of land, especially in relation to its appearance” (Cambridge dictionary). In the context of my thesis, this requires a more concrete description. “A large area” is not a fixed value and in my thesis can mean an area of several hundreds of hectares, when it comes to landscapes in which birds occur, up to a landscape over 100,000 hectares when it comes to forest management planning. Furthermore, in my thesis “in relation to its appearance” mainly refers to the characteristics of the forest and the distribution of hydrological features. A landscape can additionally mean “all the features of a situation”. For example, we can talk about the political landscape or the economic landscape of forest management. Such definitions are also important and more implicitly present in the thesis.

Non-Industrial Private Forest

Non-Industrial Private Forest (NIPF) is an ownership classification of forest properties. The owners of such properties are private individuals instead of companies or public owners. 60% of European forests occurs in such properties and in many countries, the main land use in NIPF properties is timber production (Živojinović et al. 2015; Weiss et al. 2019). The production goals are often mixed with spiritual, recreational, aesthetic and other goals because of the personal connection of the individual owner with their forest (Ficko et al. 2019).

Production forest

Production forests are those forests, often non-natural planted but also naturally regenerated forest, where managers prioritize the production of timber.

Production Possibility Frontier

In the context of ES, a production possibility frontier (PPF) is a curve that describes the maximum simultaneously possible production of two services. This means that any point on the curve is Pareto optimal, i.e. that any increase in one of the two services is paired with a decrease in the other service.

Riparian Buffer Zones

Riparian Buffer Zones (RBZ), are strips of forest along open water in production forests that are set-aside or managed with continuous cover forestry.

Tack, thank you, bedankt!

Writing this PhD would not have been possible without the guidance, support, and friendship of many people. I am grateful to everyone who has joined me along the way.

First of all, my supervisors. **Cecilia**, thank you for so many things throughout the past years. I'm grateful for your trust in me. Right from the beginning you have encouraged me to train what I admire as one of your greatest strengths: To reach out and connect with other scientists and do research across disciplinary boundaries. You taught me that, no matter what, science is a social endeavour shared with many people. Thank you also for your patience and support in times when my learning curve had to be the steepest. **Renats**, thank you for being my teacher in forestry and mentor in managing my scientific ambitions. Our meetings are always a joy and I'm grateful that you generously shared your sharp mind with me. **Henrik**, thank you for sharing your visionary ways with me in the past years. Your tireless drive to understand some of the greatest societal challenges is infectious.

My other co-authors, **Jeannette, Øystein, Martin G, Åke, Nils,** and **William,** thank you all for your contributions to the papers. Meeting all of you and learning about a wide variety of skills and topics has been great.

Martin B, thank you for supporting me as my department representative and helping to keep the project on track throughout.

Åke, **Martin G**, **Fredrik**, and **Paul** thank you all for welcoming me to the Ecology building when I first came to Sweden. From the master thesis and working with the bird survey until the end of the PhD, you have all supported me throughout!

Keeli and **Hanna**, thank you for going along with the idea to organize a symposium! It was so much fun to do it together! Good luck with your projects! **Cheryl** and **Dimitri**, the help from you personally and the research schools made the whole symposium possible and a breeze to organize.

Thank you to everyone who gave me valuable feedback, advice, and answers to small and large questions to help me make important progress. Special thanks to, **Giuliana, Salim, Kristina, Maj-Lena, Martin S., Petter, Anders Å., Anders L., Patrik,** and **Per Ola.**

Thank you to everyone at INES for the past years. All the staff at the CGB-kansli and other technical staff, especially **Ekaterina, Yvonne, Rafael,** and **Ricardo**, for your help in making all the practical things go so smoothly.

Jonathan, Micael, and **Harry,** I learned so much from teaching with you on the different courses, thank you for all your advice.

A special thanks to my fellow PhD candidates at INES for all the nice times on the journey that we shared. Thank you to **Klas, Veronika, Jalisha, Didac, Alexandra, Adrian, Deborah, Arti, Hanna, Xueying, Mitro, Kimberly, Antje, Erica, Shubham**, and all other PhD colleagues past and present. **Joel**, my big brother in the PhD circus. We just needed to say “bike” and went from there. Thanks for all the bike rides and great talks! I’m looking forward to riding together soon again in Göteborg or Spain. **Akash** thank you for all the laughs, the racing Sundays, and badminton. **Carlos** thanks for the racing Sunday as well and for all the dog sitting and now also dog playdates! My office mates: **Virginia**, thank you for helping me get settled in at the department. **Shangharsha**, thanks for all the great times, helping me solve coding and GIS issues, and all the badminton games.

It has been an invaluable experience to share the ClimBEco Mentor Program with a great group of people. **Katarina**, thank you for all your teachings.

I’m also grateful to have been welcomed to the Ecology building in Lund. Thank you to everyone for the lunches, drinks at the pub, interesting seminars and meetings. **Aivars, Daniel, Albert, William, Lovisa, Julia K., Groa, Ola, Micaela, Hakim, Nikos, Pernilla, Yann, Ivette, Ciara, Pedro, Veronica, Melanie, Anna P., Romain, Jesica, Johanna,** and many others throughout the years, I look back on many interesting conversations and fun evenings with board games and delicious food. **Dafne**, jouw project was de reden voor mij om naar Zweden te komen, dus heel veel dank aan jou. Ik ben blij dat het ook in een mooie vriendschap heeft geresulteerd! **Océane,** I will have many great memories of all our shared bike rides! **Josefin** and **Joel,** you are amazing people to have as friends, I’m looking forward to sharing many more holidays together. **Theresia** and **Alex,** I’m beyond grateful for all the times together and so much enjoy going over all of our and your plans for the future!

My friends outside of work. The Bike Kitchen has been a great place for me to join when I needed to make and repair things with my hands instead of my head. I really enjoyed the many evenings fixing up all the bikes and organizing the workshop with **David, Sandro, Martanda, Clemens**, and others.

Bedankt **Stephan** voor onze langdurige vriendschap en je interesse in dit PhD gedoe. Jij leert me het belang van je passies volgen. Iedereen van de comida buena eetclub, **Elmar, Dorian, Bernd, Titus** en **Clea**, ik ben gelukkig om zoveel van de studietijd en erna met jullie gedeeld te hebben en kijk uit naar het volgende etentje!

Magda, Joan, Mane (Maria), Anna, Joan, and **Mattias,** merci per vostre suport durant tot el doctorat!

Aan mijn familie in Nederland, het spijt me dat ik zo lang zo ver weg ben. Dat ik ondanks de afstand altijd op jullie kan rekenen is een geweldig geschenk. **Papa** en **Mama**, oneindig veel dank voor alles. Jullie hebben mij altijd gesteund en gemotiveerd om nieuwschierig, kritisch en zelfstandig te zijn. Zusjes, dankjulliewel voor alle reality-checks en loopbaancoaching. **Carmen** dankjewel voor je luisterend oor, je aanstekelijke enthusiasme en goede muzieksmaak. **Julia** het was voor mij altijd heel fijn om samen te klagen over onze PhDs en om over knutselprojecten te praten. Jullie eigen succes en de richting die jullie op gaan zijn voor mij altijd een grote inspiratie.

Artur, I dedicate my thesis to you even though you haven't made writing it any easier. I have a hope that the thesis makes a small contribution to a nice world for you. **Donna** for your endless enthusiasm and dedication. **Maria**, you are there for me every single day with so much love. I don't have enough words to describe how grateful I am for all your support throughout the years. I know I can always count on you. You encouraged me to step out of my comfort zone and take on this project, paved the way for me with your own PhD, always listen to my long stories, and most importantly always believed in my success. Moltes gràcies i espero amb moltes ganes la propera aventura.

Rationale and thesis structure

Climate change, biodiversity declines, and other environmental changes have diversified and are diversifying the pressures and demands on forests and forest management. Different measures are being deployed in forest landscapes to enhance environmental values, biodiversity, and ecosystem services other than timber. The scope at which these measures are used has to increase to reach international policy targets. The new goals and associated management practices introduce novel trade-offs and synergies in forests that increase the complexity of forestry planning. This inherently means that forest landscapes will need to be managed differently and that each forest owner needs to adapt their management to their specific changing circumstances. Each forest owner and their property has its own history, status, and goals, which makes adapting forest management in landscapes with many owners complex. Additionally, forest ecosystems harbour an important diversity of species and are dependent on this biodiversity to support ecosystem functioning and the delivery of ecosystem services. To ensure this, biodiversity has to be better protected than is the case today.

Using Sweden as a case study, I studied landscape forest diversity, the effects of the implementation of environmental considerations in forest landscapes, and the potential of prioritizing landscapes for biodiversity conservation. **Papers I**, **II**, and **III** are about forest characteristics, forest ownership distribution, and the potential for ecosystem services in production forest landscapes. In **Paper IV**, I study the potential of a prioritization of forest landscapes for the conservation of forest bird diversity.

The thesis starts with a broad introduction to the scientific problem that I studied, followed by the aims and methods that we used to study the problem. In the results and discussion section, I first discuss how the diversity of forests in a landscape is distributed among privately owned forest properties and which characteristics of the landscape and forest owners can affect what the forest looks like (**Paper I**). Second, I discuss how the introduction of environmental considerations in forest properties leads to scale and timing-dependent inefficiencies and distributional inequalities between forest owners (**Papers II and III**). Third, I evaluate if forest landscapes that were prioritized for future nature conservation are inhabited by the forest birds that they are intended to be beneficial for (**Paper IV**).

In this way, I study, at the landscape scale, the pre-existing conditions for future attempts to increase sustainability in forestry, the financial consequences of implementing such attempts in landscapes with many owners, and, at the national scale, the potential for prioritizing landscapes to improve biodiversity protection in them.

Introduction

Towards more sustainably managed production forest landscapes

Forestry and environmental change

In Europe, 75% of forest area is available for timber production (Forest Europe 2020). These forests might be managed for multiple objectives, but the timber production objective is often the primary objective because it directly benefits the forest owner while other ecosystem services (ES) are usually public and are thus less attractive to prioritize, especially for private owners (Lant et al. 2008). However, the diverse ecosystem services from forests provide opportunities to contribute to solving environmental problems if forests are managed to capitalize on these opportunities. The continuing worsening of climate change and other environmental crises is increasing the societal pressure to manage forests for multiple goals (IPBES 2019; IPCC 2019). For example, timber can be used to substitute fossil products at a lower carbon footprint and the demand for substitution is expected to increase and diversify in Europe with a larger emphasis on biomass and construction materials, helping to reach climate targets (Mantau et al. 2010). At the same time, carbon stock in standing forests is expected to increase also contributing to reaching those same goals (Cintas et al. 2017; European Union 2018; Korosuo et al. 2023). It will be paradoxical to both increase harvests for substitution and increase standing carbon stocks in forest landscapes as the required management is opposite for both goals. Additionally, forests provide resources such as berries, mushrooms, and game meat that are commonly extracted and the long-term supply of those resources is important as well.

The currently dominant silvicultural system of intensive even-aged forest management has complex and often negative environmental effects on biodiversity (Bremer and Farley 2010; Kuuluvainen et al. 2012), greenhouse gas balances (Naudts et al. 2016; Mayer et al. 2020; Mäkipää et al. 2023), and water quality (Shah et al. 2022) as well as on other values (Kuuluvainen et al. 2012). This necessitates changes in forest management to reduce the negative effects of production-oriented forestry on the environment. Furthermore, a changing environment alters the growing conditions and disturbance risk for forests and management needs to adapt to those changes to ensure future growth and survival of forests (e.g. Lloret et al. 2012; Buma 2015; Seidl and Rammer 2017; Yuan et al. 2019). The need to simultaneously reduce the negative environmental effects of forestry, adapt forest management to changing climate, and diversify the provisioning of ecosystem services creates a complex problem for forestry in which trade-offs and synergies between those goals need to be studied.

A landscape approach to increase sustainable forestry

The environmental conditions for ecosystems to produce different ES are heterogeneously distributed in landscapes. So, the trade-off or synergy relationships between ES are dependent on the location where these ES are to be produced in a landscape (Nelson et al. 2009; Tallis and Polasky 2009). Landscape approaches utilize this spatial heterogeneity in growing conditions by adapting management locally to reach multiple goals at the landscape scale through spatial targeting (i.e. applying location-specific management), land sharing (i.e. multi-purpose management), and land sparing (i.e. spatial separation of ecosystem services, Ekroos et al. 2014; Fischer et al. 2014; Lindborg et al. 2017). In this way, it is a method to find management solutions for complex sustainability problems of terrestrial systems that is increasingly studied to meet the various demands in forests (Arts et al. 2017). Landscape approaches are designed by iteratively adapting management to stimulate multifunctionality at multiple scales while considering the needs of multiple stakeholders (Sayer et al. 2013). Desirable compromises are difficult to achieve since the manager has to not only account for the production of each ecosystem service but also for how trade-offs and synergies are distributed in the landscape (Zheng et al. 2019). The overall aim is to maximize synergies between ES and to minimize trade-offs to reach a desirable compromise of multiple goals. A landscape approach and associated management can be applied across scales adapted to the requirements of the targets; On the one hand, the planning of nature conservation infrastructure can be done at large scales if the targeted species and potential management solutions operate at that scale (Ekroos et al. 2016). On the other hand, the selection of forests to set aside for carbon sequestration can be done at much smaller scales since the relevant heterogeneity in growing conditions exists at a much smaller scale (e.g. Pohjanmies et al. 2017).

Policy goals for sustainable forest development

To effectively transform forest landscapes to reach a variety of sustainability targets, effective policy instruments are needed. Multiple international policy targets have been set up in response to past, present and predicted future deteriorations of the natural world as a result of climate and other environmental disturbances. From the United Nations, these include the United Nations Framework Convention on

Climate Change Paris Agreement with the main goal to limit the average global temperature increase, the Aichi targets and Kunming-Montreal Global Biodiversity Framework both adopted to halt and reverse biodiversity loss, and the 2030 Agenda on Sustainable Development to achieve fair and just sustainable development. These targets have potentially far-reaching implications for how forests are managed. First, because forestry will determine the availability of species habitat in a large share of forests and, second, the most efficient way to reach the targets will be through the design of management that capitalized on forests' ES potential.

Consequential to the international policy targets, different legislative frameworks and strategies that (will) affect forests exist and are in preparation in the European Union. These laws have and will shape EU land use and change how forestry can be done. The Habitats and Species directives, the proposed EU Nature Restoration Law, and the Biodiversity Strategy for 2030 outline ecosystem and species conservation and are expected to introduce large-scale changes in land use in the EU (Hoek 2022). The Water Framework Directive has introduced goals for improving water quality across the continent which has come with increased considerations for water quality in forestry (Maher Hasselquist et al. 2020). Potentially most importantly, the land use land cover and forestry regulations as part of the EU Fit for 55 package and EU Forest Strategy for 2030 plans to adapt forest management to environmental change and to ensure long-term timber production while increasing the consideration for other ecosystem services and ecosystem functioning (Lier et al. 2022).

Policy goals in privately owned landscapes

International, EU and national policy goals, legislation and strategies for mitigating and adapting to environmental changes need to be implemented in a way that leads to management for ES at appropriate scales from country-wide to individual landscapes, properties, and forests. In this process, future management of production forests needs to find strategies that ensure long-term timber provisioning while increasing, restoring, and maintaining ecosystem functioning and other ecosystem services. Besides legislation and regulation, other policy instruments can be used to persuade forest owners to aid in reaching sustainability targets. Voluntary nature conservation agreements exist to protect privately owned forest land (Miljand et al. 2021). To alleviate the cost of ecosystem service production it is possible to compensate land owners for their economic losses (so-called payments for ecosystem services; Matthies et al. 2015). Additionally, market-based instruments such as certification schemes (e.g. Forest Stewardship Council, FSC, and the Program for the Endorsement of Forest Certification, PEFC) can increase the sustainability of forestry by creating additional value for certified products (Auld et al. 2008).

Multiple studies have shown that landscape-scale forest management planning can be used to efficiently manage for multiple ES (e.g. Eggers et al. 2019; Schwaiger et al. 2019; Eyvindson et al. 2021). However, forest management is rarely planned at the landscape scale because 61% of EU forests are privately owned in often small properties (Živojinović et al. 2015; Weiss et al. 2019). Forest owners are limited in their management options as they can only plan over the limited heterogeneity of forests that they own instead of the full landscape heterogeneity. Besides, nature environmental considerations in production forests do not provide a direct benefit to the forest owner as timber production does and there is thus no clear incentive to manage for those ES (Lant et al. 2008). This lack of incentive stems from mismatches in the spatial scale of production and benefits of ES (Raudsepp-Hearne and Peterson 2016). For example, in the case of carbon sequestration, the whole world benefits from this so the total benefit is large but per person (of which the land owner is one) the benefit is small and thus there is no reason to manage for carbon sequestration. Alternatively, there might not be any policy or regulation that operates at the scale at which ecosystem services are produced, which can be the case with water quality management since watersheds often cross through multiple administrative regions.

This means that to successfully adapt forestry to the changing environment and societal goals, it is of great importance to motivate private forest owners and understand how prospective changes in forestry and the environment affect them. In many parts of Europe, forest owners, especially non-industrial private forest (NIPF) owners, have strong connections to their property[1] and manage it primarily for timber but also for example for recreation, spiritual and cultural customs, nature conservation, and non-timber resources like berries, mushrooms, and game (Lovrić et al. 2020; Westin et al. 2023). Furthermore, NIPF owners are known to be very diverse in their preferences and forestry objectives (Ficko et al. 2019). Depending on their views they can be generally classified into investors, farmers, recreationists, multi-objective and indifferent owners. These management objectives partially shape the forests on the property but the owner preferences are also often related to owner and property characteristics. Larger properties are often more intensively managed, older owners can reduce their management intensity to prepare their inheritance, and female owners are more often conservation-oriented than male owners (Kuuluvainen and Salo 1991; Tornqvist 1995; Joshi and Arano 2009; Umaerus et al. 2019; Tiebel et al. 2022).

Besides the forest owner, the forest is shaped by environmental conditions such as climate, soils, hydrology, and topography. These biogeographical factors set the limits within which forest develops and the owner has to operate. Climate is mainly important at large scales (e.g. national or continental) in determining on a general

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[1] In this thesis, “property” always refers to the land that can be considered as possession. “Property” is not used as “feature” / ”characteristic” in this thesis.

level the climate niche for forests although microclimatic conditions contribute to local growing conditions. At a landscape scale, weather patterns and extreme events (e.g. storms or droughts) are important in shaping the forest as they can cause disturbances within forest landscapes. Similarly, major soil classes are distributed globally and within regions only a subset of all soil types can be found but the landscape distribution of soil types determines the growing conditions for each forest stand. Finally, the topography intersects with climate and soils to create niches for different forest types and also strongly determines the hydrology of a landscape.

The intersection of the distributions of property boundaries and ES provisioning potential can lead to both a concentration of hotspots of ES in large properties (e.g. Benra and Nahuelhual 2019) and a perceived unfair distribution of responsibility for environmental protection among small properties (Carlsson et al. 1998). The potential for each ecosystem service varies spatially and the trade-offs between them are therefore also spatially variable. Consequently, the heterogeneity of different management goals within small properties can be expected to be smaller than within large properties. Therefore, the marginal gains that can be made through within-property adapted management for ES will usually be smaller than the potential marginal gains at the landscape scale. This issue cannot be solved because the options for coordination of management between owners or financial alleviation of trade-offs are limited (Angelstam et al. 2011; Górriz-Mifsud et al. 2019). Potential policy solutions should be adapted to the scale at which the trade-offs operate (Raudsepp-Hearne and Peterson 2016).

Knowledge gaps in improving sustainability in forest landscapes with diverse ownership have been identified (Nocentini et al. 2017; Felton et al. 2020; Wu 2021). First, what diversity of forest properties exists in a forest landscape and how is this related to geographical and ownership characteristics? Second, how does the distribution of the potential for ES in the landscape intersect with the distribution of forest properties? Third, what is the effect of that intersection on the costs of implementing sustainability improvements according to the policy goals in management for private forest owners? The knowledge gained from answering such questions could in the future be used to improve policy instruments and incentives specifically for the diversity of forest properties, management goals, and opportunities.

Swedish forestry as a case study

This thesis focuses on a case study of forest landscapes in Sweden, with a particular focus on the south of Sweden. Throughout the Holocene, forest cover has been high in Sweden and while forests have been used throughout, large-scale changes in forest cover and structure have only happened in the past three centuries (Östlund et al. 1997; Axelsson 2001; Zanon et al. 2018). Since 1903, forestry has been legally regulated to ensure the regeneration of forests and the long-term provisioning of forest resources (Beland Lindahl et al. 2017). The forest law has changed multiple times since then. The two largest changes were the move to strict regulations requiring even-aged forestry with clear-cutting around 1950 and the requirement to include environmental objectives and considerations in forest management in the 1993 revision if the Swedish Forestry Act (Beland Lindahl et al. 2017). This change in the 1990s was accompanied by a relaxation of management requirements, in the spirit of deregulation trends broadly present in Swedish politics at the time, with the hope to increase environmentally sound management, which gave forest owners so-called "freedom with responsibility" (Appelstrand 2012).

The regulation of forestry since the early 20th century has resulted in large increases in forest growth and reversed some forest losses from earlier centuries (Roberge et al. 2023). However, the environmental impacts of Swedish forestry have come under strong criticism, also after the inclusion of environmental aspects in the 1993 revision of the law (e.g. scientifically, Beland Lindahl et al. 2017, and in society in the 2021 documentary "More of Everything" by Protect the Forest Sweden and Greenpeace Nordic). Besides the negative environmental impacts of Swedish forestry, the country has also set goals for environmental quality and emission net neutrality by 2045 to which forestry is expected to contribute (Lundmark et al. 2014; Swedish Government 2016; Cintas et al. 2016; Swedish Environmental Protection Agency 2020). Furthermore, as a member state of the EU, Sweden shares the policy targets set at the EU level in regards to biodiversity, water and other environmental protection.

In the south of Sweden, forests are mostly owned by non-industrial private forest owners (77% of forest land, Roberge et al. 2023), dividing the forest landscapes into mosaics of properties. Since the mid-20th century, even-aged forestry has been the dominant silvicultural system with ~60-120 year-long rotations that optimize timber production for mostly roundwood (~50%) and pulpwood (42%; Swedish Forest Agency 2022). With this system, the standing forest stock has steadily increased throughout the past 100 years but the area of old forest has mostly decreased and only started to recover since the 1990s (Roberge et al. 2023). Only a little of the old forest in Sweden exists in the south of the country and more than half of it is in the youngest category which is considered to be old (121-140 years old; Roberge et al. 2023). Several biotic, abiotic and anthropogenic factors have favoured the establishment of Norway Spruce in the south of Sweden while the historically more common temperate broadleaved forests declined due to overharvesting and land clearing for agriculture (Lindbladh et al. 2000; 2014).

Storing carbon in standing forests

Climate regulation is an important regulating ES provided by forests through carbon sequestration and carbon storage. Carbon sequestration in forest vegetation and soils can be achieved through, for example, expansion of forest area, restoration of degraded forest, or increases in carbon stocks in existing forests (Canadell and Raupach 2008; Lewis et al. 2019). In production forests, this carbon sequestration can then be utilized for climate mitigation either by harvesting timber and utilizing it to substitute fossil products to reduce fossil emissions or by storing the carbon in the forest (Fahey et al. 2010). In my thesis, I studied carbon storage in standing forests to mitigate climate change and the effect on the financial value of forest harvests.

In even-aged production forests, carbon storage can be increased through for example prolonging rotation periods and reduced thinning (Nunery and Keeton 2010). This however implies financial costs because forest owners will harvest later than the economic optimum or will grow wood that is less valuable due to higher stand densities. Further, delaying harvesting will disturb the existing age-class structure of the forest property implying a less even flow of income in the future.

In heterogeneous forest landscapes with many forest properties, the potential for storing carbon is likely heterogeneously distributed among properties. When considering a forest landscape, e.g. a municipality, the variation in growing conditions can be at its highest at the landscape-scale while at the stand scale, the variation in growing conditions is lowest. In between the smallest and the largest scale of management, the variation of growing conditions can be assumed to gradually increase until it approaches the landscape heterogeneity. This could allow larger management units to increase carbon stocks at a lower financial penalty than smaller units as the larger variation of stands gives a greater variety of options for management optimization. One case study of a Finnish landscape showed that the simultaneous carbon storage and timber production could increase with increasing management scale of up to several hundred hectares (Pohjanmies et al. 2017). It is important to quantify this relationship between production possibilities and the spatial scale of management in different contexts as well. It is of particular interest to study if the scale at which inefficiencies disappear is similar.

Besides the spatial scale of management planning, the timing of carbon storage is important for both climate change mitigation and the finances of forest owners. Even-aged forest management is usually a slow process where the forest owner plans across multiple stands to distribute costs and income over long periods but timely climate change mitigation is necessary to limit global warming to 1.5 ° C (Rogelj et al. 2022). In many countries such mitigation targets are sometime between 2030 and 2050 and in forest-rich countries, forests are expected to contribute to this timely climate change mitigation (Cintas et al. 2017; European Union 2018). This creates a temporal discrepancy between the normal “pace” of the production forest system and the need for climate change mitigation at a faster rate. The costs of this earlier carbon storage to aid mid-century climate targets will be relatively high because the forest management options will be more limited and opportunity costs will be higher due to changes in the timing of income.

Protecting riparian forests

Riparian forests are some of the most valuable forests for ecosystem functioning and ES production (Gundersen et al. 2010; Kuglerová et al. 2014). Some of these ES are water quality regulation, biodiversity conservation, and scenic beauty. Riparian forests provide a buffer for lateral groundwater and runoff flow towards surface waters and filter contaminants from groundwater. In managed even-aged forests this is especially important because groundwater levels rise after clear-cutting and nutrients and pollutants leach from the soil and flow towards surface waters (Akselsson et al. 2004; Kreutzweiser et al. 2008; Bishop et al. 2020). Riparian vegetation can reduce groundwater pollution and reduce the leaching of chemicals to surface water and so contain and mitigate water quality problems (Burt et al. 1999; Anbumozhi et al. 2005; Hefting et al. 2005). Additionally, seasonal hydrological processes lead to a natural disturbance regime in boreal riparian zones with the highest disturbance close to the stream which creates higher biodiversity (Nilsson and Svedmark 2002; Yarnell et al. 2015). This disturbance regime and associated vegetation responses together with a strong soil moisture gradient in the riparian zone can lead to a relatively high plant species richness compared to upland forests (Kuglerová et al. 2017). Furthermore, temperate and boreal riparian forests more often have broadleaved trees and higher fungal diversity (Barker et al. 2002; Komonen et al. 2008). Permanent protection of riparian forests can increase the connectivity of habitats in the forest landscape (Fremier et al. 2015; Rojas et al. 2020).

For these reasons, riparian buffer zones (RBZ) are commonly recommended or required in production forest management (Richardson et al. 2012; Ring et al. 2017). In even-aged forestry, RBZs are strips of forest around streams that are untouched or harvested at a lower intensity than a clear-cut. Policies for the implementation and requirements of characteristics of RBZs vary regionally meaning that large variation exists in the prevalence and characteristics of RBZs in different countries (Ring et al. 2017; Kuglerová et al. 2020). To the forest owner, retaining RBZs at final fellings implies a cost in terms of lost harvest. At the landscape scale, this loss is roughly proportional to the set-aside area and, considering that the recommended RBZ size is generally small, the cost is relatively low (Sonesson et al. 2021).

Hydrologically relevant areas for RBZs are heterogeneously distributed in forest landscapes and RBZ size should be adapted to the hydrological characteristics of the land to maximize the cost-effectiveness (Laudon et al. 2016; Ploum et al. 2021). In landscapes with diverse ownership, it can be hypothesized that some forest owners will incur higher relative cost than other forest owners due to a larger fraction of their land in RBZs. This way, some forest owners would have to pay disproportionately for the ES benefits of all of society which could lead to suboptimal uptake and provision of public ES if not alleviated within policy schemes (Lant et al. 2008; Fisher et al. 2008; Muradian 2013). A thorough understanding of this distributional inequality is needed to be able to alleviate potential policy implementation problems.

Landscapes of biodiversity conservation value

Protected areas have been the cornerstone of species protection for decades (Watson et al. 2014) but existing protected areas are considered to be insufficient to reach international policy targets for nature conservation (Haavik and Dale 2012; Chauvenet and Barnes 2016; Angelstam et al. 2020). One of the most common ways to follow biodiversity trends is through the development of bird populations because they are closely monitored (Gregory et al. 2005; Fraixedas et al. 2020). While common forest bird populations have been stable in Europe in recent decades, forests in Europe harbor fewer and fewer specialist forest birds that are often threatened (Helle et al. 1986; Virkkala 1991; Fraixedas et al. 2015; Gregory et al. 2019). Recently some of these negative trends have halted or even reversed, but previous losses have not been compensated (Ram et al. 2017; Lehikoinen and Virkkala 2018). Additionally, a recent European continental study of bird diversity trends showed that positive trends in forest cover have not coincided with increases in forest birds, which indicated that the additional forest cover is not providing high-quality habitat or that it cannot compensate fully for declines in forest quality elsewhere (Rigal et al. 2023).

While it can be difficult to increase the area of strictly protected land due to competing land use, one potential improvement to current protected areas is to increase the connectivity of protected areas by creating networks (Moilanen et al. 2011; Kremen and Merenlender 2018). To achieve this in a cost-efficient manner, it is necessary to prioritize landscapes where such improvements are to be made. A prioritization focus can be on landscapes with a high density of high-quality habitat so that conservation efforts can be focused there and the increased connectivity leads to improved access to supplementary and complementary habitats (Häkkilä et al. 2017; 2018; Svensson et al. 2020). Ideally, the quality of habitat patches is evaluated before prioritization (e.g. through species distribution modelling: Moilanen et al. 2022). In Sweden, a landscape prioritization has been proposed to the government for increasing habitat connectivity in the form of so-called Areas of High Conservation Value (AHCV; Bovin et al. 2017b; 2017a). This prioritization assumed that the existing protected areas as well as unprotected but deemed valuable areas indeed constitute the habitat patches of highest conservation value. Consequently, the AHCVs were drawn around the landscapes with the highest densities of these valuable patches.

Because the prioritization is only based on this administrative status of supposed valuable forests, it is important to evaluate the conservation potential of the landscape prioritization. One study evaluated a previous iteration of AHCV prioritization from 2005 and found no effect of AHCV on saproxylic insect diversity on clear-cuts (Hallinger et al. 2018). A limited evaluation of the current AHCV prioritization found that some forest birds are likely more common inside AHCVs than outside them but this study did not account for potential confounding factors (Green 2019). Another evaluation of the AHCVs is needed to evaluate if they are suitably placed to potentially protect the intended biodiversity. If so, the prioritization scheme could be used to contribute to Sweden’s efforts towards international conservation targets.

Aims

In this thesis, I take an interdisciplinary approach to study the relationship between forests, ownership, ecosystem services, and biodiversity within and between forested landscapes. The thesis aims to increase knowledge of the opportunities and challenges of improving sustainability in forest landscapes. The sustainability objectives that I cover in the thesis are climate change mitigation through carbon storage, improved water protection, and biodiversity conservation.

I pursue the aim through four separate studies:

Forest landscapes are known to have a diversity of forests and often many forest owners. In **paper I**, we aim to characterize groups of similar non-industrial private forest properties in a mostly forested landscape in Southern Sweden. We cluster forest properties based on forest characteristics and study how the clusters relate to ownership characteristics, biogeography, and storm damage.

In the next two papers, we aimed to quantify how trade-offs between ecosystem services are modified by the scale of management. Due to the diversity in forest landscapes, not all forest owners face the same challenge in a time of diversifying demands on management. In **paper II**, we quantify the effects of spatial and temporal planning scales on the severity of the trade-off between the financial value of future timber sales and the total carbon stock in production forests in Southern Sweden.

In **paper III**, we study how the distribution of the opportunity cost of riparian buffer zones is affected by the size of forest properties. Riparian buffer zones are proposed in production forests to support a wide variety of ecosystem services, but the unequal distribution of streams and forest characteristics lead to different impacts between forest properties in the landscape.

In **paper IV**, we study if a proposed prioritization of forested landscapes for biodiversity conservation has the potential to contribute to the conservation of forest biodiversity, forest (specialist) birds in particular, in Sweden.

Methods

Overview

As described in the introduction and aims, this thesis used Swedish production forest landscapes as a case study for investigating the potential for different ecosystem services and biodiversity within and between forest landscapes.

The study areas of **papers I, II**, and **III** were single landscapes of production forests in South Sweden with many private forest owners. **Paper IV** studied the distribution of forest birds in all parts of Sweden with some forest cover.

I used different methods in each paper to answer the specific research questions with a few commonalities. The methodology of **paper I** was centred around a model-based clustering approach to find clusters of similar forest properties[2]. **Papers II** and **III** used the forestry decision support system (DSS) Heureka to simulate forest management and model ES outcomes. **Paper IV** used a joint species distribution model (jSDM) to model the distribution of 70 bird species in Swedish forest landscapes with and without a high density of high conservation value forests.

Study area

All studies in this thesis were set in Sweden, situated in northern Europe spanning a broad latitudinal range (between 55° N and 70° N). The climates range from temperate in the far south to polar in the north-western mountain range and boreal continental climates in the rest of the northern half of the country. Forests cover most of the Swedish land area (69%) and most parts of the country have some forest cover in the landscape. Large landscapes without forests can only be found above the treelines in the mountainous regions and agriculture-dominated landscapes in

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[2] To remind: in this thesis, “property” always refers to the land that can be considered as possession. “Property” is not used as “feature” / ”characteristic” in this thesis.

southern Sweden (e.g. in Scania county, Östergötland county, and Västra Götaland county).

Papers I, II, and **III** were set in two municipalities in southern Sweden: Alvesta municipality in Kronoberg County (**paper I**, 1080 km^2, 56° 50' N, 14° 29' E, Figure 1) and Hässleholm municipality, in Scania County (**papers II** and **III**, 1306 km^2, 56° 10' N, 13° 46' E, Figure 1). Both municipalities have a humid continental climate with warm summers and no dry season, and the soils are mostly nutrient-poor postglacial sediments and peat. The forests consist of species that are typical for the region such as Norway Spruce (*Picea abies*), Scots Pine (*Pinus sylvestris*), European Beech (*Fagus sylvatica*), European Oak (*Quercus robur*), and Silver Birch (*Betula pendula*). In Hässleholm, Norway spruce does not occur naturally but was introduced in southernmost Sweden for timber production. Alvesta municipality has a forest cover of 67% (721 km^2), most of which is owned by NIPF owners (71% of forest area). Hässleholm municipality has a forest cover of 63% (840 km^2) of which 86% is owned by NIPF owners. In all three studies, we used the forest properties as our sampling unit. NIPF forest properties in Hässleholm include on average 16 ha of productive forest and in Alvesta they include on average 40 ha of productive forest. **Paper IV** included all parts of Sweden with at least some forest cover (Figure 1). We excluded landscapes without forest from the study.

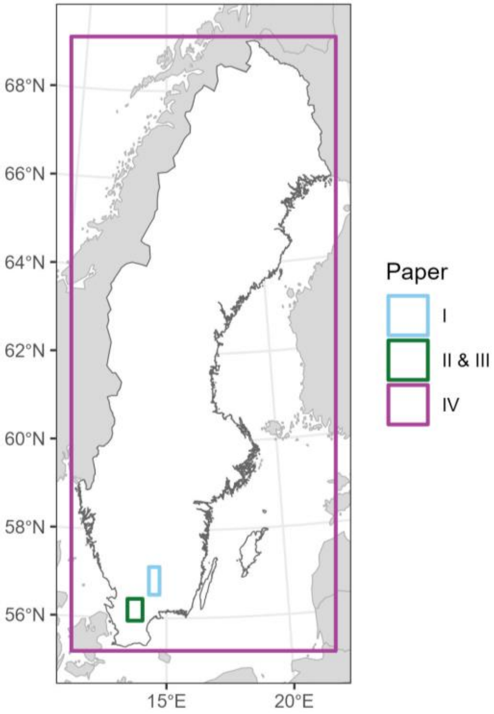

Figure 1. Map of the spatial extents of the four papers in the thesis

Quantifying the diversity of forest properties in the landscape

In **Paper I**, we studied the distribution of forest diversity in Alvesta municipality in terms of species, age, and voluntary nature conservation by summarizing forest characteristics derived from publicly available forest data as metrics in non-industrial private forest properties derived from a cadastral map. We clustered forest properties according to similarities in their forest characteristics using latent profile analysis (LPA; Weller et al. 2020). We then related the clusters from the LPA to the owner's gender and age, the size of ownership, the vicinity of properties to lakes and the area of windfall damage from a storm in 2005.

Forest properties and metrics

We used a cadastral map of Alvesta municipality with an anonymized owner identifier and selected all non-industrial privately-owned properties with at least 2 ha of forest (n = 1255 properties from 1092 owners). The total forest area included in the study was ~50,000 ha. We calculated the forest area in each property from the national landcover data, as well as the area of forest under nature conservation agreements or designated as biotope protection areas, or recognized as woodland key habitats retrieved from the Swedish Environmental Protection Agency.

The age structure of the forest is indicative of forest owner behaviour and preferences but there is no wall-to-wall up-to-date map of forest age in Sweden. Instead, we statistically linked each pixel from the SLU forest map (12.5 m resolution) to the most similar national forest inventory (NFI) plot in Southern Sweden based on volume by species, height, and basal area, and used the age of the NFI plot as the age for each pixel where the tree height was >1.3 m. For shorter trees, we used an age of 0 years because the uncertainties of the SLU forest map for young stands are bigger and the link with the NFI data therefore weaker. With this, we could calculate the average age of the forest in each property, the proportion of forest area that is older than the lowest allowable final forest area (LAFFA; i.e. the minimum age at which trees can be harvested according to the 1993 revision of the Forestry Act 1979:429), the mean volume of forest between 40 and 60 years old (as a thinning activity indicator), and the broadleaved volume in forests of the same age (as an indicator of tendency to keep or clean out broadleaves).

We used the executed fellings data from the Swedish Forest Agency to quantify the area of each property that was clear-cut between 2001 and 2010 and between 2011 and 2021 as an indicator of harvesting activity.

We used the tree species volumes from the SLU forest map 2015 to identify forest types. We classified the tree species into conifers (Norway Spruce and Scots Pine), noble broadleaved (mainly Oak and Beech) and other broadleaves. Where no species group had dominance (>70% volume in a pixel), we classified the forest as mixed. We then for each property calculated the proportion of forest area that was of each of the four forest types (coniferous, noble broadleaved, other broadleaved, mixed) as well as the area of forest <20 years old that was mixed to quantify the tendency of owners to leave species admixture in young plantations.

Latent Profile Analysis

We used latent profile analysis (LPA) with the *mclust* package in R to assign the properties into clusters of similar properties based on the quantified metrics (Scrucca et al. 2016). LPA assumes that each of the properties belongs to a latent sub-population that has a Gaussian distribution for each of the metrics. The combination of the modelled Gaussian distributions sums up the distribution of the total population for that metric. Each property is assigned to the cluster for which it has the highest probability. The benefits of this approach are the ability to quantify assignment uncertainty using bootstrapping and the ability to calculate mean values and confidence intervals for each metric per cluster. We fitted a variety of models with different cluster shapes and sizes and 3 to 5 clusters and selected the best-fitting model.

Relating clusters to characteristics of properties and owners

After determining the cluster assignment, we related the clusters to additional descriptors of the properties and their owners. From the cadastral data, we had the owner's birth year and gender. We used birth year to explore the hypothesis that older owners manage their forest differently to prepare the inheritance (Kuuluvainen and Salo 1991; Tornqvist 1995; Joshi and Arano 2009) and gender for the hypothesis that women are more conservation-oriented (Umaerus et al. 2019; Tiebel et al. 2022). From the same data, we calculated the total property forest area as well as the total forest area owned by an owner in Kronoberg County to quantify the size of ownership since owners with more land have been found, by earlier studies to be more active managers (Eggers et al. 2014). To investigate if the vicinity to lakes correlated with the occurrence of more broadleaved forest we quantified the vicinity of each property to the nearest lake and if properties were situated on a lakeside (Barker et al. 2002; Komonen et al. 2008).

The study area was heavily affected by storm Gudrun on the 8th and 9th of January 2005. We could use the satellite-derived executed felling data from the Swedish Forest Agency, which includes all types of harvests since 2003, to quantify the area lost to that storm by assuming that all harvests in 2005 were due to the storm damage. The storm occurred at the very beginning of the year and for the remainder of the year the regional forestry industry was fully occupied with cleaning up storm damage, so no other fellings were executed (Swedish Forest Agency 2006; Lodin and Brukas 2021).

Simulating forest management and ecosystem service production

In **papers II** and **III**, we simulated forest management in forest landscapes in Hässleholm municipality, to study the trade-offs between multiple ecosystem services at different scales. We used a forestry decisions support system that models forest growth and management, and remote sensing and field inventory-based forest data in combination with property maps.

Heureka

We used the empirical decision support system Heureka to investigate the link between the spatial scale of management and the financial cost of ecosystem service production. Heureka is an empirical model based on observations of forest development mainly from the Swedish National Forest Inventory (Wikström et al. 2011; Lämås et al. 2023). Heureka consists of multiple software packages that all lean on the same simulation models for forest growth and responses of forest growth to different management interventions.

We used the PlanWise package in Heureka for the planning and simulation of forest management of many stands in a landscape. It generates different management alternatives for each stand within user-defined constraints and simulates the outcomes for each alternative based on the initial state, management actions, and a set of sub-models that represent ecosystem processes. Usually, the simulation period is around 100 years long and the time-step of the model is five years. Then the best solution to achieve a management target (e.g. maximize timber harvest or maximize carbon sequestration) can be found with an optimization model that uses linear programming (a method to maximise an objective value given set constraints).

Forest data

The initial state of the forest in Heureka was taken from raster data of forest characteristics (25 x 25 m resolution) and data from the Swedish NFI (SLU 2010; first published in Eggers et al. 2015). The raster data was derived from the SPOT5 satellite and the product included basal area, volume by species, biomass, height, diameter and age. After segmenting the raster data into forest stands, additional forest characteristics were needed to enable forest development simulation in

Heureka. We matched each stand to the most similar NFI plot from the region using neighbour matching on the available variables and extracted the remaining necessary data. In total, there were 23,617 stands in a 725 km^2 area of forest in Hässleholm municipality. For each stand, we included the environmental and vegetation characteristics (location, elevation, slope, climate, site index, soil type, soil moisture, tree species composition, mean age and height, and understorey vegetation type; see heurekaslu.se/wiki/Import_of_stand_register for a detailed description of all required variables). The resulting map represents the forest state around 2010. It has a relatively low accuracy in terms of representing the actual forest in each stand but represents well what production forests in this region look like.

Quantifying carbon storage-NPV trade-offs at different scales

In **paper II**, we studied the forest in one watershed in Hässleholm municipality (46 km2 with 71% forest cover, 1068 forest stands, a subset of the forest data described above).

The overall objective of the methodology was to generate a set of six Production Possibility Frontiers (PPF), representing the combinations of three spatial scales of management and two scenarios for the timing of carbon sequestration. A PPF is a curve that describes the maximum simultaneously possible production of two commodities, in this case, ecosystem services. This means that any point on the curve is Pareto optimal, i.e. that any increase in one of the two services is paired with a decrease in the other service. The different spatial and temporal constraints on forest management are expected to affect the shape of the PPFs, with more restraints on forest management at smaller spatial scales and at faster carbon storage. The two axes of the PPF in our study were the carbon stock in the forest and the net present value (NPV) of the harvested timber.

We calculated the NPV of harvested timber as the difference between the sum of the discounted revenues and the costs of management for an approximately infinite time horizon. We set the discount rate to 3%, which is a commonly used discount rate in Swedish forestry (Hansson et al. 2016).

We calculated the carbon stock as the sum of above-ground carbon, below-ground carbon, and carbon stored in deadwood. The above-ground carbon was modelled according to Claesson et al. (2001) for young forests, and according to Marklund (1988) for older forests both with 0.5 kg C per kg dry-weight biomass. The C in deadwood was modelled according to Harmon et al. (2000) with a percentage C per kg dry weight depending on the state of decomposition of the deadwood (Sandström et al. 2007). Below-ground carbon was calculated as the biomass of stumps, roots, and litter, taking into account associated decomposition rates according to Petersson and Ståhl (2006).

We simulated a range of even-aged forestry programs for each stand including several different rotation lengths and thinning regimes, as well as a set-aside alternative. This represented the variety of conventional management practices that currently can be found in Swedish forestry.

To create the PPFs, we optimized management for a gradient of NPV and Carbon stock targets while constraining it with two temporal scales and three spatial scales.

The temporal scales were implemented as different timings of storing carbon in the forest. In the first scenario, the carbon stock must increase to a set target in the year 2100 and not drop below it after 2100 while minimizing the loss of NPV compared to a scenario without a carbon storage constraint. In the second scenario, we kept the same constraint as in the first for the year 2100 and after but also added a constraint for the year 2045 and after. This was to simulate a scenario where forest carbon stocks are expected to contribute to mid-century emission neutrality targets (Swedish Government 2016).

The three spatial scales were implemented by assigning each stand to fictional properties. At the largest spatial scale, the watershed, all 1068 stands were included in a single optimization. At the intermediate spatial scale, we assigned each stand to one of 11 spatially adjacent fictional properties with on average ~300 ha of forest and ~100 stands. At the smallest spatial scale, we assigned each stand to one of 56 spatially adjacent fictional properties with on average ~60 ha of forest and ~20 stands. These scales represent management at the landscape scale, by private industrial forest owners, and by small-scale non-industrial private forest owners, respectively.

Then we optimized the management for NPV at each of the six combinations of the spatial and temporal scales along a of carbon stock. First, we found the minimum carbon stock by optimizing for NPV without any constraint and the maximum by optimizing for maximum carbon stock in 2045 and 2100. Then we optimized for maximum NPV with a carbon stock constraint increasing at 10% intervals between the minimum and maximum carbon stock. The constraints for 2045 were always set to the same relative levels, % of increase from minimum to maximum, as the connected 2100 constraint. The resulting carbon stock in 2100 and NPV levels formed the production possibility frontiers.

Quantifying the cost variation of riparian buffer zones at different scales

In **paper III**, we studied the distribution of riparian buffer zones among forest properties, again in Hässleholm municipality. We used all the forest data described above. In short, we created a topography-based stream network and overlaid it with the stand map to split stands into parent stands and variable-width riparian buffer zones. Then we simulated management according to two scenarios, without riparian buffer zones (RBZ) and with alternative management (set-aside or continuous cover forestry) in the riparian buffer zone and calculated the difference in the harvest levels and NPV between the two scenarios as the cost of RBZ implementation. We then overlaid the forest map with a range of simulated property maps of different average property sizes and the real forest property map. For each of the simulated property maps we calculated the standard deviation of the RBZ implementation cost and for a range of size classes in the real property map we did the same.

We modelled a stream network from a 1 m resolution Digital Terrain Model (DTM; Lantmäteriet 2021). Essentially, we modelled how water flows over the landscape topography from high to low ground and created streams where a threshold value of upland inflow was exceeded. Around the streams, we defined the variable width RBZs by calculating the Depth-To-Water index (DTW; Murphy et al. 2008) to the stream network. The Swedish Forest Agency recommends average RBZ widths of 12.5 m so we calculated the total area of such fixed-width buffers and set the DTW threshold to a value which would result in a similar area of variable-width buffers. This resulted in a DTW threshold of 0.25 m and 3027 ha of RBZs (4% of the total forest area).

We simulated the management of the forest with two alternatives: one scenario with default management in the RBZs and one alternative scenario with set aside or continuous cover forestry in the RBZs. We used largely default Heureka settings for the default management but lengthened rotation times by 20% to better reflect real-world management. In the scenario with alternative management in the RBZs, we set aside all RBZs except for RBZs with spruce as the dominant species. In those RBZs, we applied continuous cover forestry since in real-world conditions, even-aged spruce RBZs would be susceptible to windfall if left unmanaged. Then we optimized both scenarios for maximum NPV and calculated the NPV and harvest loss per stand.

We overlaid the results with the real-world property map from Hässleholm municipality and classed the properties into seven size classes: 0-10, 10-25, 50-75, 75-100, 100-200, 200-500, >500 ha. Additionally, we simulated 49 property maps with average property sizes from ~25 to ~3800 ha and minimal variation in property size to enhance the generalizability of the results. We calculated the standard deviation of NPV and harvest loss per size class for the real-world map and per property map for the simulated maps. Then we quantified the relationship between mean property size and the standard deviation of NPV and harvest loss.

Evaluating the conservation potential of landscape prioritization

In **Paper IV**, we used a joint Species Distribution Model (jSDM) to show the relationship between bird diversity and areas designated as being of high conservation value. This method takes influences from multivariate statistics to extend generalized linear models to relate independent variables to multiple dependent variables in a single model (Warton et al. 2015). Benefits of this type of model include amongst other benefits, the possibility to account for species interactions, inference of multivariate response to independent variables, and accounting for missing predictors through latent variables.

We specifically used the Hierarchical Modelling of Species Communities jSDM framework (HMSC; Ovaskainen and Abrego 2020). This framework allowed us to do several things that were essential to the research.

First, we could relate the occurrence and abundance of 70 forest birds to the Areas of High Conservation Values while considering the variation in environmental variables in the forest landscape. We did this so that the marginal effect of AHCV would not be confounded by climate, land cover, and altitude. The remaining effect of AHCV should stem from the larger fraction of the area with a higher forest quality.

Second, we could include a spatially and a temporally structured latent variable in the model to account for the remaining spatially and temporally structured variation in the response data. The spatially structured latent variable could account for unintentionally left-out environmental variables. The temporally structured latent variable could account for repeat visits to the same locations and between-year variation in bird diversity.

Third, HMSC can use a hierarchical layer in the model to infer the influence of phylogenetic relationships between species on how they respond to the independent variables. This meant that the phylogenetic data mitigated the uncertainty in estimating the response of rare species to independent variables since they were assumed to respond somewhat similarly to their more common relatives.

After modelling the relation of the 70 species with AHCV, we interpreted the relation by species group. We contrasted the responses of forest specialist species with forest generalist species and red-listed with not red-listed species, to see if birds that only rely on forests or threatened species in particular respond positively to AHCVs.

Results and Discussion

A diverse forest landscape

The forest properties[3] in Alvesta could be grouped into five clusters of properties with similar forests, using the LPA methodology (**Paper I**, Table 1). We called these clusters: *Average coniferous* (32.7% of properties), *Average broadleaved* (22.6%), *Young mixed* (15.5%), *Old coniferous* (26.1%), and *Protected noble broadleaved* (3.1%). The main differences in the characteristics of the first four clusters of forest properties were related to their age structure and species composition while differences in voluntary nature conservation, forest cover, and management behaviour were generally smaller. The fifth cluster, *Protected noble broadleaved*, was distinct because of the high noble broadleaved tree cover (mainly oak and beech) and the occurrence of areas set aside under voluntary nature conservation agreements. These properties were also most often owned by women, in agreement with previous research on NIPF ownership showing that women are more conservation-oriented (Umaerus et al. 2019; Tiebel et al. 2022). Further, they were most often situated on a lakeside, which is generally less intensively managed and has higher broadleaf occurrence (Barker et al. 2002; Ellen Macdonald et al. 2006).

The *Average coniferous* and *Average broadleaved* properties were similar in most metrics except species composition and forest cover, with the former having an above-average amount of coniferous forest and high coverage and the latter having more broadleaved forest and low coverage. In the other metrics, the characteristics of these properties were around the average. This makes them relatively close to the Swedish forestry ideal (Beland Lindahl et al. 2017). Together with the knowledge that they were large they are likely managed with a priority for production and economic gain (Eggers et al. 2014). We found that the *Average broadleaved* properties were close to lakes. This is likely related to broadleaf occurrence and better soils for agriculture at lakesides (Barker et al. 2002; Ellen Macdonald et al. 2006). Such properties with low forest cover were usually combined farm-forestry properties (Tornqvist 1995). The *Old coniferous* properties were, as the name indicates, the oldest and most conifer-dominated properties. The clear-cut area between 2011 and 2020 was average compared to the other clusters but in the decade

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[3] To remind: in this thesis, “property” always refers to the land that can be considered as possession. “Property” is not used as “feature” / ”characteristic” in this thesis.

before it was among the lowest. We hypothesized that old owners would save up their forest to prepare their inheritance (Kuuluvainen and Salo 1991; Joshi and Arano 2009), but neither recent harvesting nor owner's age differed from other clusters. A hypothetical explanation is that some conservation and aesthetics-minded owners delay or refrain from harvesting in the oldest forests on their property (Lodin and Brukas 2021).

Besides the differences, there were also clear similarities between all clusters. This was to be expected since the Southern Swedish forest landscapes have experienced a similar history of felling of natural forest, fire suppression, and conversion to even-aged forestry since the 1950s (Östlund et al. 1997). Mixed forest was also abundant in most properties. This could be explained by the fact that 69% of the forest in this area is FSC or PEFC certified requiring a certain level of broadleaved species presence, either in pure stands or as mixture increases in natural birch regeneration since storm Gudrun or uncertainties in the tree species data (Brukas et al. 2013; Lodin and Brukas 2021; Swedish Forest Agency 2023). The high proportion of forest older than the lowest allowable final felling age is also in line with known owner attitudes towards delaying forest harvest (Eggers et al. 2015; Lodin and Brukas 2021).

The amount of forest area lost during 2005 as a result of storm Gudrun was unequally distributed between the clusters. The properties in the *Young mixed* cluster lost 34% of the forest cover on average while the *Average coniferous/broadleaved* properties lost 12-14% on average and the *Protected noble broadleaved* and *Old coniferous* properties lost 3-5% on average. The *Protected noble broadleaved* properties likely had less forest with leaves when the storm hit in January 2005 making it likely less susceptible to storm damage. The *Young mixed* and *Old coniferous* properties were spatially clearly separated, which indicates that storm damage could be related to the spatial distribution of forest type, the path of the highest intensity of the storm, topography, or soils (Mitchell 2013). Diverse forest management has been proposed at the landscape scale to mitigate disturbance risk (Seidl et al. 2018) and should be investigated concerning forest ownership.

Other factors can also influence what forest properties look like, but we could not include them due to data unavailability. Soils, rivers, and streams are important in shaping ecosystems but readily available data is of low precision or resolution. Forest management in this part of Sweden includes, besides clear-cutting, thinning, planting, and site preparation, and ideally more management data could give more insight into the management activity profile of the forest owner, but such data is not available. Forest management behaviour is largely determined by forest owner preferences and we did not elicit owner preferences, nor did we have data on ownership duration that could inform to what extent management of the current owner has shaped the forest. Previous studies showed that Swedish forest owner preferences can be classified into more and less engaged owners, as well as owners with mainly production, mainly conservation or multiple objectives as their management goals (Ingemarson et al. 2006; Eggers et al. 2014). We did not find a clear correspondence between these preference typologies and the clusters in our study. This was likely because of the external factors influencing forests in addition to management preferences, but future studies could combine typologies of property characteristics and owner preferences to study the relationship between the owner and their forest in further depth. Another future research question could be to which extent the landowners are impacted by past management and biophysical conditions when they try to adapt their management to the new demands of environmental change.

These results set the scene for the diversity of challenges that different forest owners face to manage their forests, adapt to environmental change, and introduce new environmental considerations.

Table 1. Five clusters of forest properties with different forest characteristics in Alvesta municipality (Paper I).

The cluster column shows the name of the cluster from the typology and the percentage of properties in that cluster. Forest characteristics shows the most important distinguishing characteristics of the forest in those properties. Property characteristics shows the other property and ownership characteristics as well as storm damage to the properties in that cluster. For a full account of the results see Paper I.

Cluster	Forest characteristics	Property characteristics
Average coniferous (~32.7%)	- Average in most metrics - More than average coniferous	- Large properties - Intermediate storm damage
Average broadleaved (~22.6%)	- Average in most metrics - Lowest forest cover - More than average broadleaved	- Small properties - Intermediate storm damage
Young mixed (~15.5%)	- Most mixed - Youngest	- Most affected by storm - Farthest from lakes - Small properties
Old coniferous (~26.1%)	- Oldest forest - Most conifer dominated	- Large properties - Least affected by storm
Protected noble broadleaved (~3.1%)	- Noble BL forest - Voluntary nature conservation - Large area harvested 2011-2020	- Often female-owned - Lakeside - Small properties - Least affected by storm

Landscape heterogeneity and the effect of spatial and temporal scale on ecosystem service trade-offs

We found that storing additional carbon came at a low cost for initial increases in C-stocks compared to a maximum NPV scenario because the trade-off between carbon storage and NPV was concave at all scales (**Paper II**). We found that the management of production forests for simultaneous storage of carbon and NPV was slightly more efficient at the two large scales of management (~300 ha and ~3000 ha) than at the smallest scale of management (~60 ha; Figure 2). This spatial scale effect was caused by the positive relationship between forest heterogeneity and the size of management units (Fisher et al. 2008; Hou et al. 2017). Furthermore, increasing carbon storage early in the 21st century to increase the contribution of standing forests to climate change mitigation goals strongly reduced the NPV. In our results, the earlier carbon storage also led to variable harvest rates over time which is unfavourable for both forest owners because incomes will be inconsistent and the timber market because the supply will be uneven. Including even timber flow constraints in the study design would have further increased the trade-off severity (Mathey et al. 2009). This means that the likely necessary contribution of standing forest carbon to reaching mid-century targets (Cintas et al. 2017) can come at a relatively high cost compared to long-term planned increases.

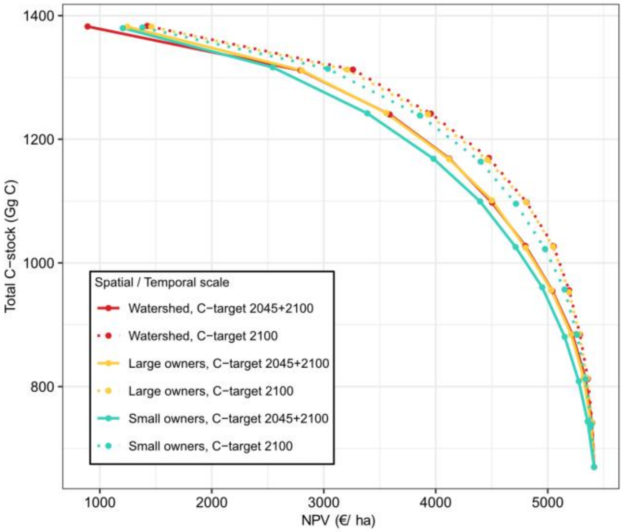

Figure 2. The Pareto frontiers of the C-stock vs. NPV trade-off for each of the combinations of the three spatial and two temporal scales.

The figure represents the potential production of C-stock and NPV in the year 2100, the target year of the optimizations. (Figure from paper II)

We also showed that the distribution of the cost of RBZs between forest properties was highly unequal (**Paper III**). For most properties, the per hectare loss of NPV and harvest due to RBZs was close to the average loss at the landscape level but for some properties, the loss was much higher. This was especially clear among small properties as the standard deviation of NPV loss and harvest loss (~25-35 ha) was 4.2 to 6.9 times higher than among large properties (~700-2300 ha; Figure 3). Privately owned properties in the study area were generally small and most forest privately owned properties in Europe are smaller than 10 ha while public properties are larger (Forest Europe 2020). Consequently, the unequal cost distribution affects private owners disproportionally. The landscape average cost was lower than the area of forest that was set aside because we applied continuous cover forestry to spruce-dominated RBZs. As explained in the methods, we did this to increase the resilience of those RBZs and the CCF management generated income. Applying CCF in RBZs of other species could be a strategy to further reduce the financial implications of RBZs for forest owners. However, other studies showed that, in general, wider buffer zones than we implemented here are needed to sustain ecosystem functioning (Elliott and Vose 2016; Oldén et al. 2019b; 2019a; Jyväsjärvi et al. 2020). Additionally, if CCF is applied in RBZs instead of setting them aside completely, even wider RBZs are needed to achieve similar levels of ecosystem functioning (Oldén et al. 2019b; 2019a).

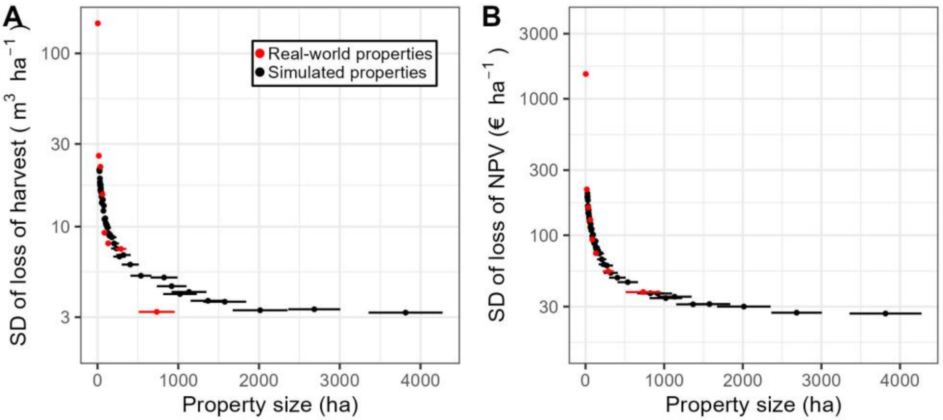

Figure 3. The standard deviation of harvest loss (panel A) and NPV loss (panel B) over map-mean property size for simulated property maps (black dots), and for size classes of the real-world mixed-size property map (red dots). Horizontal lines indicate are 1 standard deviation around the mean property size within each simulated property map or each real-world property map size class.
The size classes of the real-world properties are as follows: 0-10 ha, 10-25 ha, 25-50 ha, 50-75 ha, 75-100 ha, 100-200 ha, 200-500 ha, and >500 ha. (Figure from paper III)

The results of **papers II** and **III** show that the patterns of trade-off inefficiency and distributional unfairness disappear at a scale of several hundred hectares and this fits in with other research. Previous research by Pohjanmies et al. (2017) found that carbon vs. timber harvest inefficiencies also disappeared at a similar scale. Property boundaries have also been identified as a limiting factor in effective nature conservation in privately owned forest landscapes as forest owners are limited in their possibilities to collaborate (Angelstam et al. 2011). Furthermore, watershed-scale planning of water protection measures, such as RBZs, has been highlighted to be important to achieve successful environmental protection (Futter et al. 2010). Similar inefficiencies and inequalities can exist for a multitude of ecosystem service relationships and environmental consideration measures. It is important to study such distributional issues related to sustainability and private forestry in future research. The effect of scale of management on the cost of carbon storage was only small and the inequality of costs of RBZs only affected a minority of forest owners, so the implication for future policies to consider these patterns might be small. However, if there is a spatial correlation between multiple environmental considerations, the effects of them on forest owners might be more severe and need to be considered. Targeting of specific forest properties for environmental considerations in forestry might provide an opportunity for the alleviation of goal conflicts. For example, taking the results from the property typology (**Paper I**), the *Old coniferous* and *Noble broadleaved, protected* properties could be suitable candidates for increased nature conservation, and could provide the synergistic provisioning of nature conservation with carbon storage and water protection, respectively.

One important difference in the approaches among **papers II** and **III** was that **paper II** compared management optimization constrained at the property level with management optimization unconstrained by property boundaries while **paper III** did not include any spatial constraints in the management optimization. Therefore, **paper III** does not show potential inefficiencies of the property-wise management compared to the landscape scale but is limited to distributional inequalities of RBZs.

In **paper II** we did not simulate CCF and in **paper III** we only used it minimally in the spruce-dominated RBZs. There is evidence that CCF provides opportunities for alleviating conflicts in even-aged forestry landscapes and has recently been incorporated in forest management guidelines from the European Commission (Eyvindson et al. 2021; Savilaakso et al. 2021; Duflot et al. 2022; Directorate-General for Environment - European Commission 2023). It is technically possible to simulate it in the Heureka model, however, the model underestimates the growth of CCF and it can therefore not be reliably used as the dominant management strategy (Lämås et al. 2023). Previous studies that used CCF in Heureka for similar purposes either replaced the Heureka CCF simulations with external, deemed more reliable, simulations or had to extensively explain the limitations of their approach (Nordström et al. 2013; Lundmark et al. 2016). For our purposes, we decided that it would be best to minimize the use of CCF and focus on the implications of potential changes in management within the currently dominant system.

Biodiversity in landscapes of conservation value

We showed that a larger number of species occurred more often in Areas of High Conservation Value (AHCV) than outside (n = 26) than species that occurred less often inside AHCVs than outside (n = 9). This shows that for a large number of the studied species, this prioritization can provide conservation opportunities (**Paper IV**, Figure 4). However, the variance explained by AHCVs in the model was low, suggesting that, while consistent, differences in habitat-relevant forest quality were generally not large. Many of the species that occurred more frequently in AHCVs are included in the Swedish indicator for forest biodiversity, showing that the AHCVs capture similar forest aspects as the indicator is intended to capture (Swedish Environmental Protection Agency 2020). The mixed responses of species to AHCVs in the model indicate that while providing conservation possibilities for some species, more conservation prioritizations will be needed besides AHCVs to protect a wide range of forests and taxonomic groups. We only predicted significantly higher abundances for 10 species and overall confidence of the abundance model was lower. This was likely because the model and study design were less suited to abundance data: occurrence patterns are relatively easy to predict across large spatial gradients while individual abundances locally don't always follow such gradients, and the data was summarized along 8 km survey transects which masks habitat amount and quality.

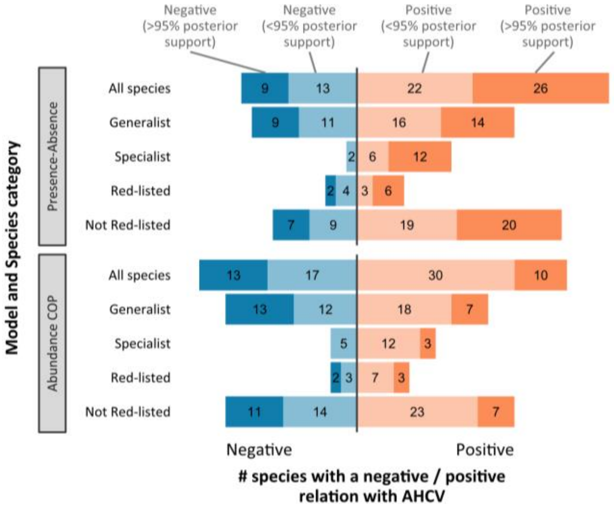

Figure 4. Summary of the relations of all species to Areas of High Conservation Value (AHCV) in the presence-absence and abundance conditional on presence models.

On the left side of the x-axis in blue is the number of species negatively related to AHCV. On the right side of the x-axis in orange is the number of species positively related to AHCV. Light colours indicate <95% posterior support, and dark colours indicate >95% posterior support. The species are summarised in three different ways: all species together, split by forest generalists or specialists and split by red-listed or not red-listed. Figure 3 from paper IV.

Unsurprisingly, northward-distributed species correlated positively most strongly to the AHCVs because the distribution of existing protected and deemed valuable forest areas is biased to the north where the competition with other land uses is less severe than in the South (Angelstam et al. 2020). Additional prioritizations are needed to also cover forest specialist birds occurring mainly in Southern Sweden. Moreover, conservation measures are needed to ensure that forest biodiversity benefits from this prioritization scheme. The remaining relatively natural forests, especially along the mountains in the north of Sweden, should all be protected (Mikolāš et al. 2023) and this needs to be complemented by restoration and protection of more low-lying forest areas in the north and south of the country (Angelstam et al. 2020).

Suggestions for future research

Sustainability issues are complex and exist across disciplinary boundaries and should thus be studied in a multi- or interdisciplinary manner (Defries and Nagendra 2017). In this thesis, I mainly combined physical geography, forestry, and ecology to study current and future challenges in Swedish forested landscapes. The four papers contribute to answering some core questions in landscape sustainability science according to Wu (2021). It is important to answer questions regarding spatial patterns and configuration as well as the distribution of ecosystem functioning and services in the landscape to better understand how human welfare, socioeconomic processes, disturbances, and biodiversity interact.

Future studies should further leverage interdisciplinarity to study forest landscape sustainability. For this to be successful, disciplinary gaps and differences in definitions need to be overcome. Differences in approach, definitions, and subject exist between different disciplines that are engaged with landscape sustainability (Arts et al. 2017). For example, I did not model the nature conservation benefits of different forest management approaches in Heureka because the implementation of biodiversity results is limited (Felton et al. 2017b; 2017a). A reason for this limitation is that there are strong and persistent discrepancies in the approach to studying biodiversity between forestry and ecology (Hunault-Fontbonne and Eyvindson 2023). For future forests to be more suitable to a wide range of organisms, ecologists need to provide actionable knowledge to foresters and foresters need to deepen the incorporation of biodiversity in forest management.

I have followed the principles of landscape approaches to study forest sustainability because it encourages science to approach environmental problems holistically (Sayer et al. 2013). I aimed to study different ecosystem functions and services across a broad range of scales. Further research should continue to combine multiple ES across scales to study trade-offs and synergies in forest landscapes so that potential future forest policies can be designed with sufficient information about the potential implications. This thesis has a strong focus on (privately owned) forest properties and their distribution in the landscape in relation to ES and forest characteristics distributions. These relationships directly influence stakeholders. The effects of future policies for land use change on stakeholders can affect their willingness to implement such policies (Clayton 2018; Maestre-Andrés et al. 2019).

Our forest property typology was limited to mostly studying the characteristics of the forests. A combined approach of interviewing forest owners and studying the characteristics of their forest can further uncover the relationship between forest owners and their property. This will be valuable for designing forest policies that are both effective for the environment and attractive for forest owners.

The thesis presents two cases of two-dimensional ES trade-offs from the forest property to the landscape level. Future research should aim to increase the number of ecosystem services considered. This will allow for an improved understanding of how the distribution of hotspots of ecosystem service trade-offs and synergies affects forest owners in a landscape. It would be interesting to propose the results of such a study at the property level to a group of included forest owners to study their perception of proposed sustainability opportunities.

To study the structures within AHCV that provide high-quality habitat so that management can be designed to achieve such structures and the necessary spatial organization of them. Likewise, the cost of additional conservation measures inside and outside AHCV landscapes can be quantified and compared. Further, increasing carbon stocks in standing forests may increase the amount of habitat through increased availability of deadwood and complex vegetation structures (Felton et al. 2016).

We only evaluated the AHCVs concerning the distribution of forest birds in Sweden. This means that the potential of the proposed green infrastructure remains unknown for other taxa. A multi-taxonomic approach should be employed to increase our confidence in the designation of these landscapes. Currently, data on the distribution of many taxa is limited but potential candidate taxa with decent coverage in Sweden are butterflies and vascular plants.

Conclusions

This thesis shows how the heterogeneity of forest landscapes influences the potential to increase sustainability for different environmental targets in forest management in Sweden. I show how the diversity of forests in mostly privately-owned landscapes is distributed among properties and how that relates to distributional aspects of ES production potential. I also show that a government-proposed landscape prioritization scheme has the potential to benefit certain specialist forest birds if appropriate conservation action is taken. Together, these studies improve our understanding of the obstacles and opportunities for landscape-scale forest management.

We found that the non-industrial private forest properties can be distinguished by the characteristics of the forest into five clusters, meaning that each property only includes part of the landscape-level heterogeneity of forest types. Forest properties mainly differed from each other by forest age structure and species composition. While some differences between properties are likely due to diverse views of forest owners on management, we showed that these differences can also be linked to the position of properties in the landscape and natural disturbance. Voluntary nature conservation agreements were rare but those properties with forests under such agreements were more often owned by women. A significant portion of properties was severely damaged by the storm Gudrun in 2005. Over fifteen years later, the effects of this storm still clearly impacted the age structure and species composition of those properties and this will continue to be so in the coming decades. Natural disturbances are predicted to increase with environmental change and could thus have an even larger impact on future forest landscapes and further limit the management possibilities for forest owners. These differences between forest properties are of importance for planning ecosystem service provisioning in forestry. This provisioning is often best planned at the landscape level but in reality, planning decisions are made at the property level by an owner with only a limited decision space.

We illustrated planning problems of including C-storage and riparian buffer zones (RBZ) into conventional management in two studies. Both the efficiency of ES trade-offs and the equality of cost distribution can be greater at larger scales of management. In one study, in a landscape with many small-scale forest owners, where each owner was expected to contribute equally, the cost of increasing C stocks in the standing forest was higher than in landscapes with fewer larger-scale forest owners. Furthermore, the timing of storing C was important for the consequences to the forest owners as earlier C sequestration was paired with higher costs. In the other study, we showed that at the landscape scale RBZs could be relatively cheap depending on the requirements for their implementation, but the cost for implementing them was highly unequally distributed between forest owners. This unequal cost distribution was highest among small forest properties and the magnitude of the inequality declined non-linearly to approach the landscape scale cost average. Future policies must alleviate such issues of scale-related inefficiency and inequality to effectively allow forest owners to contribute to solving environmental issues.

The Areas of High Conservation Value (AHCV) that were previously identified for the prioritization of conservation measures in those landscapes supported more specialist forest birds. Unsurprisingly, northward distributed species correlated positively most strongly to the AHCVs because the distribution of existing protected and deemed valuable forest areas is biased to the north where the competition with other land uses is less severe than in the South. Additional prioritizations are needed to also cover forest specialist birds occurring mainly in Southern Sweden. Still, this prioritization scheme needs to be implemented through effective conservation measures to ensure that forest biodiversity benefits from it. For example, the remaining relatively natural but unprotected forests along the mountains in the north of Sweden should all be protected. In the more low-lying and southern parts of the country, this needs to be complemented by restoration of degraded forests and protection of valuable forests but some of those areas likely need to be found through additional prioritizations.

Overall, in the Swedish forest landscapes with their diverse property distributions, increasing sustainability is possible by better utilizing and planning existing tools such as lengthening rotations for C sequestration, consequently implementing RBZs and landscape-level planning of conservation efforts. Because of the many forest owners and relatively liberal regulations in Sweden, the fairness of policies that promote these solutions will be important for success in reaching policy goals.

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A window into forest landscapes

Production forests are faced with the challenge of adapting to environmental change and simultaneously helping mitigate it and host rich biodiversity, leading to new conflicts in forest management. Many management options have been proposed to achieve these goals efficiently. In a landscape, solutions for increased sustainability can be limited by the distribution and size of non-industrial privately-owned forest (NIPF) properties. Nationally, it is important to prioritize which landscapes are most important for their natural values. In this thesis, I explore the status and future of forest landscapes through multiple disciplines including physical geography, ecology, and forestry. I studied how NIPF properties could be classified by the characteristics of the forest within them and how such a classification can be related to different factors that might explain it. Differences between forest properties and their size can affect the potential of owners to implement environmental considerations. I illustrate this using the cost of carbon storage and the protection of riparian forests as examples. Future policies should consider that the costs of sustainability are scale-dependent and unequally distributed to persuade NIPF owners to adapt management. Finally, I evaluated if a proposed prioritization of Swedish landscapes for conservation measures can target specialist and threatened forest birds. Overall, my thesis shows that the heterogeneity within and between forest landscapes influences the potential to increase sustainability for different environmental targets in forestry in Sweden. A good understanding of this is essential for solving the sustainability puzzle that 21st-century forestry faces.

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Department of Physical Geography
and Ecosystem Science
Faculty of Science

ISBN 978-91-89187-33-7

Printed by Media-Tryck, Lund 2023 NORDIC SWAN ECOLABEL 3041 0903