Pathways to sustainable bioenergy

Navigating the energy-ecosystem services-biodiversity nexus in agricultural landscapes

Winberg, Josefin

2024

Pathways to sustainable bioenergy

Navigating the energy-ecosystem services-biodiversity nexus in agricultural landscapes

JOSEFIN WINBERG
CENTRE FOR ENVIRONMENTAL AND CLIMATE SCIENCE | LUND UNIVERSITY

Pathways to sustainable bioenergy

Pathways to sustainable bioenergy

Navigating the energy-ecosystem services-biodiversity nexus in agricultural landscapes

Josefin Winberg

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 18th of October 2024 at 13.00 in Blue Hall, Department of Biology, Ecology building, Sölvegatan 37, Lund

Faculty opponent
Prof. Jens Dauber
Thünen Institute of Biodiversity & Technical University Braunschweig, Germany

Organization: LUND UNIVERSITY

Document name: Doctoral dissertation **Date of issue:** 2024-10-18

Author: Josefin Winberg

Title and subtitle: Pathways to sustainable bioenergy – Navigating the energy-ecosystem services-biodiversity nexus in agricultural landscapes

Abstract: Bioenergy plays a major role in the renewable energy supply and is projected to be an important part of the path towards a decarbonised society. Over the past decade, increasing attention has been given to agricultural bioenergy to act as a multifunctional climate mitigation strategy. Energy crops may mitigate climate change while simultaneously contributing to reducing the negative environmental impacts of agriculture if placed in intensive cropping regions or serve as alternative land use and source of income when placed on unused or marginal land. The deployment of extensive biomass production for energy is however potentially limited by competition with food, feed, and fibre production, as well as the need for nature conservation. To avoid conflicts between climate mitigation, food security, and biodiversity conservation, bioenergy strategies have to be thoroughly evaluated to ensure sustainable policy recommendations. This thesis aims to increase the knowledge of sustainable bioenergy production from Swedish agricultural landscapes and to understand the challenges and opportunities of extended agricultural bioenergy production for other societal goals. With a main focus on sustainable land use, I have studied the interaction between different bioenergy strategies, ecosystem service supply, and biodiversity conservation. I have combined methods from ecology, economy, and geography to provide a holistic view of agricultural bioenergy, covering different landscape contexts, production sites, biomass sources, spatiotemporal scales, and taxonomic groups. From the four chapters of this thesis, three main findings can be communicated: i) both ecosystem services and biodiversity impacts need to be considered when assessing bioenergy strategies to avoid trade-offs between climate mitigation and biodiversity conservation, ii) integrated production of bioenergy crops in intensive arable cropping regions may positively affect multiple ecosystem services and taxonomic groups if it is combined with protection of species-rich habitats, however, it requires substantial financial incentives and has consequences for food production, iii) there is a high risk of overestimating bioenergy potentials from marginal and unused land if land characteristics and alternative use-values are not considered. These results highlight the challenges of increasing agricultural bioenergy production without compromising other societal needs, but they also show the opportunities for sustainable bioenergy to contribute to a fossil-free society if coupled with sustainable food systems and broader reductions in energy use and consumption.

Keywords: renewable energy, climate mitigation, biodiversity conservation, multifunctionality, marginal land, abandoned land, land-use change, biomass production, afforestation, energy grass

Language: English

ISBN:

978-91-8104-147-7 (print)

978-91-8104-148-4 (pdf)

Number of pages: 60

Signature Date 2024-09-02

Pathways to sustainable bioenergy

Navigating the energy-ecosystem services-biodiversity nexus in agricultural landscapes

Josefin Winberg

Lund University

Cover illustration by: Josefin Winberg and Ida Gullberg

Faculty of Science
Centre for Environmental and Climate Science

ISBN (print) 978-91-8104-147-7
ISBN (pdf) 978-91-8104-148-4

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

"You can't go back and change the beginning,
but you can start where you are and change the ending."

C.S. Lewis

Table of Contents

Abstract

Bioenergy plays a major role in the renewable energy supply and is projected to be an important part of the path towards a decarbonised society. Over the past decade, increasing attention has been given to agricultural bioenergy to act as a multifunctional climate mitigation strategy. Energy crops may mitigate climate change while simultaneously contributing to reducing the negative environmental impacts of agriculture if placed in intensive cropping regions or serve as alternative land use and source of income when placed on unused or marginal land. The deployment of extensive biomass production for energy is however potentially limited by competition with food, feed, and fibre production, as well as the need for nature conservation. To avoid conflicts between climate mitigation, food security, and biodiversity conservation, bioenergy strategies have to be thoroughly evaluated to ensure sustainable policy recommendations. This thesis aims to increase the knowledge of sustainable bioenergy production from Swedish agricultural landscapes and to understand the challenges and opportunities of extended agricultural bioenergy production for other societal goals. With a main focus on sustainable land use, I have studied the interaction between different bioenergy strategies, ecosystem service supply, and biodiversity conservation. I have combined methods from ecology, economy, and geography to provide a holistic view of agricultural bioenergy, covering different landscape contexts, production sites, biomass sources, spatiotemporal scales, and taxonomic groups. From the four chapters of this thesis, three main findings can be communicated: i) both ecosystem services and biodiversity impacts need to be considered when assessing bioenergy strategies to avoid trade-offs between climate mitigation and biodiversity conservation, ii) integrated production of bioenergy crops in intensive arable cropping regions may positively affect multiple ecosystem services and taxonomic groups if it is combined with protection of species-rich habitats, however, it requires substantial financial incentives and has consequences for food production, iii) there is a high risk of overestimating bioenergy potentials from marginal and unused land if land characteristics and alternative use-values are not considered. These results highlight the challenges of increasing agricultural bioenergy production without compromising other societal needs, but they also show the opportunities for sustainable bioenergy to contribute to a fossil-free society if coupled with sustainable food systems and broader reductions in energy use and consumption.

Populärvetenskaplig sammanfattning

Två av de största hoten mot mänskligheten och vår omgivning är de pågående klimatförändringarna och förlusten av biologisk mångfald. Dessa är två tätt sammankopplade kriser eftersom klimatförändringar påverkar förutsättningarna för allt liv på jorden, samtidigt som en förlust av biologisk mångfald förvärrar konsekvenserna av ett förändrat klimat. Det komplexa sambandet mellan klimatförändringar och biologisk mångfald kräver att lösningar tar hänsyn till båda kriserna, så att en klimatåtgärd inte sker på bekostnad av biologisk mångfald och vice versa. Ett centralt fokus för klimatåtgärder är utsläppsminskningar från energisektorn. Det kan ske bland annat genom effektivisering och minskad användning av energi, samt genom att fossila bränslen och utsläppsintensiva energikällor fasas ut och ersätts av förnyelsebar energi. Inom Europa och i Sverige har bioenergi varit en viktig källa till förnyelsebar energi under det senaste decenniet och förutspås spela en viktig roll även framöver för att vi ska nå de uppsatta klimatmålen. Bioenergi är energi (t.ex. bränsle, värme, elektricitet) som produceras från biologiskt material så som energigrödor, skogsbiomassa och restavfall. Dock har hållbar produktion av bioenergi flera utmaningar eftersom det konkurrerar om mark och biomassa som kunde använts till annat. Detta kan få oönskade konsekvenser för andra samhällsmål så som livsmedelsproduktion och bevarande av biologisk mångfald.

Hur vi människor nyttjar naturresurser och använder mark har en stor påverkan på arter och dess livsmiljöer, men är också en starkt bidragande faktor till klimatförändringar, bland annat på grund av utsläpp av växthusgaser och lagring av kol i mark och vegetation. För att säkra en långsiktigt hållbar bioenergiproduktion som bidrar till utsläppsminskningar och inte konkurrerar med bevarandet av arter och dess livsmiljöer behöver hänsyn tas till vilken typ av biomassa som används samt hur och var denna är producerad. I denna avhandling har jag fokuserat på bioenergiproduktion från jordbrukslandskapet med syftet att undersöka hur olika strategier för att öka produktionen av jordbruksbaserad bioenergi påverkar biologisk mångfald och ekosystemtjänster (produkter och tjänster från ekosystem som gynnar oss människor). För att skapa en helhetsöversyn av bioenergistrategier har jag studerat olika typer av biomassa, däribland livsmedelsgrödor, energigrödor och skogsplantage, som producerats på olika typer av mark i jordbrukslandskapet. Dessa marktyper inkluderade jordbruksmark, gräsmarker, obrukad mark och marginalmark (d.v.s. mark som är marginellt lönsam att bruka). De studerade typerna av biomassa och produktionsplatser skiljer sig i sin markanvändnings-intensitet, men är också mer eller mindre viktiga för livsmedelsproduktion. I min avhandling har jag även kombinerat flera olika metoder för att utvärdera bioenergistrategier vilket gjort att jag kunnat inkludera studiesystem på olika geografiska skalor med olika ekosystemtjänster och organismer i fokus.

Huruvida hållbar bioenergiproduktion kan ske i jordbrukslandskapet eller ej har utvärderats av forskningsstudier under flera decennier och det finns dessvärre inga enkla svar. Mina studier visar att introduktionen av en flerårig energigröda på intensivt brukad jordbruksmark bidrar till ett mer varierat jordbrukslandskap, något som ofta medför positiva effekter för flertalet ekosystemtjänster och artgrupper. Inverkan på ekosystemtjänster och biologisk mångfald studeras dock sällan tillsammans, vilket gör att vi vet lite om den totala miljöpåverkan av sådana strategier. Dessutom finns det många arter som inte gynnas av en intensiv bioenergiproduktion samtidigt som en ökad bioenergiproduktionen få sekundära effekter i landskapet om en ändrad produktionsinriktning i jordbruket gör att artrika miljöer går förlorade. Även om bioenergigrödor kan förbättra miljöförhållanden inom jordbruket genom exempelvis ökad kolinlagring och minskad användning av bekämpningsmedel kan de inte ses som en bevarandeåtgärd för biologisk mångfald. Bevarande av biologisk mångfald i jordbrukslandskapet kräver istället riktade bevarandeåtgärder där arters specifika behov av livsmiljöer tillgodoses.

Bioenergiproduktion från aktiv jordbruksmark har dock fått mycket kritik inom både politik och forskning då energiproduktionen riskerar att konkurrera med matproduktion, vilket i så fall ökar risken för höjda matpriser och indirekta markanvändningsförändringar på andra platser för att kompensera för den förlorade produktionen. Uppmärksamheten har därför vänts mot mark som inte anses fylla en viktig funktion för livsmedelsproduktion, så som marginalmark eller obrukad mark. Dessa marktyper är ofta vagt definierade och deras potential för biomassaproduktion grundas till stor del på grova uppskattningar. Mina studier visar dessutom att arealen obrukad mark i södra Sverige är liten och dessa marker kan ha hög artrikedom. Marginalmark målas ofta upp som den ultimata lösningen på hur markanvändningskonflikterna från bioenergiproduktion kan minska, men min avhandling visar att konflikterna med matproduktion, bevarande av biologisk mångfald och rekreation till stor del kvarstår.

Min avhandling visar på vikten av att inkludera både ekosystemtjänster och biologisk mångfald i utvärderingar av bioenergistrategier för att undvika konflikter mellan klimatåtgärder och bevarandeåtgärder. Detta kräver att vi bättre förstår vilka livsmiljöer som gynnar biologisk mångfald för att styrmedel ska kunna utformas som säkerställer att dessa ekosystem bevaras samtidigt som klimatförändringar bekämpas. Även om hållbart producerad bioenergi kan vara en del av vägen mot ett fossilfritt samhälle krävs även andra samhällsförändrande åtgärder som minskar vår totala energianvändning och konsumtion för att de globala klimatmålen ska nås.

List of papers

Chapter I

Winberg J., Smith H. G., Ekroos J. (2023) Bioenergy crops, biodiversity and ecosystem services in temperate agricultural landscapes - A review of synergies and trade-offs. *GCB Bioenergy,* 15(10), 1204-1220.

Chapter II

Winberg J., Ekroos J., Eklundh L., Smith H. G. (2024) Constraints on the availability of marginal land for bioenergy production in southern Sweden. *Under review in Biomass and Bioenergy.*

Chapter III

Winberg J., Ekroos J., Smith H. G. (2024) Abandonment or biomass production? Phytodiversity responses to land-use changes of semi-natural grasslands in northern Europe. *Biological Conservation*, 294, 110632.

Chapter IV

Winberg J., Larsson C., Stjernman, M., Ekroos J., Clough, Y., Smith H. G. (2024) Grass leys as multifunctional climate mitigation strategy in intensive cropping systems require high financial incentives. *Manuscript*

Additional published papers not included in the thesis

Thomson Ek, H., Singh, J., Winberg, J., Brady, M., Clough, Y. (2024) Farmers' motivations to cultivate biomass for energy and implications. *Energy Policy*, 193, 114295.

Author contributions

Chapter I

All authors contributed to the conceptualisation of the study. **JW** designed the methodology and performed the data collection and analysis, with input from HGS and JE. **JW** wrote the first manuscript draft and all authors contributed with revisions and comments.

Chapter II

All authors conceived the idea of the study. **JW** designed the methodology and performed the statistical analyses with input from LE, HGS, and JE. **JW** wrote the first manuscript draft and all authors contributed with revisions and comments.

Chapter III

All authors contributed to the conceptualisation and design of the study. **JW** carried out the data collection and the statistical analysis with input from HGS and JE. **JW** wrote the first manuscript draft and all authors contributed with revisions and comments.

Chapter IV

JW, HGS, and YC conceptualised the study. **JW**, HGS, JE, and CL designed the methodology. CL performed the agent-based modelling with input from **JW. JW** made the agent-based modelling results spatially explicit**.** MS performed the ecological modelling in discussion with **JW**. Data analyses were made by **JW** with input from HGS and JE. **JW** led the drafting of the manuscript with input from all co-authors.

Authors: Josefin Winberg (JW), Henrik G. Smith (HGS), Johan Ekroos (JE), Lars Eklundh (LE), Yann Clough (YC), Cecilia Larsson (CL), Martin Stjernman (MS)

Abbreviations

ABM	Agent-based model
ANC	Areas of Natural Constraints
BECCS	Bioenergy with carbon capture and storage
CAP	Common Agricultural Policy
EU	European Union
FBI	Farmland Bird Index
GHG	Greenhouse gases
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
LU/LC	Land use/land cover
RED	Renewable Energy Directive
SDG	Sustainable Development Goals
SNG	Semi-natural grasslands
SNH	Semi-natural habitat
SOC	Soil organic carbon

Introduction

Despite humanity's dependence on nature, we are severely altering ecological systems to a point where the quality of life for people is threatened. Human activities have changed biophysical and biochemical systems and processes, driving planetary environmental conditions into a state outside of the safe operating space for humanity (Richardson et al., 2023). Two main factors in the stability and functioning of the Earth system are climate change and biodiversity loss (Steffen et al., 2015). Through our use and transformation of ecosystems, biodiversity is declining globally at an unprecedented rate and currently threatening more than 1 million species with extinction (Díaz et al., 2019; IPBES, 2019; Jaureguiberry et al., 2022). In addition, human-caused climate change poses a threat to humans and nature by affecting the weather and climate extremes across the globe (IPCC, 2023). One of the main challenges for humanity in the 21^{st} century is to find sustainable climate mitigation and biodiversity conservation strategies (IPBES, 2019; IPCC, 2023), a challenge that becomes increasingly urgent. However, a critical question remains: Can we mitigate climate change without harming biodiversity and ecosystems? A large focus in climate mitigation is on energy generation and there are multiple pathways to reduce greenhouse gas emissions in the energy sector. These mainly include replacing fossil fuels with renewable energy sources, such as wind, solar, or biomass energy generation, but few of these options include co-benefits for biodiversity protection (Pörtner et al., 2023). A narrow focus on emission reductions and short-term mitigation solutions carries the risk of generating new sustainability issues, but measures that are locally adapted, holistic, and have a long-term view can create robust and synergistic mitigation pathways (Smith et al., 2022). Moving forward, we need sustainable management of land resources, where climate mitigation occurs in a socially and ecologically responsible manner (Kiesecker et al., 2024) to ensure that no Sustainable Development Goal (SDG) is reached at the expense of another (United Nations, 2015). This requires integrated approaches focusing on the connections, synergies and trade-offs between societal goals. Nexus approaches enable the evaluation of sustainability impacts in complex systems by addressing the interlinkages between sectors and SDGs (Liu et al., 2018), such as providing renewable energy without compromising food production, environmental quality, and biodiversity conservation. In this thesis, I have used a nexus approach to address how different methods of adopting agricultural bioenergy as climate mitigation strategies in Sweden may affect the supply of ecosystem services and biodiversity.

The link between biodiversity loss and climate change

The term biodiversity captures the variability of all organisms, including the diversity within species, between species, and of ecosystems (Convention on Biological Diversity, 1992). In addition to the intrinsic value of ecosystems and all living organisms, i.e. their inherent worth independent of how useful they are to humans (Redford & Richter, 1999), biodiversity also has an instrumental value for humans, including pools and fluxes of materials and energy. Biodiversity loss diminishes these services by altering the ecosystem functions and stability (Cardinale et al., 2012; Isbell et al., 2017). A continued supply of ecosystem functions and resilience that benefit humanity also in the future hence requires conservation of the biodiversity that underpins these ecosystem services (Dee et al., 2019; Mace et al., 2012; Reich et al., 2012).

The conservation of biodiversity and ecosystem services is under additional threat from climate change (Pörtner et al., 2021). Anthropogenic emissions of greenhouse gases (GHG) have resulted in global warming above 1.1°C relative to preindustrial levels, creating additional stresses on human livelihoods, land resources (IPCC, 2023), and nature (Trisos et al., 2020; Urban, 2015). A changing climate forces species to adapt or to shift geographical range, leading to changes in species interactions, composition, and ecological functions (Pörtner et al., 2023). When species cannot migrate to new habitats or adapt to new climate conditions, they may face local or global extinctions (Román-Palacios & Wiens, 2020). Urgent conservation actions are required to maintain a healthy planet for all living species, but the shared drivers and mechanistic links between biodiversity and climate have increased the recognition that a more integrated approach is needed to find sustainable solutions (Pettorelli et al., 2021; Pörtner et al., 2021).

To limit global warming well below a 2°C increase from pre-industrial levels, in line with the Paris Agreement on Climate Change, major reductions of GHG emissions are required worldwide (IPCC, 2023). As a part of the European Green Deal, the European Union (EU) and its member states have set out to reduce GHG emissions by at least 55% by 2030 from 1990 levels and achieve climate neutrality by 2050 (European Commission, 2020b). After the COVID-19 pandemic and the Russian invasion of Ukraine, ensuring energy security within the EU has gained even more importance, thereby reducing the dependency on energy imports (Mišík & Nosko, 2023). This has been concretised in the RePowerEU plan, aligning climate mitigation targets with an energy independence strategy, where actions such as reducing overall energy consumption and increasing the share of renewable energy have been advocated (European Commission, 2022).

At the same time, the EU has adopted a Biodiversity Strategy for 2030 to protect and restore biodiversity and halt ecosystem degradation as a contribution to the Kunming-Montreal Global Biodiversity Framework (European Commission, 2020a). The strategy recognises the interdependence between biodiversity loss and climate change, intending to protect at least 30% of land in Europe and reach the legally binding target to restore at least 20% of degraded land and sea areas under the Nature Restoration Law. The proposed conservation actions are expected to have co-benefits for climate mitigation, in particular by avoiding deforestation and restoring ecosystems with significant carbon storage potential (Shin et al., 2022). Aligning and fulfilling the climate and biodiversity commitments is essential to achieve the transformative change needed to secure healthy ecosystems and a liveable planet (Pörtner et al., 2023).

The focus on agricultural landscapes

Agriculture plays a crucial role in modern society by providing food and biobased material to a growing global population and by supporting rural livelihoods. With more than one-third of all terrestrial land currently devoted to agricultural production, agroecosystems also greatly impact biodiversity and ecosystem functions (IPBES, 2019). In most parts of the world, agricultural productivity has increased rapidly over the last century through developments in the use of synthetic fertilisers, pesticides, machinery, and species varieties (Pellegrini & Fernández, 2018; Robinson & Sutherland, 2002). Despite the increase in agricultural productivity, around 30% of the global population faces food insecurity, with large inequalities between regions (FAO et al., 2023). In addition, intensified agricultural production has resulted in simplified landscapes with increased erosion, soil carbon loss, nutrient run-off, and pollution, which have caused environmental impacts such as eutrophication, soil degradation, global warming, and declines in biodiversity (Power, 2010). Consequently, essential ecosystem services important for agricultural production, such as pollination, biological pest control, nutrient cycling, and soil formation, have declined across intensive agricultural regions (IPBES, 2019). Further land-use intensification may temporarily compensate for some of the productivity reduction caused by declines in ecosystem services but with the risk of additional environmental externalities and productivity loss over time (Seppelt et al., 2019).

Increasing landscape and crop heterogeneity across spatiotemporal scales has been suggested to support biodiversity within agroecosystems (Benton et al., 2003; Fahrig et al., 2011), which in turn may benefit the delivery of ecosystem services (Tscharntke et al., 2005, but see Birkhofer et al., 2018). The increase or maintenance of landscape complexity often involves protecting and restoring semi-natural habitats (SNH) (Gonthier et al., 2014; Holland et al., 2017), while crop diversification in space and/or time from e.g. intercropping or crop rotation can contribute to complexity at the field level (Hufnagel et al., 2020). SNH, such as field edges, woodlands, or extensive grasslands, are important habitats for several organisms, including pollinators and natural enemies that may spill over to surrounding sites and have a positive spillover effect for pollination and pest control in the agricultural landscape (Blitzer et al., 2012; Holland et al., 2017; Öckinger & Smith, 2007). The connectivity between suitable habitats influences the dispersal of species among habitat patches, where the importance of the scale of connectivity is set by the behaviour and characteristics of the organism (Taylor et al., 2006).

Agricultural land can be both a source and sink of carbon due to anthropogenic and natural factors. With the agricultural sector accounting for more than 10% of anthropogenic GHG emissions, there is great potential for adopting land uses, agricultural practices, and food systems that contribute to climate mitigation and adaptation (IPCC, 2019). However, there are major concerns that agricultural mitigation could negatively affect the food and biomass supply (Smith et al., 2013; Valin et al., 2013), which calls for mitigation strategies that reduce the trade-off between GHG abatement and food security. Within agricultural production, such proposed strategies include for example increased sequestration of soil organic carbon (SOC) on cropland (Frank et al., 2017), sustainable intensification (Pretty & Bharucha, 2014; Rockström et al., 2017), or optimised input of mineral fertilisers (Foley et al., 2011). Together with the reduction of food waste and losses throughout the post-harvest production chain (Notarnicola et al., 2017; Vázquez-Rowe et al., 2021), and dietary shifts towards products with a lower GHG footprint (Aleksandrowicz et al., 2016; Tilman & Clark, 2014), food production could be maintained while fundamentally reducing the environmental impact.

In parallel with the intensification and regional specialisation of agriculture in Europe, an increased abandonment of marginal or remote arable land and semi-natural grasslands has been recorded (Ustaoglu & Collier, 2018). The cessation of agricultural activities and management has been attributed to biophysical, socioeconomic, and political factors that limit the profitability of maintained production in certain fields or regions (MacDonald et al., 2000; Rey Benayas et al., 2007; van der Zanden et al., 2017). Farmland abandonment may further exacerbate the competition over limited resources of arable land that already faces increasing demand for agricultural commodities, environmental consideration, and biodiversity conservation (Lécuyer et al., 2021). At the same time, abandoned land is also seen as a promising resource for alternative uses to avoid land-use conflicts (Muscat et al., 2022). If abandoned farmland does not remain abandoned for natural succession to revegetate the former fields towards semi-natural landscapes, it is often afforested, urbanised, or transformed back to agricultural use (Fayet et al., 2022).

The environmental impacts of farmland abandonment are context-dependent and can further be influenced by site characteristics, former land use, and the surrounding landscape (MacDonald et al., 2000; van der Zanden et al., 2017). Abandonment in intensively farmed agricultural landscapes may offer opportunities for regenerating natural ecosystems that can enhance the local and landscape heterogeneity, increase SOC sequestration, and reduce the use of chemical inputs (Navarro & Pereira, 2012; van der Zanden et al., 2017). On the contrary, abandoning fields in low-intensity traditional farmland landscapes can cause negative environmental and ecological impacts as they are dependent on the extensive management that has shaped unique conditions for biodiversity and ecosystem services over hundreds or even thousands of years (MacDonald et al., 2000; Queiroz et al., 2014). When considering abandoned land for alternative uses, studies that consider both local and landscape context-specific conditions are necessary to avoid further land-use conflicts.

Agricultural landscapes have undergone considerable changes over the past centuries, and Sweden is no exception. In the high-productive arable regions fields have become larger and more intensely managed, while landscape openness has decreased in the marginally productive regions due to afforestation (Ihse, 1995). Furthermore, more than 50% of grasslands with a long history of extensive grazing and mowing, so-called semi-natural grasslands (SNGs), have been lost over the past 100 years due to reduced number of cattle, arable intensification, afforestation, or abandonment (Aune et al., 2018; Swedish Board of Agriculture, 2008). SNGs are often characterised by a high biodiversity consisting of species adapted to and dependent on biomass removal from grazing and mowing (Eriksson et al., 2002). The loss of grasslands from Swedish landscapes has not only resulted in a decline in biodiversity (Cousins, 2009), but likely also in a loss of ecosystem functionality as SNGs are important for ecosystem services such as carbon storage, pollination, and erosion control (Bengtsson et al., 2019).

Even if other open habitats similar to SNGs in the boreal landscape can serve as alternative habitats for grassland species (Andersson et al., 2022; Johansen et al., 2022), the surrounding landscape has successively become less suitable for most grassland species to survive. Increasing demand for forest products has driven the intensification of Swedish forestry, resulting in a forest landscape dominated by even-aged stands of monocultural spruce plantations, managed in rotational clear-felling (Petersson et al., 2019). The land use within agriculture and forestry, including deforestation and the increasing overgrowth of abandoned land, are the main factors driving the red-listing of species in Sweden (Eide et al., 2020).

With a growing population to feed (Godfray et al., 2010), higher demand for biobased material (Muscat et al., 2020), and an urgent need for climate mitigation and biodiversity conservation (Pörtner et al., 2021), the agricultural landscape is under higher pressure than ever. When selecting the pathway forward, research and policy must focus on identifying synergies between these demands and how these can be balanced in different landscape contexts.

Bioenergy – a sustainable source of renewable energy?

The main source of renewable energy in the EU is bioenergy produced from agricultural, forestry, and organic waste feedstock, accounting for around 60% of the renewable energy consumption (European Commission, 2023). To meet the global and European GHG reduction targets, bioenergy coupled with carbon capture and storage (BECCS) is expected to play an important role also in the future energy supply (European Commission, 2017; Rogelj et al., 2018) by offering opportunities for domestic energy markets and a predictable energy supply to sectors that are difficult to decarbonise or electrify (Davis et al., 2018; Debnath et al., 2019). The current main utilisation of bioenergy is for heating and cooling, but biomass is also used to produce biofuels and bioelectricity (European Commission, 2023). Sweden is one of the countries in the EU that has the largest supply and per capita consumption of bioenergy (Wu & Pfenninger, 2023), with forest biomass accounting for more than 80% of the utilised bioenergy (Black-Samuelsson et al., 2017). While Swedish forestry mainly supplies wood for pulp and timber, the residues from harvests and industries (e.g. slash, stumps, and sawdust) are important for bioenergy production. However, the sustainability of forest-derived bioenergy has been questioned because of the negative impacts on biodiversity and uncertain GHG emission reductions of the current silvicultural production system and intensive forest management (de Jong & Dahlberg, 2017; Harper et al., 2018; Norton et al., 2019). The ongoing climate change is putting further pressure on the Swedish forests to provide increased harvests of wood for supplying bioenergy and biobased materials for the decarbonisation of society (Cintas et al., 2017; Hildebrandt et al., 2017), at the same time as the importance of sustainable forest management to enhance carbon storage in forests has been emphasised (IPCC, 2019). The impossible task of managing forests to maximise both the carbon storage and the harvest of forest biomass to substitute fossil fuels within the same timeframe (Rummukainen, 2021) suggests other sources of biomass, such as agricultural feedstock, are needed for future bioenergy production (Searchinger et al., 2022).

The first generation of agricultural bioenergy crops was derived from oils, starches, and sugars of food biomass, such as wheat, corn, or oil crops. These crops were mainly used to produce biofuel but because of their direct competition with food production and negative effects on biodiversity, attention has been turned to second-generation bioenergy crops (residues or lignocellulosic, woody crops) (Havlik et al., 2011; Immerzeel et al., 2014). However, the choice of biomass matter is not the only factor important for ensuring emission reductions from bioenergy, but also the land used for biomass production and how the energy is being used (Harper et al., 2018). Cultivation of bioenergy crops on agricultural land risks indirect land-use changes and displacement effects on GHG emissions and biodiversity, as additional land is needed to maintain food production (Nunez-Regueiro et al., 2019; Searchinger et al., 2008). In addition, the context-specific biophysical and socio-economic conditions may increase the risk of land degradation, displacement of local actors, food insecurity, water scarcity, and biodiversity loss (IPCC, 2019; Vera et al., 2022). The controversial sustainability implications of agricultural bioenergy have been debated for the past decades (Leemans et al., 1996; Robledo-Abad et al., 2017; Tilman et al., 2009), leading to increasingly ambitious sustainability requirements for bioenergy to minimise trade-offs between energy production, food security, and the protection of the environment. For energy used within the EU, these requirements are specified in the EU Renewable Energy Directive (RED) (EU Directive 2023/2413) and include for example restrictions on using biomass that undermines food and feed production, land carbon sinks, or biodiverse habitats, with GHG emissions saving criteria for the energy that is produced.

One alternative source of bioenergy that reduces environmental trade-offs as well as competition over land and food is the energy production from municipal waste and residues from agriculture and forestry (Vera et al., 2022). However, the supply of residues does not meet the full demand for bioenergy (Daioglou et al., 2019) which has created a growing body of literature that investigates the potential to integrate perennial energy crops strategically in the agricultural landscape to mitigate the negative impacts of intensive agriculture (Asbjornsen et al., 2014; Carlsson et al., 2017; Dauber & Miyake, 2016; Englund et al., 2020a; Milner et al., 2016), or to produce dedicated bioenergy feedstock on marginal or abandoned cropland (Dauber et al., 2012; Muscat et al., 2020; Næss et al., 2023).

Marginal land is a wide term, often used to describe low-productive or remote land in the agricultural landscape that is on the economic margin for food or feed production (Elliott et al., 2024; Shortall, 2013; Tilman et al., 2006). The marginality of land may be defined due to the biophysical characteristics of the land (such as the soil quality or erodibility) (Gelfand et al., 2013; Gopalakrishnan et al., 2011), the utilisation (Dale, 2010; Gopalakrishnan et al., 2011; Shortall, 2013), the geographical location (Beilin et al., 2014; MacDonald et al., 2000), or the socio-economic setting (Khanna et al., 2021; Strijker, 2005). Driven by the limited economic viability or any other factors that hinder production, marginal arable fields or grasslands risk abandonment if no incentives are in place to maintain the production (Elliott et al., 2024; Munroe et al., 2013). Marginal and abandoned land have received wide attention for the potential to produce bioenergy crops that thus will not compete with food production at the same time as it provides an alternative source of income for rural communities as the perennial energy crops often are better adapted to poor production conditions (Khanna et al., 2021; Mehmood et al., 2017). Depending on the characteristics of the site and land owner preferences, marginal or abandoned land may be used for the production of agricultural feedstock or forest biomass to generate bioenergy (Csikós & Tóth, 2023). However, the feasibility of cultivating bioenergy crops on marginal land has been questioned due to low economic incentives (Bryngelsson & Lindgren, 2013), poor yields (Dauber et al., 2012), and limited willingness from farmers to supply marginal land for bioenergy crop production (Skevas et al., 2016). Many types of marginal land may also have alternative use values, such as sequestering carbon or providing valuable sites for biodiversity conservation or recreational activities (Dauber et al., 2012; Gopalakrishnan et al., 2011) that have to be taken into account before being considered for biomass production.

While utilisation of marginal land for bioenergy production does not fully resolve sustainability trade-offs, growing perennial energy crops on marginal land or in intensively farmed landscapes can reduce environmental problems such as erosion, nutrient leakage, and flooding (Englund et al., 2020a), as well as increasing SOC sequestration (Carlsson et al., 2017; Xu et al., 2022). If bioenergy systems are developed sustainably, they could increase the multifunctionality of agroecosystems to promote synergies between bioenergy production, biodiversity, and the provisioning of ecosystem services (Carlsson et al., 2017; Englund et al., 2023). In the Nordic countries, including Sweden, one such strategy is including perennial grass in crop rotations with annual crop production (Englund et al., 2023; Prade et al., 2017). Growing grass leys for feed and pastures is a common practice in Sweden, where nearly half of the agricultural land presently is used for grass ley production (Swedish Board of Agriculture, 2023b), but the same biomass could also be used as a biogas substrate (Ahlgren et al., 2017; Gustafsson & Anderberg, 2023).

Marginal and abandoned land, as well as additional integration of grass leys in intensive agriculture, could play an important role in increasing the domestic bioenergy supply in Sweden, but more knowledge is needed on how such climate mitigation strategies may impact ecosystem services and biodiversity across spatial scales. This thesis contributes with new aspects to the overarching question of how Swedish agricultural landscapes could be used for sustainable bioenergy production without compromising the supply of ecosystem services and biodiversity.

Thesis aims and scope

This interdisciplinary thesis aims to increase the knowledge of sustainable bioenergy production from the Swedish agricultural landscape and to understand the challenges and opportunities of increased agricultural bioenergy production for other societal goals. To achieve this goal, I have studied the interaction between bioenergy strategies, ecosystem services supply, and biodiversity conservation, where sustainable land use is a central focus. The thesis evaluates different pathways to sustainable bioenergy by covering multiple alternative production sites and biomass sources (Figure 1). First, I provide an overview of the sustainability and research gaps in agricultural bioenergy (**Chapter I**). I then address two strategies for sustainable bioenergy production: i) using abandoned or marginal land to produce bioenergy to avoid conflicts with food production (**Chapters II and III**), and ii) integrating grass biomass production in the intensive agricultural landscape as a multifunctional climate mitigation action (**Chapter IV**).

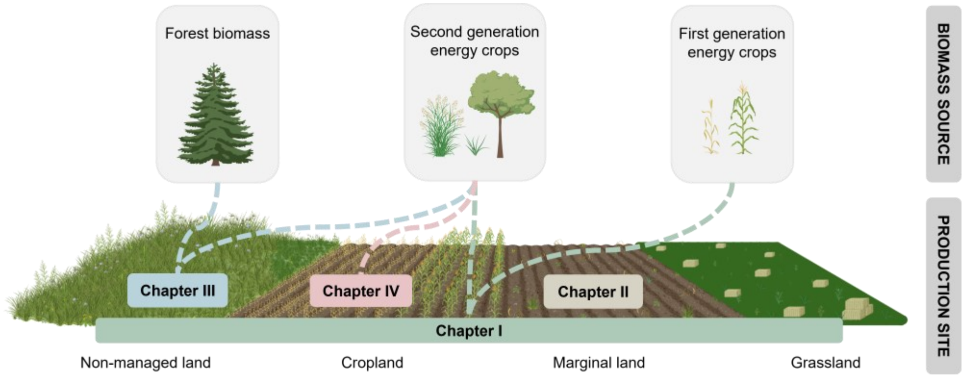

Figure 1. A conceptual overview of the biomass sources and production sites in focus of the different chapters of the thesis. Image source: BioRender.com

For each of the chapters I addressed the following research questions and aims:

Chapter I: *How does introduction of bioenergy crops on different types of agricultural land impact the supply of ecosystem services and biodiversity?*

In Chapter I, I give an overview of the sustainability of agricultural bioenergy by reviewing the impact of bioenergy-driven land-use changes in temperate agricultural landscapes on ecosystem services and biodiversity. The literature review was limited to only considering studies of land conversions that have been suggested within policy and/or research as potential production sites for agricultural bioenergy (arable land, grasslands, marginal land, abandoned land, and fallows), and I included both first- and second-generation bioenergy crops. The aims of Chapter I were to i) identify potential synergies or trade-offs between biodiversity conservation and ecosystem services from the studied land-use changes, ii) analyse patterns in how bioenergy land-use changes are studied and how this may impact the interpretation of results, and iii) identify research gaps for how an introduction of bioenergy crops in the agricultural landscape impacts biodiversity and ecosystem services. The findings from Chapter I guided the aims of the following chapters to cover research gaps and uncertainties in Swedish and European bioenergy research.

Chapter II: *To what extent can easily identified marginal land contribute to sustainable bioenergy production?*

In Chapter II, I studied marginal land in south Swedish arable landscapes to improve the understanding of its potential for bioenergy production. Using public databases, I mapped, quantified, and characterised marginal land, and with the aid of remote sensing I identified the current land use. The aims of Chapter II were to i) understand what type of marginal land can be identified from public databases, ii) study how marginal land differs from productive arable land in biophysical characteristics and socioeconomic settings, and iii) assess potential alternative use values of marginal land and how these may affect the availability for feedstock cultivation.

Chapter III: *What are the biodiversity consequences of using abandoned grasslands for bioenergy production?*

Chapter III builds further on the findings from Chapters I and II by focusing on land-use changes of SNG in a mixed farm-forest region of south Sweden that is sensitive to agricultural abandonment. Using a space-for-time substitution approach, I studied how plant communities of SNG respond to three land-use change scenarios: grazing abandonment, spruce afforestation, and grassland improvement by intensification. The aims of this chapter were to i) evaluate the contribution of abandoned, afforested, and improved SNG to local plant diversity, and ii) assess what effects an increased production of wood and grass for bioenergy purposes on abandoned SNG could have on biodiversity.

Chapter IV: *Can the integration of agricultural bioenergy production in intensive cropping regions act as a multifunctional climate mitigation strategy?*

Finally, in Chapter IV, I studied the potential of agricultural bioenergy production as a multifunctional climate mitigation strategy in intensively farmed regions. Focusing on grass leys for bioenergy production and using an agent-based model

(ABM) in combination with an ecological model on farmland bird diversity, this chapter aimed to i) assess how incentivising energy ley production affects the farm structure and land use in an intensive cropping region, and ii) evaluate how increased uptake of energy ley in crop rotations affects the supply of ecosystem services and conservation of farmland birds.

Methods

Study systems and data collection

This thesis is set in the agricultural landscape and includes land-use studies for bioenergy production across spatiotemporal scales. **Chapter I** gives an overview of bioenergy-driven land-use changes of agricultural land in the temperate climate zone using literature from North America and Europe, and **Chapters II**, **III**, and **IV** study the potential for and impacts of producing agricultural bioenergy in southern Sweden (Figure 2).

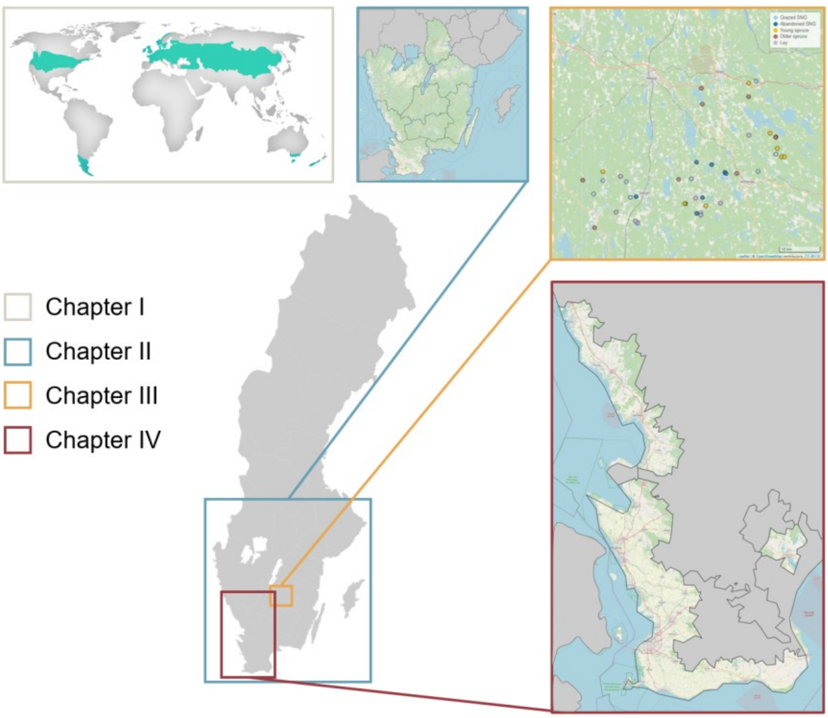

Figure 2. Maps of the spatial extent of the study systems in the four chapters. Chapter I reviewed studies from the temperate climate zone (illustrated in turquoise). For Chapters II-IV, the study systems are illustrated with a background map sourced from OpenStreetMap. Chapter II included the nine southernmost counties in mainland Sweden, Chapter III focused on 42 field sites in Jönköping county, and Chapter IV studied the production region GSS (Götalands Södra Slättbygder).

In **Chapter I**, a literature review was conducted to synthesise the biodiversity and ecosystem service impacts from land-use changes to bioenergy production in temperate agroecosystems (Figure 2). The search for literature was performed in the Web of Science Core Collection to access peer-reviewed research articles, using methods for systematic reviews to reduce biases (Haddaway et al., 2015). The literature search was based on a pre-determined search string and the identified papers were screened for relevance with a decision tree, resulting in 54 original research papers in the review. A review matrix was used to extract the relevant information from each article, including details of the reference land use, bioenergy crop, taxonomic group to represent biodiversity, examined ecosystem service(s), geographical scope, methodology used, production scale, and the assessed impact (on the species, taxonomic group, or ecosystem service). Studies were subdivided into land-use change cases to synthesise how specific land-use changes affected individual ecosystem services or taxonomic groups. The reference land use was categorised into four groups: arable land, grassland, marginal land, and non-managed land, and bioenergy crops were grouped into first- or second-generation energy crops. The categorisation of ecosystem services was based on the Millennium Ecosystem Assessment classification (Millennium Ecosystem Assessment, 2005), and the biodiversity assessments were classified into taxonomic groups: amphibians, birds, reptiles, mammals, invertebrates, plants, microorganisms and, in cases where no explicit organism was studied, unspecified biodiversity. The methodology used in the reviewed literature was grouped into direct (empirical) and indirect (modelling, simulations) measurements, and the geographical scope was categorised into local and regional scales. For each land-use change case, the assessed impact on a specific ecosystem service or species/taxonomic group from the literature was noted as positive, neutral/mixed, or negative.

Chapter II focused on the nine southernmost counties of mainland Sweden to identify and characterise marginal land. The nine counties (Skåne, Blekinge, Kronoberg, Halland, Kalmar, Jönköping, Örebro, Östra Götaland, and Västra Götaland; Figure 2) contain the majority of agricultural land in Sweden but differ in land-use intensity, landscape complexity, and socioeconomic conditions. The present utilisation of land was used as an indicator to detect marginal land that either had no evident uses or was used in arable production but without receiving agricultural subsidies. In a raster-based analysis, we developed a spatial analysis funnel approach to identify marginal land from land-use and land cover data from official databases (Lantmäteriet, 2021; Statistics Sweden, 2021; Swedish Board of Agriculture, 2021; Swedish Environmental Protection Agency, 2020, 2021; Swedish University of Agricultural Science (SLU), 2015; The Swedish Transport Administration, 2021). The analysis started from the broad land-cover classes "Agricultural land" and "Open land with vegetation" in the National Land Cover Database of Sweden and from these two classes all other apparent land uses were removed, including arable land that received any CAP subsidies during 2015-2020, forested land, urban areas, military areas, recreation facilities, nature protected areas, infrastructure, buildings, and waterfronts by oceans, lakes, or rivers. All connecting raster cells larger than 0.1 ha were kept for further evaluation of the marginal land availability for bioenergy production.

In **Chapter III**, we conducted a space-for-time substitution study (Pickett, 1989) to assess the potential biodiversity effects of biomass production on abandoned grasslands in a mixed farm-forest study area in southern Sweden (Figure 2). The study area was located in Jönköping county (57°45′N, 14°12′E), a forest-dominated region with agricultural landscapes mainly consisting of animal farms and small holdings that are susceptible to farmland abandonment (Perpiña Castillo et al., 2018). We identified 42 sites of grazed, abandoned, spruce afforested, and improved SNG, using agricultural and forest land-use data (Swedish Board of Agriculture, 2021, 2022; Swedish Environmental Protection Agency, 2020) and times-series of orthophotos (Lantmäteriet, 2022). Plant surveys were conducted in two survey rounds between June and August 2022 to identify vascular plants to species level for each site (Figure 3). The sampling was randomly distributed along site borders and within the site to achieve a similar sample completeness for all sites and habitats (Chao & Jost, 2012).

Figure 3. Field assistants and the author conducting plant surveys in grazed semi-natural grassland (to the left) and afforested semi-natural grassland (to the right). Photos taken by author (2022).

For **Chapter IV** we combined agent-based economic modelling with multiple ecosystem services and biodiversity production functions to estimate the consequences of policies incentivising energy leys as a climate mitigation strategy. The combined assessment of ecosystem services and biodiversity under different policy and land-use scenarios allowed the identification of synergies or trade-offs between different outputs and societal goals (cf. Nelson et al., 2009). The study focused on Götalands Södra Slättbygder (GSS, i.e. the arable plains of southern Sweden; Figure 2), the most productive arable region in Sweden that extends over the two counties Skåne (55°59′N, 13°26′E) and Halland (56°43′N, 12°49′E).

Data analysis

After using a systematic approach to identify and classify relevant literature for the literature review in **Chapter I**, we summarised the land-use change cases into a total impact assessment for specific taxonomic groups or ecosystem services following Immerzeel et al. (2014). The total impact included five classes: 1) strong positive impact (≥ 75% of the cases reported a positive impact), 2) moderate positive impact (≥50% but <75% of cases reported a positive impact), 3) no or mixed impact (no impact or equally many cases with positive and negative impacts), 4) moderate negative impact (≥50% but <75% of cases reported a negative impact), or 5) strong negative impact (≥ 75% of the cases reported a negative impact).

The marginal land identified in **Chapter II** was characterised by analysing the land use/land cover (LU/LC), soil moisture, crop productivity, and socioeconomic setting, to assess the type of marginal land that may be identified from public databases and its potential for bioenergy production. The LU/LC was determined for a subset of the marginal land using remote sensing (Google, 2022; Lantmäteriet, 2022). We also identified the land cover surrounding these sites (Swedish Environmental Protection Agency, 2020) to identify in which landscapes marginal land generally occurs. The same subset of marginal land was used to compare the soil moisture index (Swedish Environmental Protection Agency, 2020) of marginal land to the surrounding 1 km arable landscape using a Wilcoxon signed-rank test and to existing energy crop sites using a Mann-Whitney U test. The relationship between marginal land and site productivity was analysed using generalised linear models with the standard yield of spring barley across crop yield areas from Swedish Board of Agriculture (2023a) as the dependent variable. The analysis was weighted by the influence of organic farming on yields and the geographical coordinates were added as fixed terms to the model to account for spatial autocorrelation in the model residuals. Further analysis of how the farming conditions (regional productivity and socioeconomic setting) were associated with the area of marginal land identified was made by comparing marginal land coverage across areas of natural constraints (ANCs) using a Kruskal-Wallis rank-sum test.

In **Chapter III**, we investigated the impact of biomass production on abandoned grasslands for local plant diversity and community composition. To analyse local diversity, generalised linear models were constructed with species richness and Shannon diversity as response variables and habitat type, landscape composition in a 1 km radius of each site, time since land conversion/abandonment, and sampling intensity as predictors. The difference in plant community composition between habitats and its relationship to SNG coverage in the surrounding landscape was analysed using nonmetric multidimensional scaling (NMDS) ordination analysis and permutational multivariate analysis of variance (PERMANOVA). The community dissimilarity was further analysed by calculating its turnover and nestedness components to assign the dissimilarity pattern to species replacement or species loss (Baselga, 2010). Species of conservation concern were identified using information on red-listing, signal species, and/or protected species (SLU Artdatabanken, 2023).

In **Chapter IV**, the ABM AgriPoliS (Happe et al., 2006) was used to simulate how farm structure and land use responded to three policy scenarios differentiated by increasing area-based subsidies to the production of energy leys for biomethane (50, 200, and 350 € ha^{-1}). These were compared to a reference scenario where the subsidy for energy ley was set to zero. From the AgriPoliS model and the submodels coupled to it, we also extracted information on soil carbon content (% SOC in topsoil; Brady et al., 2019), pesticide use (kg active substance of fungicides, herbicides, and insecticides; Agriwise, 2017), and contribution to food production (kcal produced from food crops, meat, and dairy; Boke Olén et al., 2021). To assess ecological consequences contingent on landscape configuration on fine spatial scales, the AgriPoliS model output was extended from a simple landscape representation to spatially explicit results, using the farm typology of GSS (Boke Olén et al., 2021) and spatial agricultural information from the Integrated Administration and Control System (IACS) database. The resulting land-use maps with detailed crop information were used to predict farmland bird diversity impacts, using the estimates of relationships from a joint-species distribution model (Hristov et al., 2020; Stjernman et al., 2019). The predicted farmland bird abundance was aggregated to species-specific regional abundances for each scenario and normalised by dividing the regional abundance in the energy ley scenario by the corresponding value in the reference scenario, to ultimately calculate a composite farmland bird index (FBI) following the method of Gregory et al. (2005).

Results and discussion

Sustainability of agricultural bioenergy

Strategies to increase the sustainability of agricultural bioenergy have revolved around the land-use changes surrounding biomass production (Dauber et al., 2012; Tilman et al., 2009; Valentine et al., 2012), but few studies have considered the combined impact of these strategies on ecosystem services and biodiversity. **Chapter I** provides an overview of how ecosystem services and biodiversity are affected under bioenergy-related land-use change scenarios suggested by policy and research. We found that agricultural bioenergy research is highly segregated between those focusing on ecosystem services and those focusing on biodiversity, with a predominance of the former (Figure 4). This raises concern about the policy recommendations given by bioenergy research, not only because of the risk for biodiversity loss but also because biodiversity and many ecosystem services are highly interlinked such that a loss of biodiversity could diminish ecosystem services important for agriculture (Le Provost et al., 2023). Furthermore, our results show that the cultivation of bioenergy crops in the agricultural landscape comes with two main trade-offs, either for food production or for biodiversity conservation. Despite the risk of decreased food security due to displacement effects, deploying perennial energy crops on arable land is widely researched and our review shows that this strategy has the potential to reduce the negative environmental and ecological impacts of intensive agriculture. Several previous studies have shown similar results (e.g. Dauber et al., 2010; Englund et al., 2020b; Werling et al., 2014), highlighting the potential role of feedstock cultivation on arable land as a multifunctional strategy to mitigate climate change.

To alleviate the competition with food production, biomass production on marginal land or abandoned land has been promoted as a sustainable bioenergy alternative (Gelfand et al., 2013; Gopalakrishnan et al., 2011; Vera et al., 2022), however, the results of **Chapter I** suggest that few studies have assessed the environmental and ecological impacts of using non-managed land for agricultural bioenergy production (Figure 4). In addition, we identified a large knowledge gap on the ecological implications of cultivating energy crops on marginal land, with the few studies focusing on biodiversity impacts predominantly reporting negative effects. Bioenergy production from marginal or abandoned land could hence be in direct conflict with biodiversity conservation (Plieninger & Gaertner, 2011), emphasising the importance of a joint recognition of ecosystem services and biodiversity for bioenergy-related land-use changes in future strategies for and research on agricultural bioenergy to avoid trade-offs between different societal goals.

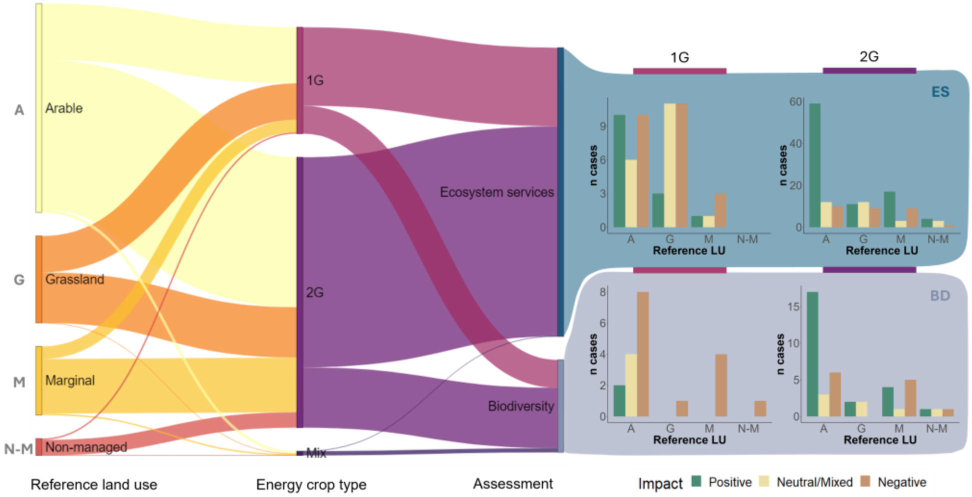

Figure 4. Overview of the reviewed literature in Chapter I, showing reference land use, energy crop type, assessment type, and impact. Starting from the left, the Sankey diagram shows the division of reference land uses that were included in the reviewed literature, the land use change to energy crops (first generation (1G) annual food crops, second generation (2G) perennial crops, or a mix of the two (Mix)), the assessment type of energy crops (ecosystem services or biodiversity), and the impact of the assessed land-use changes (number of positive, neutral/mixed, or negative cases). The bar plots on the right show the synthesised impact on ecosystem services and biodiversity for 1G and 2G crops. Abbreviations: ES: Ecosystem services, BD: Biodiversity, A: Arable land, G: Grassland, M: Marginal land, N-M: Non-managed land, 1G: First generation energy crops, 2G: Second generation energy crops, Mix: Mix of 1G and 2G crops.

Biomass production on marginal and abandoned land

To address the existing knowledge gap on the environmental and ecological effects of biomass production on marginal and abandoned land identified in **Chapter I**, we focused on identifying and characterising Swedish marginal land in **Chapter II** and evaluating the biodiversity implication of using abandoned farmland for bioenergy production in **Chapter III**. When studying marginal land, the definition and framing of marginality are central to what type of land will be identified (Csikós & Tóth, 2023; Muscat et al., 2022). Earlier studies of bioenergy potential from marginal land in Sweden have made general production estimates based on official land use data (cf. Börjesson, 2016; Nilsson & Rosenqvist, 2018; Olofsson & Börjesson, 2016; Prade et al., 2017), but without further studies of alternative use values and availability, these assessments are prone to large uncertainties. In **Chapter II** we defined marginal land as unused open land (such as abandoned land) and arable land outside the agricultural subsidy system. Agriculture without financial support was included in our marginal land definition as it is more sensitive to abandonment (Renwick et al., 2013) and is likely less intensively managed (Brady et al., 2017), which could indicate limitations for cost-effective production. The total area of marginal land identified in the nine Swedish counties ranged from 0.74% of the county area in Jönköping to 1.56% in Skåne (Figure 5). Out of all the marginal land, only a minor share (11%) was without management. The remainder of the land was either unsuitable for biomass production (wetlands or rock surfaces), was already used for biomass production to some extent (managed grasslands, agricultural fields, or tree plantations), or served as pastures for horses or livestock. Assuming all these land types as available for biomass production could compromise alternative use values, such as food production, recreation, or biodiversity conservation.

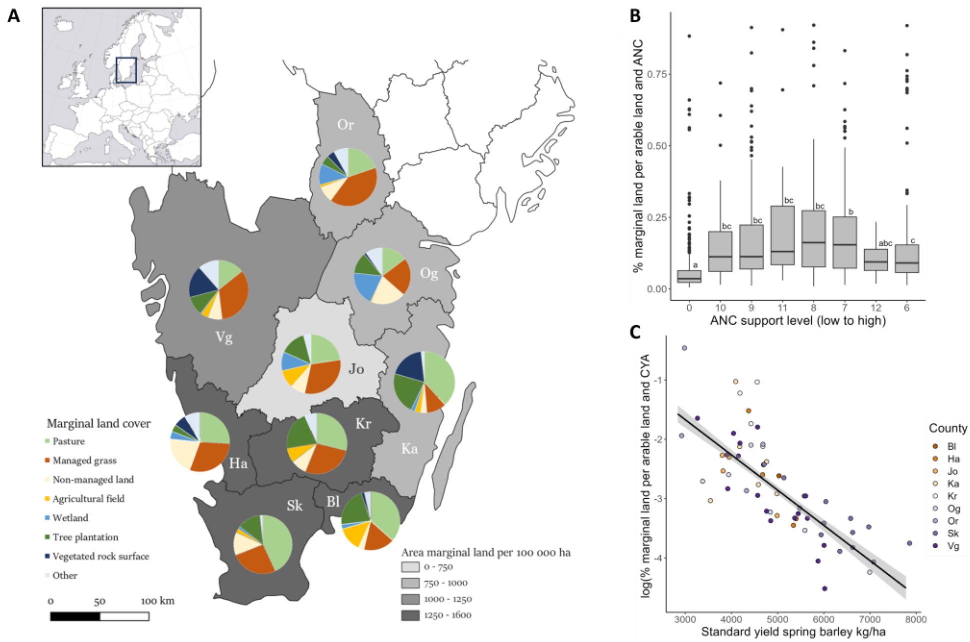

Figure 5. Area, land use, farming conditions, and productivity of the marginal land identified for the nine south Swedish counties in Chapter II. **A)** The total identified area of marginal land and the land use of 200 randomly selected marginal land sites within each county. County abbreviations: Sk: Skåne, Bl: Blekinge, Ka: Kalmar, Kr: Kronoberg, Ha: Halland, Vg: Västra Götaland, Jo: Jönköping, Og: Östergötland, Or: Örebro. **B)** The share of marginal land identified per arable land across ANCs (areas with natural or other area-specific constraints, i.e. farming conditions) and the level of ANC payments (compensatory economic support level). Category 0 has no ANC support (good farming conditions), category 10 has the lowest support, and category 6 has the highest support (constraining farming conditions). **C)** The relationship between the share of marginal land identified per arable area and the standard yield of spring barley across crop yield areas (CYA).

We found that about half of the marginal land were parcels that formerly received agricultural subsidies, but that currently either continued to be agriculturally managed without economic support, had been abandoned, or converted, mainly because of afforestation, infrastructure, or recreation. Even if the highest density of marginal land was identified in high-productive regions, we found a negative correlation between the relative share of marginal land per agricultural area and productivity. Moreover, the marginal land generally consisted of small land parcels (less than 0.5 ha). The small size and lower productivity of the identified marginal land would likely make biomass production difficult and unattractive due to the low cost- and time efficiency (Bryngelsson & Lindgren, 2013; Skevas et al., 2016). The use of marginal land for sustainable bioenergy production is commonly suggested within research and policy, but marginal land is also framed as important for food security, rural development, and ecosystem restoration, resulting in the same competing claims over marginal land as for productive land (Muscat et al., 2022). Improved mapping of marginal land will not remove these competing claims, nor will it change farmers' views of how marginal land could and should be used (Helliwell, 2018; Skevas et al., 2016). Bioenergy production from marginal land could make an important contribution to climate mitigation, however as shown in **Chapter II**, the use of marginal land will not overcome the land-use debate surrounding agricultural bioenergy if alternative use values are not considered.

The findings of **Chapter II** suggested that marginal land mainly occurs in mixed arable-forest landscapes and that a large share of the marginal land is grazed, passively managed, or abandoned SNGs. These results informed the focus of **Chapter III**, in which we studied the ecological implications of using abandoned SNGs for energy biomass production (ley and spruce) in a mixed farmland-forest region of southcentral Sweden. We found that both abandonment, afforestation, and grassland improvement of SNGs reduced local phytodiversity and altered plant communities compared to grazed SNGs, with the most profound negative effects from grassland afforestation and improvement to grass ley production (Figure 6). The difference in species communities was almost entirely explained by species turnover, i.e. species replacement. SNGs are among the most species-rich ecosystems in temperate landscapes with a manifold of rare species dependent on their continued management (Habel et al., 2013), and cessation of grazing or mowing generally affects plant diversity negatively (Elliott et al., 2023; Pykälä et al., 2005). Interestingly, our results showed that abandoned SNGs remain relatively important habitats for grassland species at an early stage of abandonment with similar plant species composition to grazed SNGs (Figure 6B). The abandonment of grasslands however resulted in a loss of rare species and even if there are studies claiming that the natural succession occurring after abandonment could create rewilded semi-natural habitats important for conservation (cf. Navarro & Pereira, 2012), a loss of species richness in grassland habitats could reduce both biodiversity as well as the supply of ecosystem services and the ecosystem multifunctionality (Prangel et al., 2023). However, both local and landscape processes are important for the structure of plant diversity (Foster, 2001; Schmucki et al., 2012). In addition to the effect of local management, we found that increased coverage of SNG in the surrounding landscape had a positive spill-over effect on plant species richness and Shannon diversity for all habitat types.

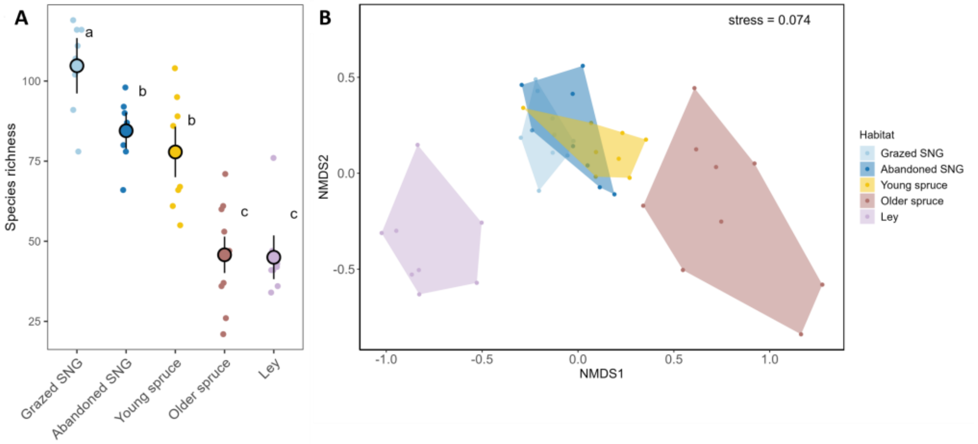

Figure 6. A) Observed (smaller coloured points) and predicted (larger filled points) plant species richness for the different habitat types. The letters a, b, and c show significant differences ($p<0.05$) in predicted species richness between habitats. The habitat types that do not share a letter are significantly different. **B)** The result of a non-metric multidimensional scaling (NMDS) showing the dissimilarity in plant species composition between the surveyed sites, grouped by habitat type.

The results of **Chapter III** highlight the importance of SNGs for local and landscape diversity but also suggest that abandoned grassland may hold high conservation values and should not be seen as available for intensive biomass production by default. Even if it also exits grasslands with low conservation values that could be better suited for biomass production, additional and updated assessments are needed to identify the grasslands with the highest biodiversity values (Larsson et al., 2020). However, despite the risk to grassland biodiversity, abandonment of SNGs is an ongoing process in Sweden (Eriksson et al., 2002), enhanced by dietary shifts (Röös et al., 2016) and increased costs for cattle farming (Söderberg & Hasund, 2021). When grazing is no longer possible, extensive management of abandoned grasslands, such as mowing, offers an opportunity for biomass harvesting that also may contribute to restoring the grassland flora (Heinsoo et al., 2010; Huhta et al., 2001).

In summary, **Chapters II** and **III** overview the availability of marginal land and abandoned land for energy biomass production, suggesting that neither of the two land types offers a simple and unproblematic solution to the increasing demand for biobased energy and material (Hertel et al., 2013). The competition for land is further amplified by climate change (IPCC, 2023) and the growing demand for food from an increasing population (Barthel et al., 2019), putting additional pressure on all types of land to produce food, feed, fuel, or nature conservation (Muscat et al., 2022). Moving forward, an integrated approach to biomass production, ecosystem service supply, and biodiversity conservation should be a priority to promote bioenergy production that does not compromise other societal needs.

Figure 7. A field with grass ley being harvested. Photo taken by author (2022).

Integrated biomass production in intensive agriculture

In **Chapter IV** we explored an alternative agricultural bioenergy strategy where grass biomass production (grassland ley; Figure 7) is integrated into intensively farmed agriculture as a multifunctional climate mitigation strategy (Carlsson et al., 2017; Englund et al., 2023). In contrast to earlier studies, we wanted to understand how incentivising energy grass production in an intensive cropping region in southern Sweden affects the uptake of energy grass in crop rotations and how the changes in farm structure and land-use change could affect the supply of ecosystem services and biodiversity. By comparing three different subsidy levels for energy ley production to a reference scenario without any such subsidy, our results showed that the total ley production only increased when very high financial incentives were introduced. For the lower payment levels (50 or 200 € ha^{-1}) the increase in energy ley was mainly achieved at the cost of fodder ley, an outcome that could be expected in productive agriculture with high cereal prices (Ford et al., 2024; Stürmer et al., 2013). In contrast, a subsidy of 350 € ha^{-1} resulted in 40% of the utilised agricultural area dedicated to ley production, which increased soil carbon storage, reduced pesticide use, and increased the overall abundance of farmland birds, in addition to the generation of substrate for biogas production (Figure 8). The simulated production changes however reduced the regional food production (the number of calories produced from food crops, dairy, and meat) as energy leys replaced spring barley. Even if some of the lost food production could be compensated by dietary shifts to less red meat and dairy products (Aleksandrowicz et al., 2016), the conflict with food production is one of the major limitations for increased production of agricultural bioenergy (Popp et al., 2014; Tilman et al., 2009; Vera et al., 2022).

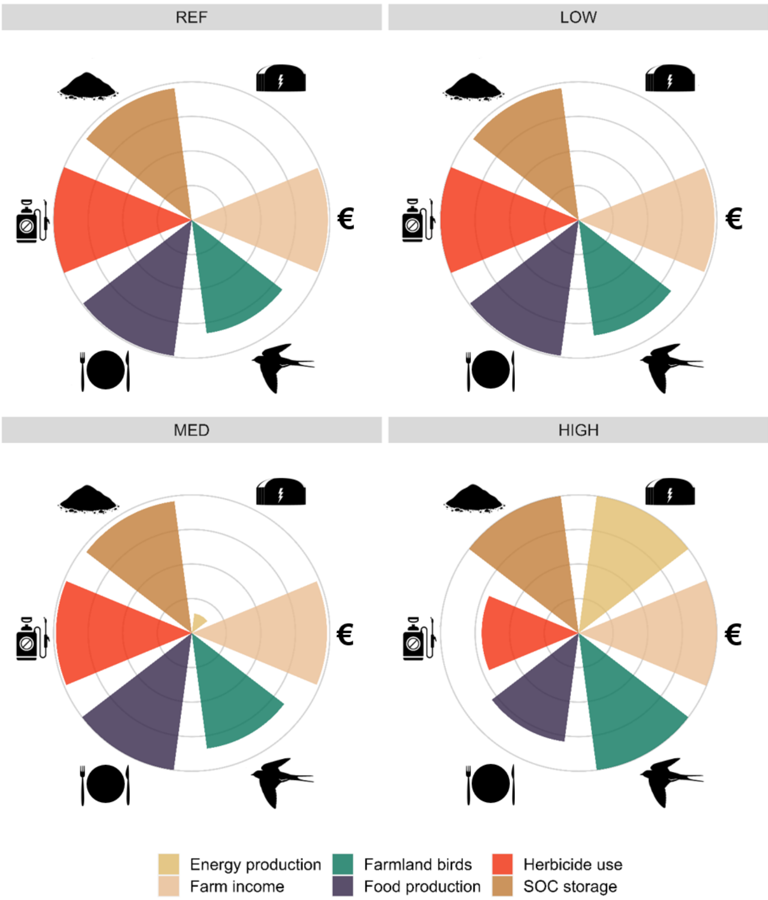

Figure 8. The predicted impact on energy production, farm income, farmland birds, food production, pesticide use, and soil organic carbon (SOC) storage in the reference scenario (REF) and the three energy ley scenarios (LOW, MEDIUM, HIGH). The impact for all variables has been normalised by dividing the impact value by the maximum variable value (scale 0-1). The figure is taken from Chapter IV, with variable icons sourced from BioRender.com.

The results of **Chapter IV** suggest that agricultural bioenergy could not only contribute to the decarbonisation of society by providing renewable energy but potentially also mitigate some of the environmental problems of intensive agriculture. Integrating grassland leys in crop rotations is a relatively easy and low-risk practice for farmers (Ford et al., 2024) that could benefit multiple agriculturally important ecosystem services in intense agriculture (Martin et al., 2020). In the studied region, grassland leys are already commonly used in crop rotations to produce ensiled fodder and hay for cattle and horses, indicating few practical barriers to the uptake of additional ley production. However, our results show that the increased uptake of energy ley reduced the production of fodder ley, resulting in a shift in livestock production towards fewer cattle and more granivores for the higher energy ley scenarios. While we found no major loss of utilised SNGs in our energy ley scenarios, a reduction in the number of grazing cattle generates risks for grassland abandonment with concurrent biodiversity loss (Elliott et al., 2023).

Given the high opportunity costs on productive arable land, our results show that the uptake of energy ley comes at a high cost. A hectare-based subsidy of 350 € ha^{-1} for energy ley production is likely unrealistically high under current agricultural policies but was used in our study to simulate a high demand for biogas substrate. Sweden has set ambitious climate targets, including no net emissions of GHG by 2045 and a 70% emission reduction of domestic transportation by 2030 (Swedish Environmental Protection Agency, 2024), indicating that the need for fossil-free energy and fuel is becoming increasingly important. Whether agricultural bioenergy is included in the pathway towards a low-carbon society is uncertain and highly dependent on the trade-offs or synergies society and landowners are willing to accept.

Conclusion and final remarks

Climate change and biodiversity loss are two interconnected and complex global challenges. The urgency of finding and adopting mitigation and conservation strategies however carries the risk of generating new sustainability issues if these interlinkages are not addressed. Climate change and biodiversity loss hence have to be tackled together. In this thesis, I have focused on bioenergy production from the agricultural landscape – a source of renewable energy that has received increasing attention as a multifunctional climate mitigation strategy. By comparing different bioenergy strategies and their impact on biodiversity and ecosystem services, my thesis highlights the challenges of increasing agricultural bioenergy production without causing competition with the demand for food, feed, fibre, and resources from other sectors, including nature conservation.

I found that one of the most promising bioenergy strategies is the integrated production of bioenergy crops in intensive arable cropping regions. It could serve as a multifunctional climate mitigation strategy by positively affecting multiple ecosystem services and taxonomic groups (Chapter I). These benefits are nevertheless difficult to achieve without substantial financial incentives and consequences for food production (Chapter IV). Moreover, intensive biomass production is not beneficial for all taxonomic groups and species, and the increased bioenergy production may indirectly harm biodiversity by the loss of species-rich habitats when farm structure and agricultural production are altered (Chapter IV). Despite the environmental benefits offered by energy crops, such as increased carbon sequestration and reduced use of pesticides, multifunctional bioenergy systems cannot replace sustainable circular food systems that maintain food production or biodiversity conservation measures that preserve or recreate the habitats needed by the diverse group of species inhabiting the agricultural landscape.

An alternative bioenergy strategy is to produce bioenergy crops on marginal and abandoned land. In theory, this strategy offers an opportunity for sustainable biomass production without conflicting with other land uses, but as shown in Chapters II and III, neither of these land types offers a simple and unproblematic solution to the increasing demand for biobased energy. My thesis shows that the area of unused land in southern Sweden is small, and these sites may hold high biodiversity values. In addition, I found that marginal land generally has a smaller area and lower productivity than the surrounding arable land, indicating lower cost-efficiency for intensive production. Using remote sensing, I showed that marginal land in most cases still has various use values, suggesting that the conflicts with food production, recreation, and biodiversity conservation are not resolved when marginal land or abandoned land is used for bioenergy production.

My thesis emphasises the importance of including both ecosystem services and biodiversity when evaluating bioenergy strategies to avoid conflicts between climate action and biodiversity conservation. This requires a more representative inclusion of multiple taxonomic groups in bioenergy studies, as well as a better understanding of which habitats benefit biodiversity so that policies can be designed that ensure that these ecosystems are preserved while mitigating climate change. However, the climate is already changing, and multifunctional bioenergy strategies may also offer opportunities for climate adaptation by increasing the productivity and climate resilience of arable land. Further research is needed to better understand the effect of climate change and climate adaptation on farming decisions and farmer attitudes to bioenergy crop cultivation in different landscape contexts. Finally, although sustainably produced bioenergy can be part of the path towards a fossil-free society, global climate goals cannot be reached without substantial reductions in energy use and consumption.

Acknowledgements

The work in this thesis was funded by the Swedish Research Council for Sustainable Development FORMAS (2018-01726). Additional funding to enable conference participation and research visits was received from the Royal Physiographic Society of Lund, Stiftelsen Knut och Alice Wallenbergs forskarstipendiefond, and Landshövding Per Westlings Minnesfond. The empirical data collection in Chapter III would never have been possible without the farmers and landowners who let us conduct plant surveys on their land. I thank them, the field assistants, all my colleagues, and family who made this thesis possible:

First and foremost, I would like to thank my supervisors who have supported me throughout my PhD. You three have made my life so much easier (and harder). **Henrik**, thank you for your ambition, support, and guidance. Your dedication to research and hard work have been inspiring, thanks for believing in me. **Johan**, thank you for all the helpful discussions and for always being a present and excellent supervisor despite the distance, your support has meant a lot to me. **Lars**, thank you for your insightful comments on my project and for helping me explore remote sensing, there is so much more I would like to learn from you.

Katarina, thank you for being an endless support and for having an open door throughout my PhD. You have been so much more than my departmental representative, your dedication to education and equality is truly inspiring – thanks for showing an alternative side of academia that I needed to see!

Yann, thanks for bringing together the Land4Biomass team, the lunch group meetings, and all helpful discussions on my projects. **Jagdeep**, **Cecilia**, and **Raül**, it has been a pleasure working with you and figuring out all our pathways of agricultural bioenergy research together! Special thanks to **Mark** and **Cecilia** for answering my many policy and modelling questions with great patience, and **Raül** for our discussions on data and analyses (and for being the first to cite my work!). Thanks to the entire project team for the feedback in our meetings, with extra thanks to **Pål** for your kind feedback and for being there to answer questions!

Thanks to the biodiversity research group for inspiring Thursdays and a special thank you to **Pernilla**, for organising us and being a kind and fun colleague, always ready to decipher the cryptic schedule. The shared interests in our research group have not only been academically inspiring, but it has also been a friendly and supportive environment. Thank you all, and a particular thank you to **Anna** (for all support and gardening talks), **Ciara** (for sharing your plant wisdom with me), **Hakim** (for your helpful comments on my analysis of marginal land), **Martin S** (for your contribution to my final project and excellent explanations on statistical modelling), **Océane** (for allowing me to highjack our shared computer and well-needed sauna mornings), **Peter** (for sharing your computer, data, and expertise with me), and **Romain** (for your feedback on field design and cheerful presence).

I have had the privilege to be a part of both CEC and the Biology department which has brought the best of two worlds (including twice as much fika), but above all, so many nice colleagues to share this time with! Life as a double-affiliated PhD would have been much harder without help from some of the most important people in the building: **Ella, Ewa, Izabella, Annika, Rebecca, Felix, Louise, Janne, Karl, Henrik, Cecilia,** and **Susanne**. Without your contributions: no office, salary, grants, administration, or functioning computer!

To all present and past biodiversity unit (and biology) colleagues, thank you for making our corridor a second home and the most welcoming space. A special thanks to **Carsten** (for your kind and supportive spirit), **Cilla** (for great friendship and dog-sitting exchanges), **Dániel** (for the final support and proofreading), **Hanna** (for your inspiring determination and our fun (and confused) teaching in the lab), **Johanna** (for your kindness and endless energy), **Julia W** (for your unfiltered friendship and sharing Sölvi with me), **Laura** (for the perks of being neighbours in Gunnesbo at work), **Lydwin** (for your contagious optimism), **Simon** (for the good break talks), **Sofia** (for all pet and non-pet related fun in our friendship), and **Theodor** (for well-needed laughs and writing sessions).

To my current office mates, **Jöran** (the youngest old man I know with so many talents) and **Etka** (the humble and friendly master of souvenirs), the office would not have been an office without you! Thank you both for the needed chat breaks, feedback, and great company. Best of luck with your PhDs!

Ola and **Magne**, thanks for steering the biodiversity ship and spreading your positive energy in our unit. **Helene**, not only do you make us feel safe, but you have also been a great support. Thank you for your kindness and for saving the flower arrangements at my wedding!

Being an environmental scientist, my educational home has been with CEC which has been a truly inspiring workplace. Thank you **Natascha, Katarina,** and **Tobias** for coordinating the research education, and to **Camilla, Ylva,** and **Åsa-Katrin** for all your help with the educational administration. By taking part in the ClimBEco research school, I have had the luck to broaden my sustainability perspective and learn from peers from other disciplines. **Cheryl** and **Ylva**, thanks for making ClimBEco an inspiring platform and for being great colleagues. **Katarina, Helena** and all mentees, thank you for making the mentoring programme a developing experience, I'm grateful for all the advice and experiences that you shared!

I would also like to thank my present and former CEC PhD colleagues for their contribution to a supportive community with inspiring symposia, productive writing retreats, and good friendships. Thanks to **Jesica** (for the great support on our shared land-use and remote sensing journey and final thesis writing together), **Johan** (for being a friendly rant buddy and inspiring research celebrity), **Maria** (for our rediscovered friendship and all the fun times shared with **Tristan**, Artur and Donna), **Melanie** (for being a kind, cheerful, and excellent travel companion, proofreader, and friend), **Micaela** (for your kindness and the beautiful energy you spread), **Pedro** (for your endless enthusiasm, randomness, pastries, friendship, and Egon fan club), **Theresia** (for good friendship and great gardening together with **Alex** and Felix), and all other CEC PhD students not named here.

To all other colleagues not named but who probably should have been named, thank you for making my doctoral education a memorable journey!

Finally, I would not have been where I am without my family and our shared passion for nature. Thank you for your love, understanding, and encouragement. Your dog-sitting of Egon made conferences possible! And **Joel**, my endless supporter and beloved husband, thank you for accompanying me on this journey and bringing me up in hard times. You and Egon are the best companions I could ever have asked for.

Tack!

References

Agriwise. (2017). Agriwise: Data book for production planning and regional enterprise budgets. Department of Economics, Swedish University of Agricultural Sciences (SLU), Uppsala.

Ahlgren, S., Björnsson, L., Prade, T., & Lantz, M. (2017). *Biofuels from agricultural biomass - Land use change in Swedish perspective.* f3 2017:13. The Swedish Knowledge Centre for Renewable Transportation Fuels.

Aleksandrowicz, L., Green, R., Joy, E. J. M., Smith, P., & Haines, A. (2016). The Impacts of Dietary Change on Greenhouse Gas Emissions, Land Use, Water Use, and Health: A Systematic Review. *Plos One*, *11*(11), e0165797. https://doi.org/10.1371/journal.pone.0165797

Andersson, G. K. S., Boke-Olén, N., Roger, F., Ekroos, J., Smith, H. G., & Clough, Y. (2022). Landscape-scale diversity of plants, bumblebees and butterflies in mixed farm-forest landscapes of Northern Europe: Clear-cuts do not compensate for the negative effects of plantation forest cover. *Biological Conservation*, *274*, 109728. https://doi.org/10.1016/j.biocon.2022.109728

Asbjornsen, H., Hernandez-Santana, V., Liebman, M., Bayala, J., Chen, J., Helmers, M., Ong, C. K., & Schulte, L. A. (2014). Targeting perennial vegetation in agricultural landscapes for enhancing ecosystem services. *Renewable Agriculture and Food Systems*, *29*(2), 101-125. https://doi.org/10.1017/S1742170512000385

Aune, S., Bryn, A., & Hovstad, K. A. (2018). Loss of semi-natural grassland in a boreal landscape: impacts of agricultural intensification and abandonment. *Journal of Land Use Science*, *13*(4), 375-390. https://doi.org/10.1080/1747423X.2018.1539779

Barthel, S., Isendahl, C., Vis, B. N., Drescher, A., Evans, D. L., & van Timmeren, A. (2019). Global urbanization and food production in direct competition for land: Leverage places to mitigate impacts on SDG2 and on the Earth System. *The Anthropocene Review*, *6*(1-2), 71-97. https://doi.org/10.1177/2053019619856672

Baselga, A. (2010). Partitioning the turnover and nestedness components of beta diversity. *Global Ecology and Biogeography*, *19*(1), 134-143. https://doi.org/10.1111/j.1466-8238.2009.00490.x

Beilin, R., Lindborg, R., Stenseke, M., Pereira, H. M., Llausàs, A., Slätmo, E., Cerqueira, Y., Navarro, L., Rodrigues, P., Reichelt, N., Munro, N., & Queiroz, C. (2014). Analysing how drivers of agricultural land abandonment affect biodiversity and cultural landscapes using case studies from Scandinavia, Iberia and Oceania. *Land Use Policy*, *36*, 60-72. https://doi.org/10.1016/j.landusepol.2013.07.003

Bengtsson, J., Bullock, J. M., Egoh, B., Everson, C., Everson, T., O'Connor, T., O'Farrell, P. J., Smith, H. G., & Lindborg, R. (2019). Grasslands-more important for ecosystem services than you might think. *Ecosphere*, *10*(2), Article e02582. https://doi.org/10.1002/ecs2.2582

Benton, T. G., Vickery, J. A., & Wilson, J. D. (2003). Farmland biodiversity: is habitat heterogeneity the key? *Trends in Ecology & Evolution*, *18*(4), 182-188. https://doi.org/10.1016/S0169-5347(03)00011-9

Birkhofer, K., Andersson, G. K. S., Bengtsson, J., Bommarco, R., Dänhardt, J., Ekbom, B., Ekroos, J., Hahn, T., Hedlund, K., Jönsson, A. M., Lindborg, R., Olsson, O., Rader, R., Rusch, A., Stjernman, M., Williams, A., & Smith, H. G. (2018). Relationships between multiple biodiversity components and ecosystem services along a landscape complexity gradient. *Biological Conservation*, *218*, 247-253. https://doi.org/10.1016/j.biocon.2017.12.027

Black-Samuelsson, S., Eriksson, H., Henning, D., Janse, G., Kaneryd, L., Lundborg, A., & Niemi Hjulfors, L. (2017). *Bioenergi på rätt sätt - om hållbar bioenergi i Sverige och andra länder. Rapport av Skogsstyrelsen, Energimyndigheten, Jordbruksverket, Naturvårdsverket. Rapport 10.* . Skogsstyrelsen. https://www.skogsstyrelsen.se/globalassets/om-oss/rapporter/rapporter-2017/rapport-201710-bioenergi-pa-ratt-satt.pdf

Blitzer, E. J., Dormann, C. F., Holzschuh, A., Klein, A.-M., Rand, T. A., & Tscharntke, T. (2012). Spillover of functionally important organisms between managed and natural habitats. *Agriculture, Ecosystems & Environment*, *146*(1), 34-43. https://doi.org/10.1016/j.agee.2011.09.005

Boke Olén, N., Roger, F., Brady, M. V., Larsson, C., Andersson, G. K. S., Ekroos, J., Caplat, P., Smith, H. G., Dänhardt, J., & Clough, Y. (2021). Effects of farm type on food production, landscape openness, grassland biodiversity, and greenhouse gas emissions in mixed agricultural-forestry regions. *Agricultural Systems*, *189*, 103071. https://doi.org/10.1016/j.agsy.2021.103071

Brady, M., Hristov, J., Höjgård, S., Jansson, T., Johansson, H., Larsson, C., Nordin, I., & Rabinowicz, E. (2017). *Impacts of Direct Payments - Lessons for CAP post-2020 from a quantitative analysis*. A. E. Centre. https://pub.epsilon.slu.se/16201/7/brady_m_et_al_190614.pdf

Brady, M., Hristov, J., Wilhelmsson, F., & Hedlund, K. (2019). Roadmap for Valuing Soil Ecosystem Services to Inform Multi-Level Decision-Making in Agriculture. *Sustainability*, *11*(19), 5285. https://www.mdpi.com/2071-1050/11/19/5285

Bryngelsson, D. K., & Lindgren, K. (2013). Why large-scale bioenergy production on marginal land is unfeasible: A conceptual partial equilibrium analysis. *Energy Policy*, *55*, 454-466. https://doi.org/10.1016/j.enpol.2012.12.036

Börjesson, P. (2016). *Potential för ökad tillförsel och avsättning av inhemsk biomassa i en växande svensk bioekonomi*. Lund University. Department of Technology and Society. Environmental and Energy Systems Studies.

Cardinale, B. J., Duffy, J. E., Gonzalez, A., Hooper, D. U., Perrings, C., Venail, P., Narwani, A., Mace, G. M., Tilman, D., Wardle, D. A., Kinzig, A. P., Daily, G. C., Loreau, M., Grace, J. B., Larigauderie, A., Srivastava, D. S., & Naeem, S. (2012). Biodiversity loss and its impact on humanity. *Nature*, *486*(7401), 59-67. https://doi.org/10.1038/nature11148

Carlsson, G., Martensson, L. M., Prade, T., Svensson, S. E., & Jensen, E. S. (2017). Perennial species mixtures for multifunctional production of biomass on marginal land. *Global Change Biology Bioenergy*, *9*(1), 191-201. https://doi.org/10.1111/gcbb.12373

Chao, A., & Jost, L. (2012). Coverage-based rarefaction and extrapolation: standardizing samples by completeness rather than size. *Ecology*, *93*(12), 2533-2547. https://doi.org/10.1890/11-1952.1

Cintas, O., Berndes, G., Hansson, J., Poudel, B. C., Bergh, J., Börjesson, P., Egnell, G., Lundmark, T., & Nordin, A. (2017). The potential role of forest management in Swedish scenarios towards climate neutrality by mid century. *Forest Ecology and Management*, *383*, 73-84. https://doi.org/10.1016/j.foreco.2016.07.015

Convention on Biological Diversity, opened for signature 5 June 1992, 1760 U.N.T.S. 69 (entered into force 29 December 1993).

Cousins, S. A. O. (2009). Landscape history and soil properties affect grassland decline and plant species richness in rural landscapes. *Biological Conservation*, *142*(11), 2752-2758. https://doi.org/10.1016/j.biocon.2009.07.001

Csikós, N., & Tóth, G. (2023). Concepts of agricultural marginal lands and their utilisation: A review. *Agricultural Systems*, *204*, 103560. https://doi.org/10.1016/j.agsy.2022.103560

Daioglou, V., Doelman, J. C., Wicke, B., Faaij, A., & van Vuuren, D. P. (2019). Integrated assessment of biomass supply and demand in climate change mitigation scenarios. *Global Environmental Change*, *54*, 88-101. https://doi.org/10.1016/j.gloenvcha.2018.11.012

Dale, V. H., Kline, K. L., Wiens, J., Fargione, J. (2010). *Biofuels: Implications for Land Use and Biodiversity. Biofuels and Sustainability Reports*. Ecological Society of America. www.esa.org/biofuelsreports

Dauber, J., Brown, C., Fernando, A. L., Finnan, J., Krasuska, E., Ponitka, J., Styles, D., Thrän, D., Van Groenigen, K. J., Weih, M., & Zah, R. (2012). Bioenergy from "surplus" land: environmental and socio-economic implications. *BioRisk*, *7*. https://doi.org/10.3897/biorisk.7.3036

Dauber, J., Jones, M. B., & Stout, J. C. (2010). The impact of biomass crop cultivation on temperate biodiversity. *Global Change Biology Bioenergy*, *2*(6), 289-309. https://doi.org/10.1111/j.1757-1707.2010.01058.x

Dauber, J., & Miyake, S. (2016). To integrate or to segregate food crop and energy crop cultivation at the landscape scale? Perspectives on biodiversity conservation in agriculture in Europe. *Energy, Sustainability and Society*, *6*(1), 25. https://doi.org/10.1186/s13705-016-0089-5

Davis, S. J., Lewis, N. S., Shaner, M., Aggarwal, S., Arent, D., Azevedo, I. L., Benson, S. M., Bradley, T., Brouwer, J., Chiang, Y.-M., Clack, C. T. M., Cohen, A., Doig, S., Edmonds, J., Fennell, P., Field, C. B., Hannegan, B., Hodge, B.-M., Hoffert, M. I., Ingersoll, E., Jaramillo, P., Lackner, K. S., Mach, K. J., Mastrandrea, M., Ogden, J., Peterson, P. F., Sanchez, D. L., Sperling, D., Stagner, J., Trancik, J. E., Yang, C.-J., & Caldeira, K. (2018). Net-zero emissions energy systems. *Science*, *360*(6396), eaas9793. https://doi.org/10.1126/science.aas9793 de Jong, J., & Dahlberg, A. (2017). Impact on species of conservation interest of forest harvesting for bioenergy purposes. *Forest Ecology and Management*, *383*, 37-48. https://doi.org/10.1016/j.foreco.2016.09.016

Debnath, D., Khanna, M., Rajagopal, D., & Zilberman, D. (2019). The Future of Biofuels in an Electrifying Global Transportation Sector: Imperative, Prospects and Challenges. *Applied Economic Perspectives and Policy*, *41*(4), 563-582. https://doi.org/10.1093/aepp/ppz023

Dee, L. E., Cowles, J., Isbell, F., Pau, S., Gaines, S. D., & Reich, P. B. (2019). When Do Ecosystem Services Depend on Rare Species? *Trends in Ecology & Evolution*, *34*(8), 746-758. https://doi.org/10.1016/j.tree.2019.03.010

Díaz, S., Settele, J., Brondízio, E. S., Ngo, H. T., Agard, J., Arneth, A., Balvanera, P., Brauman, K. A., Butchart, S. H. M., Chan, K. M. A., Garibaldi, L. A., Ichii, K., Liu, J., Subramanian, S. M., Midgley, G. F., Miloslavich, P., Molnár, Z., Obura, D., Pfaff, A., Polasky, S., Purvis, A., Razzaque, J., Reyers, B., Chowdhury, R. R., Shin, Y.-J., Visseren-Hamakers, I., Willis, K. J., & Zayas, C. N. (2019). Pervasive human-driven decline of life on Earth points to the need for transformative change. *Science*, *366*(6471), eaax3100. https://doi.org/doi:10.1126/science.aax3100

Eide, W., Ahrné, K., Bjelke, U., Nordström, S., Ottosson, E., Sandström, J., Sundberg, S., & (red). (2020). *Tillstånd och trender för arter och deras livsmiljöer - rödlistade arter i Sverige 2020. SLU Artdatabanken rapporterar 24. SLU Artdatabanken, Uppsala* (https://www.artdatabanken.se/publikationer/tillstand-och-trender/

Elliott, J., Tindale, S., Outhwaite, S., Nicholson, F., Newell-Price, P., Sari, N. H., Hunter, E., Sánchez-Zamora, P., Jin, S., Gallardo-Cobos, R., Miškolci, S., & Frewer, L. J. (2024). European Permanent Grasslands: A Systematic Review of Economic Drivers of Change, Including a Detailed Analysis of the Czech Republic, Spain, Sweden, and UK. *Land*, *13*(1), 116. https://doi.org/10.3390/land13010116

Elliott, T., Thompson, A., Klein, A.-M., Albert, C., Eisenhauer, N., Jansen, F., Schneider, A., Sommer, M., Straka, T., Settele, J., Sporbert, M., Tanneberger, F., & Mupepele, A.-C. (2023). Abandoning grassland management negatively influences plant but not bird or insect biodiversity in Europe. *Conservation Science and Practice*, *5*(10), e13008. https://doi.org/10.1111/csp2.13008

Englund, O., Börjesson, P., Berndes, G., Scarlat, N., Dallemand, J.-F., Grizzetti, B., Dimitriou, I., Mola-Yudego, B., & Fahl, F. (2020a). Beneficial land use change: Strategic expansion of new biomass plantations can reduce environmental impacts from EU agriculture. *Global Environmental Change-Human and Policy Dimensions*, *60*, Article 101990. https://doi.org/10.1016/j.gloenvcha.2019.101990

Englund, O., Börjesson, P., Berndes, G., Scarlat, N., Dallemand, J.-F., Grizzetti, B., Dimitriou, I., Mola-Yudego, B., & Fahl, F. (2020b). Beneficial land use change: Strategic expansion of new biomass plantations can reduce environmental impacts from EU agriculture. *Global Environmental Change*, *60*, 101990. https://doi.org/10.1016/j.gloenvcha.2019.101990

Englund, O., Mola-Yudego, B., Börjesson, P., Cederberg, C., Dimitriou, I., Scarlat, N., & Berndes, G. (2023). Large-scale deployment of grass in crop rotations as a multifunctional climate mitigation strategy. *Global Change Biology Bioenergy*, *15*(2), 166-184. https://doi.org/10.1111/gcbb.13015

Eriksson, O., Cousins, S. A. O., & Bruun, H. H. (2002). Land-use history and fragmentation of traditionally managed grasslands in Scandinavia. *Journal of Vegetation Science*, *13*(5), 743-748. https://doi.org/10.1111/j.1654-1103.2002.tb02102.x

EU Directive 2023/2413. *Directive (EU) of the European Parliament and of the Council of 18 October 2023 amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652.* http://data.europa.eu/eli/dir/2023/2413/oj.

European Commission. (2017). Sustainable and optimal use of biomass for energy in the EU beyond 2020. Final report. [VITO, Utrecht University, TU Wien, INFRO, Rütter Soceco, PwC]. *To EC Directorate General for Energy Directorate C1 – Renewables and CCS policy*. *PricewaterhouseCoopers EU Services EESV's consortium*.

European Commission. (2020a). COM/2020/380 final. Communication from the Commission to the European Parliament, the European council, the council, the European Economic and Social Committee, and the Committee of the Regions. EU biodiversity strategy for 2030 bringing nature back into our lives. European Commission. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0380.

European Commission. (2020b). COM/2020/562 final. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Stepping up Europe's 2030 climate ambition: Investing in a climate-neutral future for the benefit of our people. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0562.

European Commission. (2022). *Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions REPowerEU Plan*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2022:230:FIN

European Commission. (2023). *REPORT FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS State of the Energy Union Report 2023 (pursuant to Regulation (EU) 2018/1999 on the Governance of the Energy Union and Climate Action). COM/2023/650 final* (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52023DC0650

Fahrig, L., Baudry, J., Brotons, L., Burel, F. G., Crist, T. O., Fuller, R. J., Sirami, C., Siriwardena, G. M., & Martin, J.-L. (2011). Functional landscape heterogeneity and animal biodiversity in agricultural landscapes. *Ecology Letters*, *14*(2), 101-112. https://doi.org/10.1111/j.1461-0248.2010.01559.x

FAO, IFAD, UNICEF, WFP, & WHO. (2023). *The state of food security and nutrition in the World 2023. Urbanization, agrifood systems transformation and healthy diets across the rural-urban continuum.* Rome, FAI. https://doi.org/10.4060/cc3017en

Fayet, C. M. J., Reilly, K. H., Van Ham, C., & Verburg, P. H. (2022). What is the future of abandoned agricultural lands? A systematic review of alternative trajectories in Europe. *Land Use Policy*, *112*, 105833. https://doi.org/10.1016/j.landusepol.2021.105833

Foley, J. A., Ramankutty, N., Brauman, K. A., Cassidy, E. S., Gerber, J. S., Johnston, M., Mueller, N. D., O'Connell, C., Ray, D. K., West, P. C., Balzer, C., Bennett, E. M., Carpenter, S. R., Hill, J., Monfreda, C., Polasky, S., Rockström, J., Sheehan, J., Siebert, S., Tilman, D., & Zaks, D. P. M. (2011). Solutions for a cultivated planet. *Nature*, *478*(7369), 337-342. https://doi.org/10.1038/nature10452

Ford, J. S., Bale, C. S. E., & Taylor, P. G. (2024). The factors determining uptake of energy crop cultivation and woodland creation in England: Insights from farmers and landowners. *Biomass and Bioenergy*, *180*, 107021. https://doi.org/10.1016/j.biombioe.2023.107021

Foster, B. L. (2001). Constraints on colonization and species richness along a grassland productivity gradient: the role of propagule availability. *Ecology Letters*, *4*(6), 530-535. https://doi.org/10.1046/j.1461-0248.2001.00266.x

Frank, S., Havlík, P., Soussana, J.-F., Levesque, A., Valin, H., Wollenberg, E., Kleinwechter, U., Fricko, O., Gusti, M., Herrero, M., Smith, P., Hasegawa, T., Kraxner, F., & Obersteiner, M. (2017). Reducing greenhouse gas emissions in agriculture without compromising food security? *Environmental Research Letters*, *12*(10), 105004. https://doi.org/10.1088/1748-9326/aa8c83

Gelfand, I., Sahajpal, R., Zhang, X. S., Izaurralde, R. C., Gross, K. L., & Robertson, G. P. (2013). Sustainable bioenergy production from marginal lands in the US Midwest. *Nature*, *493*(7433), 514-517. https://doi.org/10.1038/nature11811

Godfray, H. C. J., Beddington, J. R., Crute, I. R., Haddad, L., Lawrence, D., Muir, J. F., Pretty, J., Robinson, S., Thomas, S. M., & Toulmin, C. (2010). Food Security: The Challenge of Feeding 9 Billion People. *Science*, *327*(5967), 812-818. https://doi.org/10.1126/science.1185383

Gonthier, D. J., Ennis, K. K., Farinas, S., Hsieh, H.-Y., Iverson, A. L., Batáry, P., Rudolphi, J., Tscharntke, T., Cardinale, B. J., & Perfecto, I. (2014). Biodiversity conservation in agriculture requires a multi-scale approach. *Proceedings of the Royal Society B: Biological Sciences*, *281*(1791), 20141358. https://doi.org/doi:10.1098/rspb.2014.1358

Google. (2022). *Streetview, digital images - Google Maps.* http://maps.google.com

Gopalakrishnan, G., Negri, M. C., & Snyder, S. W. (2011). A Novel Framework to Classify Marginal Land for Sustainable Biomass Feedstock Production. *Journal of Environmental Quality*, *40*(5), 1593-1600. https://doi.org/10.2134/jeq2010.0539

Gregory, R. D., van Strien, A., Vorisek, P., Gmelig Meyling, A. W., Noble, D. G., Foppen, R. P. B., & Gibbons, D. W. (2005). Developing indicators for European birds. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *360*(1454), 269-288. https://doi.org/doi:10.1098/rstb.2004.1602

Gustafsson, M., & Anderberg, S. (2023). Great expectations—future scenarios for production and use of biogas and digestate in Sweden. *Biofuels*, *14*(1), 93-107. https://doi.org/10.1080/17597269.2022.2121543

Habel, J. C., Dengler, J., Janišová, M., Török, P., Wellstein, C., & Wiezik, M. (2013). European grassland ecosystems: threatened hotspots of biodiversity. *Biodiversity and Conservation*, *22*(10), 2131-2138. https://doi.org/10.1007/s10531-013-0537-x

Haddaway, N. R., Woodcock, P., Macura, B., & Collins, A. (2015). Making literature reviews more reliable through application of lessons from systematic reviews. *Conservation Biology*, *29*(6), 1596-1605. https://doi.org/10.1111/cobi.12541

Happe, K., Kellermann, K., & Balmann, A. (2006). Agent-based Analysis of Agricultural Policies: an Illustration of the Agricultural Policy Simulator AgriPoliS, its Adaptation and Behavior. *Ecology and Society*, *11*(1), 49. http://www.jstor.org/stable/26267800

Harper, A. B., Powell, T., Cox, P. M., House, J., Huntingford, C., Lenton, T. M., Sitch, S., Burke, E., Chadburn, S. E., Collins, W. J., Comyn-Platt, E., Daioglou, V., Doelman, J. C., Hayman, G., Robertson, E., van Vuuren, D., Wiltshire, A., Webber, C. P., Bastos, A., Boysen, L., Ciais, P., Devaraju, N., Jain, A. K., Krause, A., Poulter, B., & Shu, S. (2018). Land-use emissions play a critical role in land-based mitigation for Paris climate targets. *Nature Communications*, *9*(1), 2938. https://doi.org/10.1038/s41467-018-05340-z

Havlik, P., Schneider, U. A., Schmid, E., Bottcher, H., Fritz, S., Skalsky, R., Aoki, K., De Cara, S., Kindermann, G., Kraxner, F., Leduc, S., McCallum, I., Mosnier, A., Sauer, T., & Obersteiner, M. (2011). Global land-use implications of first and second generation biofuel targets. *Energy Policy*, *39*(10), 5690-5702. https://doi.org/10.1016/j.enpol.2010.03.030

Heinsoo, K., Melts, I., Sammul, M., & Holm, B. (2010). The potential of Estonian semi-natural grasslands for bioenergy production. *Agriculture, Ecosystems & Environment*, *137*(1), 86-92. https://doi.org/10.1016/j.agee.2010.01.003

Helliwell, R. (2018). Where did the marginal land go? Farmers perspectives on marginal land and its implications for adoption of dedicated energy crops. *Energy Policy*, *117*, 166-172. https://doi.org/10.1016/j.enpol.2018.03.011

Hertel, T., Steinbuks, J., & Baldos, U. (2013). Competition for land in the global bioeconomy. *Agricultural Economics*, *44*(s1), 129-138. https://doi.org/10.1111/agec.12057

Hildebrandt, J., Hagemann, N., & Thrän, D. (2017). The contribution of wood-based construction materials for leveraging a low carbon building sector in europe. *Sustainable Cities and Society*, *34*, 405-418. https://doi.org/10.1016/j.scs.2017.06.013

Holland, J. M., Douma, J. C., Crowley, L., James, L., Kor, L., Stevenson, D. R. W., & Smith, B. M. (2017). Semi-natural habitats support biological control, pollination and soil conservation in Europe. A review. *Agronomy for Sustainable Development*, *37*(4), 31. https://doi.org/10.1007/s13593-017-0434-x

Hristov, J., Clough, Y., Sahlin, U., Smith, H. G., Stjernman, M., Olsson, O., Sahrbacher, A., & Brady, M. V. (2020). Impacts of the EU's Common Agricultural Policy "Greening" Reform on Agricultural Development, Biodiversity, and Ecosystem Services. *Applied Economic Perspectives and Policy*, *42*(4), 716-738. https://doi.org/10.1002/aepp.13037

Hufnagel, J., Reckling, M., & Ewert, F. (2020). Diverse approaches to crop diversification in agricultural research. A review. *Agronomy for Sustainable Development*, *40*(2), 14. https://doi.org/10.1007/s13593-020-00617-4

Huhta, A.-P., Rautio, P., Tuomi, J., & Laine, K. (2001). Restorative mowing on an abandoned semi-natural meadow: short-term and predicted long-term effects. *Journal of Vegetation Science*, *12*(5), 677-686. https://doi.org/10.2307/3236908

Ihse, M. (1995). Swedish agricultural landscapes — patterns and changes during the last 50 years, studied by aerial photos. *Landscape and Urban Planning*, *31*(1), 21-37. https://doi.org/10.1016/0169-2046(94)01033-5

Immerzeel, D. J., Verweij, P. A., Van der Hilst, F., & Faaij, A. (2014). Biodiversity impacts of bioenergy crop production: a state-of-the-art review. *Global Change Biology Bioenergy*, *6*(3), 183-209. https://doi.org/10.1111/gcbb.12067

IPBES. (2019). Summary for Policymakers. In: *The global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. [S. Díaz, J. Settele, E. S. Brondízio, H. T. Ngo, M. Guèze, J. Agard, A. Arneth, P. Balvanera, K. A. Brauman, S. H. M. Butchart, K. M. A. Chan, L. A. Garibaldi, K. Ichii, J. Liu, S. M. Subramanian, G. F. Midgley, P. Miloslavich, Z. Molnár, D. Obura, A. Pfaff, S. Polasky, A. Purvis, J. Razzaque, B. Reyers, R. Roy Chowdhury, Y. J. Shin, I. J. Visseren-Hamakers, K. J. Willis, and C. N. Zayas (eds.)]. , IPBES Secretariat: Bonn, Germany. https://doi.org/10.5281/zenodo.3553579

IPCC. (2019). Summary for Policymakers. In: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.- O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley (eds.)]. https://doi.org/10.1017/9781009157988.001

IPCC. (2023). *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. [Core Writing Team, Lee, H., Romero, J. (eds)]. IPCC, Geneva, Switzerland. https://doi.org/10.59327/IPCC/AR6-9789291691647

Isbell, F., Gonzalez, A., Loreau, M., Cowles, J., Díaz, S., Hector, A., Mace, G. M., Wardle, D. A., O'Connor, M. I., Duffy, J. E., Turnbull, L. A., Thompson, P. L., & Larigauderie, A. (2017). Linking the influence and dependence of people on biodiversity across scales. *Nature*, *546*(7656), 65-72. https://doi.org/10.1038/nature22899

Jaureguiberry, P., Titeux, N., Wiemers, M., Bowler, D. E., Coscieme, L., Golden, A. S., Guerra, C. A., Jacob, U., Takahashi, Y., Settele, J., Díaz, S., Molnár, Z., & Purvis, A. (2022). The direct drivers of recent global anthropogenic biodiversity loss. *Science Advances*, *8*(45), eabm9982. https://doi.org/doi:10.1126/sciadv.abm9982

Johansen, L., Henriksen, M. V., & Wehn, S. (2022). The contribution of alternative habitats for conservation of plant species associated with threatened semi-natural grasslands. *Ecological Solutions and Evidence*, *3*(3), e12183. https://doi.org/10.1002/2688-8319.12183

Khanna, M., Chen, L., Basso, B., Cai, X., Field, J. L., Guan, K., Jiang, C., Lark, T. J., Richard, T. L., Spawn-Lee, S. A., Yang, P., & Zipp, K. Y. (2021). Redefining marginal land for bioenergy crop production. *Global Change Biology Bioenergy*, *13*(10), 1590-1609. https://doi.org/10.1111/gcbb.12877

Kiesecker, J. M., Evans, J. S., Oakleaf, J. R., Dropuljić, K. Z., Vejnović, I., Rosslowe, C., Cremona, E., Bhattacharjee, A. L., Nagaraju, S. K., Ortiz, A., Robinson, C., Ferres, J. L., Zec, M., & Sochi, K. (2024). Land use and Europe's renewable energy transition: identifying low-conflict areas for wind and solar development [Original Research]. *Frontiers in Environmental Science*, *12*. https://doi.org/10.3389/fenvs.2024.1355508

Lantmäteriet. (2021). *Terrängkartan (no longer maintained, replaced by Topography 50/250)*. https://www.lantmateriet.se/en/geodata/geodata-products/product-list/topography-250-download-vector/#anchor-0

Lantmäteriet. (2022). *Orthophoto View Service, Annual*. https://www.lantmateriet.se/en/geodata/geodata-products/product-list/orthophoto-viewing-service-annual/

Larsson, C., Boke-Olén, N., & Brady, M. (2020). *Naturbetesmarkens framtid - en fråga om lönsamhet. Rapport 2020:1*. AgriFood Economics Centre. https://pub.epsilon.slu.se/27331/1/larsson_c_et_al_220317.pdf

Le Provost, G., Schenk, N. V., Penone, C., Thiele, J., Westphal, C., Allan, E., Ayasse, M., Blüthgen, N., Boeddinghaus, R. S., Boesing, A. L., Bolliger, R., Busch, V., Fischer, M., Gossner, M. M., Hölzel, N., Jung, K., Kandeler, E., Klaus, V. H., Kleinebecker, T., Leimer, S., Marhan, S., Morris, K., Müller, S., Neff, F., Neyret, M., Oelmann, Y., Perović, D. J., Peter, S., Prati, D., Rillig, M. C., Saiz, H., Schäfer, D., Scherer-Lorenzen, M., Schloter, M., Schöning, I., Schrumpf, M., Steckel, J., Steffan-Dewenter, I., Tschapka, M., Vogt, J., Weiner, C., Weisser, W., Wells, K., Werner, M., Wilcke, W., & Manning, P. (2023). The supply of multiple ecosystem services requires biodiversity across spatial scales. *Nature Ecology & Evolution*, *7*(2), 236-249. https://doi.org/10.1038/s41559-022-01918-5

Lécuyer, L., Alard, D., Calla, S., Coolsaet, B., Fickel, T., Heinsoo, K., Henle, K., Herzon, I., Hodgson, I., Quétier, F., McCracken, D., McMahon, B. J., Melts, I., Sands, D., Skrimizea, E., Watt, A., White, R., & Young, J. (2021). Chapter One - Conflicts between agriculture and biodiversity conservation in Europe: Looking to the future by learning from the past. In D. A. Bohan, A. J. Dumbrell, & A. J. Vanbergen (Eds.), *Advances in Ecological Research* (Vol. 65, pp. 3-56). Academic Press. https://doi.org/10.1016/bs.aecr.2021.10.005

Leemans, R., van Amstel, A., Battjes, C., Kreileman, E., & Toet, S. (1996). The land cover and carbon cycle consequences of large-scale utilizations of biomass as an energy source. *Global Environmental Change*, *6*(4), 335-357. https://doi.org/10.1016/S0959-3780(96)00028-3

Liu, J., Hull, V., Godfray, H. C. J., Tilman, D., Gleick, P., Hoff, H., Pahl-Wostl, C., Xu, Z., Chung, M. G., Sun, J., & Li, S. (2018). Nexus approaches to global sustainable development. *Nature Sustainability*, *1*(9), 466-476. https://doi.org/10.1038/s41893-018-0135-8

MacDonald, D., Crabtree, J. R., Wiesinger, G., Dax, T., Stamou, N., Fleury, P., Gutierrez Lazpita, J., & Gibon, A. (2000). Agricultural abandonment in mountain areas of Europe: Environmental consequences and policy response. *Journal of Environmental Management*, *59*(1), 47-69. https://doi.org/10.1006/jema.1999.0335

Mace, G. M., Norris, K., & Fitter, A. H. (2012). Biodiversity and ecosystem services: a multilayered relationship. *Trends in Ecology & Evolution*, *27*(1), 19-26. https://doi.org/10.1016/j.tree.2011.08.006

Martin, G., Durand, J.-L., Duru, M., Gastal, F., Julier, B., Litrico, I., Louarn, G., Médiène, S., Moreau, D., Valentin-Morison, M., Novak, S., Parnaudeau, V., Paschalidou, F., Vertès, F., Voisin, A.-S., Cellier, P., & Jeuffroy, M.-H. (2020). Role of ley pastures in tomorrow's cropping systems. A review. *Agronomy for Sustainable Development*, *40*(3), 17. https://doi.org/10.1007/s13593-020-00620-9

Mehmood, M. A., Ibrahim, M., Rashid, U., Nawaz, M., Ali, S., Hussain, A., & Gull, M. (2017). Biomass production for bioenergy using marginal lands. *Sustainable Production and Consumption*, *9*, 3-21. https://doi.org/10.1016/j.spc.2016.08.003

Millennium Ecosystem Assessment. (2005). *Ecosystems and human well-being: synthesis*. Washington, DC. Island Press.

Milner, S., Holland, R. A., Lovett, A., Sunnenberg, G., Hastings, A., Smith, P., Wang, S. F., & Taylor, G. (2016). Potential impacts on ecosystem services of land use transitions to second-generation bioenergy crops in GB. *Global Change Biology Bioenergy*, *8*(2), 317-333. https://doi.org/10.1111/gcbb.12263

Mišík, M., & Nosko, A. (2023). Post-pandemic lessons for EU energy and climate policy after the Russian invasion of Ukraine: Introduction to a special issue on EU green recovery in the post-Covid-19 period. *Energy Policy*, *177*, 113546. https://doi.org/10.1016/j.enpol.2023.113546

Munroe, D. K., van Berkel, D. B., Verburg, P. H., & Olson, J. L. (2013). Alternative trajectories of land abandonment: causes, consequences and research challenges. *Current Opinion in Environmental Sustainability*, *5*(5), 471-476. https://doi.org/10.1016/j.cosust.2013.06.010

Muscat, A., de Olde, E. M., Candel, J. J. L., de Boer, I. J. M., & Ripoll-Bosch, R. (2022). The Promised Land: Contrasting frames of marginal land in the European Union. *Land Use Policy*, *112*, 105860. https://doi.org/10.1016/j.landusepol.2021.105860

Muscat, A., de Olde, E. M., de Boer, I. J. M., & Ripoll-Bosch, R. (2020). The battle for biomass: A systematic review of food-feed-fuel competition. *Global Food Security*, *25*, 100330. https://doi.org/10.1016/j.gfs.2019.100330

Næss, J. S., Hu, X., Gvein, M. H., Iordan, C.-M., Cavalett, O., Dorber, M., Giroux, B., & Cherubini, F. (2023). Climate change mitigation potentials of biofuels produced from perennial crops and natural regrowth on abandoned and degraded cropland in Nordic countries. *Journal of Environmental Management*, *325*, 116474. https://doi.org/10.1016/j.jenvman.2022.116474

Navarro, L. M., & Pereira, H. M. (2012). Rewilding Abandoned Landscapes in Europe. *Ecosystems*, *15*(6), 900-912. https://doi.org/10.1007/s10021-012-9558-7

Nelson, E., Mendoza, G., Regetz, J., Polasky, S., Tallis, H., Cameron, D., Chan, K. M., Daily, G. C., Goldstein, J., Kareiva, P. M., Lonsdorf, E., Naidoo, R., Ricketts, T. H., & Shaw, M. (2009). Modeling multiple ecosystem services, biodiversity conservation, commodity production, and tradeoffs at landscape scales. *Frontiers in Ecology and the Environment*, *7*(1), 4-11. https://doi.org/10.1890/080023

Nilsson, D., & Rosenqvist, H. (2018). Marginal arable fields in Sweden - Areas, shapes, transport distances and time demand and costs for machine operations. *Agriculture for the Next 100 Years: Proceedings of the 26th NJF Congress, Lithuania*. https://pub.epsilon.slu.se/15876/1/nilsson_et_al_190131.pdf.

Norton, M., Baldi, A., Buda, V., Carli, B., Cudlin, P., Jones, M. B., Korhola, A., Michalski, R., Novo, F., Oszlányi, J., Santos, F. D., Schink, B., Shepherd, J., Vet, L., Walloe, L., & Wijkman, A. (2019). Serious mismatches continue between science and policy in forest bioenergy. *Global Change Biology Bioenergy*, *11*(11), 1256-1263. https://doi.org/10.1111/gcbb.12643

Notarnicola, B., Tassielli, G., Renzulli, P. A., Castellani, V., & Sala, S. (2017). Environmental impacts of food consumption in Europe. *Journal of Cleaner Production*, *140*, 753-765. https://doi.org/10.1016/j.jclepro.2016.06.080

Nunez-Regueiro, M. M., Siddiqui, S. F., & Fletcher, R. J. (2019). Effects of bioenergy on biodiversity arising from land-use change and crop type. *Conservation Biology*. https://doi.org/10.1111/cobi.13452

Olofsson, J., & Börjesson, P. (2016). Nedlagd åkermark för biomassaproduktion – kartläggning och potentialuppskattning. Report f3 2016:01. *The Swedish Knowledge Centre for Renewable Transportation Fuels*. https://f3centre.se/app/uploads/f3_report_2016-01_Nedlagd-%C3%A5kermark-f%C3%B6r-biomassaproduktion_20160219.pdf

Pellegrini, P., & Fernández, R. J. (2018). Crop intensification, land use, and on-farm energy-use efficiency during the worldwide spread of the green revolution. *Proceedings of the National Academy of Sciences*, *115*(10), 2335-2340. https://doi.org/10.1073/pnas.1717072115

Perpiña Castillo, C., Kavalov, B., Diogo, V., Jacobs-Crisioni, C., Batista e Silva, F., & Lavalle, C. (2018). *Agricultural land abandonment in the EU within 2015-2030. JRC113718*. European Commission. https://joint-research-centre.ec.europa.eu/system/files/2018-12/jrc113718.pdf

Petersson, L., Holmström, E., Lindbladh, M., & Felton, A. (2019). Tree species impact on understory vegetation: Vascular plant communities of Scots pine and Norway spruce managed stands in northern Europe. *Forest Ecology and Management*, *448*, 330-345. https://doi.org/10.1016/j.foreco.2019.06.011

Pettorelli, N., Graham, N. A. J., Seddon, N., Bustamante, M. M. D., Lowton, M. J., Sutherland, W. J., Koldewey, H. J., Prentice, H. C., & Barlow, J. (2021). Time to integrate global climate change and biodiversity science-policy agendas. *Journal of Applied Ecology*, *58*(11), 2384-2393. https://doi.org/10.1111/1365-2664.13985

Pickett, S. T. A. (1989). Space-for-Time Substitution as an Alternative to Long-Term Studies. In G. E. Likens (Ed.), *Long-Term Studies in Ecology: Approaches and Alternatives* (pp. 110-135). Springer New York. https://doi.org/10.1007/978-1-4615-7358-6_5

Plieninger, T., & Gaertner, M. (2011). Harnessing degraded lands for biodiversity conservation. *Journal for Nature Conservation*, *19*(1), 18-23. https://doi.org/10.1016/j.jnc.2010.04.001

Popp, J., Lakner, Z., Harangi-Rákos, M., & Fári, M. (2014). The effect of bioenergy expansion: Food, energy, and environment. *Renewable and Sustainable Energy Reviews*, *32*, 559-578. https://doi.org/10.1016/j.rser.2014.01.056

Power, A. G. (2010). Ecosystem services and agriculture: tradeoffs and synergies. *Philosophical Transactions of the Royal Society B-Biological Sciences*, *365*(1554), 2959-2971. https://doi.org/10.1098/rstb.2010.0143

Prade, T., Björnsson, L., Lantz, M., & Ahlgren, S. (2017). Can domestic production of iLUC-free feedstock from arable land supply Sweden's future demand for biofuels? *Journal of Land Use Science*, *12*(6), 407-441. https://doi.org/10.1080/1747423X.2017.1398280

Prangel, E., Kasari-Toussaint, L., Neuenkamp, L., Noreika, N., Karise, R., Marja, R., Ingerpuu, N., Kupper, T., Keerberg, L., Oja, E., Meriste, M., Tiitsaar, A., Ivask, M., & Helm, A. (2023). Afforestation and abandonment of semi-natural grasslands lead to biodiversity loss and a decline in ecosystem services and functions. *Journal of Applied Ecology*, *60*(5), 825-836. https://doi.org/10.1111/1365-2664.14375

Pretty, J., & Bharucha, Z. P. (2014). Sustainable intensification in agricultural systems. *Annals of Botany*, *114*(8), 1571-1596. https://doi.org/10.1093/aob/mcu205

Pykälä, J., Luoto, M., Heikkinen, R. K., & Kontula, T. (2005). Plant species richness and persistence of rare plants in abandoned semi-natural grasslands in northern Europe. *Basic and Applied Ecology*, *6*(1), 25-33. https://doi.org/10.1016/j.baae.2004.10.002

Pörtner, H. O., Scholes, R. J., Agard, J., Archer, E., Arneth, A., Bai, X., Barnes, D., Burrows, M., Chan, L., Cheung, W. L., Diamond, S., Donatti, C., Duarte, C., Eisenhauer, N., Foden, W., Gasalla, M. A., Handa, C., Hickler, T., Hoegh-Guldberg, O., Ichii, K., Jacob, U., Insarov, G., Kiessling, W., Leadley, P., Leemans, R., Levin, L., Lim, M., Maharaj, S., Managi, S., Marquet, P. A., McElwee, P., Midgley, G., Oberdorff, T., Obura, D., Osman, E., Pandit, R., Pascual, U., Pires, A. P. F., Popp, A., Reyes-García, V., Sankaran, M., Settele, J., Shin, Y. J., Sintayehu, D. W., Smith, P., Steiner, N., Strassburg, B., Sukumar, R., Trisos, C., Val, A. L., Wu, J., Aldrian, E., Parmesan, C., Pichs-Madruga, R., Roberts, D. C., Rogers, A. D., Díaz, S., Fischer, M., Hashimoto, S., Lavorel, S., Wu, N., & Ngo, H. T. (2021). Scientific outcome of the IPBES-IPCC co-sponsored workshop on biodiversity and climate change., IPBES secretariat, Bonn, Germany. https://doi.org/doi.org/0.5281/zenodo.4659158.

Pörtner, H. O., Scholes, R. J., Arneth, A., Barnes, D. K. A., Burrows, M. T., Diamond, S. E., Duarte, C. M., Kiessling, W., Leadley, P., Managi, S., McElwee, P., Midgley, G., Ngo, H. T., Obura, D., Pascual, U., Sankaran, M., Shin, Y. J., & Val, A. L. (2023). Overcoming the coupled climate and biodiversity crises and their societal impacts. *Science*, *380*(6642), eabl4881. https://doi.org/doi:10.1126/science.abl4881

Queiroz, C., Beilin, R., Folke, C., & Lindborg, R. (2014). Farmland abandonment: threat or opportunity for biodiversity conservation? A global review. *Frontiers in Ecology and the Environment*, *12*(5), 288-296. https://doi.org/10.1890/120348

Redford, K. H., & Richter, B. D. (1999). Conservation of Biodiversity in a World of Use. *Conservation Biology*, *13*(6), 1246-1256. https://doi.org/10.1046/j.1523-1739.1999.97463.x

Reich, P. B., Tilman, D., Isbell, F., Mueller, K., Hobbie, S. E., Flynn, D. F. B., & Eisenhauer, N. (2012). Impacts of Biodiversity Loss Escalate Through Time as Redundancy Fades. *Science*, *336*(6081), 589-592. https://doi.org/doi:10.1126/science.1217909

Renwick, A., Jansson, T., Verburg, P. H., Revoredo-Giha, C., Britz, W., Gocht, A., & McCracken, D. (2013). Policy reform and agricultural land abandonment in the EU. *Land Use Policy*, *30*(1), 446-457. https://doi.org/10.1016/j.landusepol.2012.04.005

Rey Benayas, J. M., Martins, A., Nicolau, J. M., & Schulz, J. J. (2007). Abandonment of agricultural land: an overview of drivers and consequences. *CABI International, 2007*. https://doi.org/10.1079/pavsnnr20072057

Richardson, K., Steffen, W., Lucht, W., Bendtsen, J., Cornell, S. E., Donges, J. F., Drüke, M., Fetzer, I., Bala, G., von Bloh, W., Feulner, G., Fiedler, S., Gerten, D., Gleeson, T., Hofmann, M., Huiskamp, W., Kummu, M., Mohan, C., Nogués-Bravo, D., Petri, S., Porkka, M., Rahmstorf, S., Schaphoff, S., Thonicke, K., Tobian, A., Virkki, V., Wang-Erlandsson, L., Weber, L., & Rockström, J. (2023). Earth beyond six of nine planetary boundaries. *Science Advances*, *9*(37), eadh2458. https://doi.org/doi:10.1126/sciadv.adh2458

Robinson, R. A., & Sutherland, W. J. (2002). Post-war changes in arable farming and biodiversity in Great Britain. *Journal of Applied Ecology*, *39*(1), 157-176. https://doi.org/10.1046/j.1365-2664.2002.00695.x

Robledo-Abad, C., Althaus, H.-J., Berndes, G., Bolwig, S., Corbera, E., Creutzig, F., Garcia-Ulloa, J., Geddes, A., Gregg, J. S., Haberl, H., Hanger, S., Harper, R. J., Hunsberger, C., Larsen, R. K., Lauk, C., Leitner, S., Lilliestam, J., Lotze-Campen, H., Muys, B., Nordborg, M., Ölund, M., Orlowsky, B., Popp, A., Portugal-Pereira, J., Reinhard, J., Scheiffle, L., & Smith, P. (2017). Bioenergy production and sustainable development: science base for policymaking remains limited. *Global Change Biology Bioenergy*, *9*(3), 541-556. https://doi.org/10.1111/gcbb.12338

Rockström, J., Williams, J., Daily, G., Noble, A., Matthews, N., Gordon, L., Wetterstrand, H., DeClerck, F., Shah, M., Steduto, P., de Fraiture, C., Hatibu, N., Unver, O., Bird, J., Sibanda, L., & Smith, J. (2017). Sustainable intensification of agriculture for human prosperity and global sustainability. *Ambio*, *46*(1), 4-17. https://doi.org/10.1007/s13280-016-0793-6

Rogelj, J., Popp, A., Calvin, K. V., Luderer, G., Emmerling, J., Gernaat, D., Fujimori, S., Strefler, J., Hasegawa, T., Marangoni, G., Krey, V., Kriegler, E., Riahi, K., van Vuuren, D. P., Doelman, J., Drouet, L., Edmonds, J., Fricko, O., Harmsen, M., Havlík, P., Humpenöder, F., Stehfest, E., & Tavoni, M. (2018). Scenarios towards limiting global mean temperature increase below 1.5 °C. *Nature Climate Change*, *8*(4), 325-332. https://doi.org/10.1038/s41558-018-0091-3

Román-Palacios, C., & Wiens, J. J. (2020). Recent responses to climate change reveal the drivers of species extinction and survival. *Proceedings of the National Academy of Sciences*, *117*(8), 4211-4217. https://doi.org/doi:10.1073/pnas.1913007117

Rummukainen, M. (2021). *Skogens klimatnyttor - en balansakt i prioritering (utökad utgåva). CEC Rapport Nr 6.* Centrum för miljö- och klimatvetenskap, Lunds universitet.

Röös, E., Patel, M., Spångberg, J., Carlsson, G., & Rydhmer, L. (2016). Limiting livestock production to pasture and by-products in a search for sustainable diets. *Food Policy*, *58*, 1-13. https://doi.org/10.1016/j.foodpol.2015.10.008

Schmucki, R., Reimark, J., Lindborg, R., & Cousins, S. A. O. (2012). Landscape context and management regime structure plant diversity in grassland communities. *Journal of Ecology*, *100*(5), 1164-1173. https://doi.org/10.1111/j.1365-2745.2012.01988.x

Searchinger, T., Heimlich, R., Houghton, R. A., Dong, F., Elobeid, A., Fabiosa, J., Tokgoz, S., Hayes, D., & Yu, T.-H. (2008). Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change. *Science*, *319*(5867), 1238-1240. https://doi.org/doi:10.1126/science.1151861

Searchinger, T., James, O., Dumas, P., Kastner, T., & Wirsenius, S. (2022). EU climate plan sacrifices carbon storage and biodiversity for bioenergy. *Nature*, *612*, 27-30. https://doi.org/10.1038/d41586-022-04133-1

Seppelt, R., Beckmann, M., Ceauşu, S., Cord, A. F., Gerstner, K., Gurevitch, J., Kambach, S., Klotz, S., Mendenhall, C., Phillips, H. R. P., Powell, K., Verburg, P. H., Verhagen, W., Winter, M., & Newbold, T. (2019). Trade-Offs and Synergies Between Biodiversity Conservation and Productivity in the Context of Increasing Demands on Landscapes. In M. Schröter, A. Bonn, S. Klotz, R. Seppelt, & C. Baessler (Eds.), *Atlas of Ecosystem Services: Drivers, Risks, and Societal Responses* (pp. 251-256). Springer International Publishing. https://doi.org/10.1007/978-3-319-96229-0_39

Shin, Y.-J., Midgley, G. F., Archer, E. R. M., Arneth, A., Barnes, D. K. A., Chan, L., Hashimoto, S., Hoegh-Guldberg, O., Insarov, G., Leadley, P., Levin, L. A., Ngo, H. T., Pandit, R., Pires, A. P. F., Pörtner, H.-O., Rogers, A. D., Scholes, R. J., Settele, J., & Smith, P. (2022). Actions to halt biodiversity loss generally benefit the climate. *Global Change Biology*, *28*(9), 2846-2874. https://doi.org/10.1111/gcb.16109

Shortall, O. K. (2013). "Marginal land" for energy crops: Exploring definitions and embedded assumptions. *Energy Policy*, *62*, 19-27. https://doi.org/10.1016/j.enpol.2013.07.048

Skevas, T., Hayden, N. J., Swinton, S. M., & Lupi, F. (2016). Landowner willingness to supply marginal land for bioenergy production. *Land Use Policy*, *50*, 507-517. https://doi.org/10.1016/j.landusepol.2015.09.027

SLU Artdatabanken. (2023). *Artfakta - Artinformation*. Retrieved 2023-04-12 from https://artfakta.se/artinformation

Smith, P., Arneth, A., Barnes, D. K. A., Ichii, K., Marquet, P. A., Popp, A., Pörtner, H.-O., Rogers, A. D., Scholes, R. J., Strassburg, B., Wu, J., & Ngo, H. (2022). How do we best synergize climate mitigation actions to co-benefit biodiversity? *Global Change Biology*, *28*(8), 2555-2577. https://doi.org/10.1111/gcb.16056

Smith, P., Haberl, H., Popp, A., Erb, K.-h., Lauk, C., Harper, R., Tubiello, F. N., de Siqueira Pinto, A., Jafari, M., Sohi, S., Masera, O., Böttcher, H., Berndes, G., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E. A., Mbow, C., Ravindranath, N. H., Rice, C. W., Robledo Abad, C., Romanovskaya, A., Sperling, F., Herrero, M., House, J. I., & Rose, S. (2013). How much land-based greenhouse gas mitigation can be achieved without compromising food security and environmental goals? *Global Change Biology*, *19*(8), 2285-2302. https://doi.org/10.1111/gcb.12160

Statistics Sweden. (2021). *Tätorter [2018]*.https://www.scb.se/vara-tjanster/oppna-data/oppna-geodata/tatorter/

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., de Vries, W., de Wit, C. A., Folke, C., Gerten, D., Heinke, J., Mace, G. M., Persson, L. M., Ramanathan, V., Reyers, B., & Sörlin, S. (2015). Planetary boundaries: Guiding human development on a changing planet. *Science*, *347*(6223), 1259855. https://doi.org/doi:10.1126/science.1259855

Stjernman, M., Sahlin, U., Olsson, O., & Smith, H. G. (2019). Estimating effects of arable land use intensity on farmland birds using joint species modeling. *Ecological Applications*, *29*(4), e01875. https://doi.org/10.1002/eap.1875

Strijker, D. (2005). Marginal lands in Europe - causes of decline. *Basic and Applied Ecology*, *6*(2), 99-106. https://doi.org/10.1016/j.baae.2005.01.001

Stürmer, B., Schmidt, J., Schmid, E., & Sinabell, F. (2013). Implications of agricultural bioenergy crop production in a land constrained economy – The example of Austria. *Land Use Policy*, *30*(1), 570-581. https://doi.org/10.1016/j.landusepol.2012.04.020

Swedish Board of Agriculture. (2008). *Ängs- och betesmarker – en genomgång av tillgänglig statistik. Rapport 2008:30* (https://www2.jordbruksverket.se/webdav/files/SJV/trycksaker/Pdf_rapporter/ra08_30.pdf

Swedish Board of Agriculture. (2021). *Jordbruksblock* https://jordbruksverket.se/e-tjanster-databaser-och-appar/e-tjanster-och-databaser-stod/kartor-och-gis#h-Laddanerkartskikt

Swedish Board of Agriculture. (2022). *TUVA database - Swedish National Survey of semi-natural pastures and meadows*.https://jordbruksverket.se/e-tjanster-databaser-och-appar/e-tjanster-och-databaser-stod/tuva

Swedish Board of Agriculture. (2023a). *Jordbruksverkets statistikdatabas: Normskörd efter län, gröda, typ av normskörd, variabel och år (2022)*.

Swedish Board of Agriculture. (2023b). *Jordbruksverkets statistikdatabas: Åkermarkens användning och antal företag med åkermark efter län och gröda (2022)*.

Swedish Environmental Protection Agency. (2020). *National Land Cover Database (NMD) - base layer + Land use layer (anlagda områden)*.https://www.naturvardsverket.se/en/services-and-permits/maps-and-map-services/national-land-cover-database/

Swedish Environmental Protection Agency. (2021). *Protected Nature*.https://www.naturvardsverket.se/verktyg-och-tjanster/kartor-och-karttjanster/kartverktyget-skyddad-natur/

Swedish Environmental Protection Agency. (2024). *Sweden's Climate Act and Climate Policy Framework* https://www.naturvardsverket.se/en/topics/climate-transition/sveriges-klimatarbete/swedens-climate-act-and-climate-policy-framework/

Swedish University of Agricultural Science (SLU). (2015). *SLU Forest Map*. https://www.slu.se/centrumbildningar-och-projekt/riksskogstaxeringen/statistik-om-skog/slu-skogskarta/om-slu-skogskarta/

Söderberg, T., & Hasund, K. P. (2021). *CAP-reformen hotar betesmarkerna men ger också möjligheter - Resultat från modellberäkningar (CAP reform threathens pastures but also gives opportunities - Results from a modelling study)*. Swedish Board of Agriculture.

Taylor, P. D., Fahrig, L., & With, K. A. (2006). Landscape connectivity: a return to the basics. *Conservation Biology Series-Cambridge*, *14*, 29.

The Swedish Transport Administration. (2021). *Road data + Railroad data*. https://bransch.trafikverket.se/tjanster/data-kartor-och-geodatatjanster/las-om-vara-data/

Tilman, D., & Clark, M. (2014). Global diets link environmental sustainability and human health. *Nature*, *515*(7528), 518-522. https://doi.org/10.1038/nature13959

Tilman, D., Hill, J., & Lehman, C. (2006). Carbon-negative biofuels from low-input high-diversity grassland biomass. *Science*, *314*(5805), 1598-1600. https://doi.org/10.1126/science.1133306

Tilman, D., Socolow, R., Foley, J. A., Hill, J., Larson, E., Lynd, L., Pacala, S., Reilly, J., Searchinger, T., Somerville, C., & Williams, R. (2009). Beneficial Biofuels-The Food, Energy, and Environment Trilemma. *Science*, *325*(5938), 270-271. https://doi.org/10.1126/science.1177970

Trisos, C. H., Merow, C., & Pigot, A. L. (2020). The projected timing of abrupt ecological disruption from climate change. *Nature*, *580*(7804), 496-501. https://doi.org/10.1038/s41586-020-2189-9

Tscharntke, T., Klein, A. M., Kruess, A., Steffan-Dewenter, I., & Thies, C. (2005). Landscape perspectives on agricultural intensification and biodiversity – ecosystem service management. *Ecology Letters*, *8*(8), 857-874. https://doi.org/10.1111/j.1461-0248.2005.00782.x

United Nations. (2015). *Transforming our world: the 2030 Agenda for Sustainable Development.* https://sdgs.un.org/sites/default/files/publications/21252030%20Agenda%20for%20Sustainable%20Development%20web.pdf

Urban, M. C. (2015). Accelerating extinction risk from climate change. *Science*, *348*(6234), 571-573. https://doi.org/10.1126/science.aaa4984

Ustaoglu, E., & Collier, M. J. (2018). Farmland abandonment in Europe: an overview of drivers, consequences, and assessment of the sustainability implications. *Environmental Reviews*, *26*(4), 396-416. https://doi.org/10.1139/er-2018-0001

Valentine, J., Clifton-Brown, J., Hastings, A., Robson, P., Allison, G., & Smith, P. (2012). Food vs. fuel: the use of land for lignocellulosic 'next generation' energy crops that minimize competition with primary food production. *Global Change Biology Bioenergy*, *4*(1), 1-19. https://doi.org/10.1111/j.1757-1707.2011.01111.x

Valin, H., Havlík, P., Mosnier, A., Herrero, M., Schmid, E., & Obersteiner, M. (2013). Agricultural productivity and greenhouse gas emissions: trade-offs or synergies between mitigation and food security? *Environmental Research Letters*, *8*(3), 035019. https://doi.org/10.1088/1748-9326/8/3/035019 van der Zanden, E. H., Verburg, P. H., Schulp, C. J. E., & Verkerk, P. J. (2017). Trade-offs of European agricultural abandonment. *Land Use Policy*, *62*, 290-301. https://doi.org/10.1016/j.landusepol.2017.01.003

Vázquez-Rowe, I., Ziegler-Rodriguez, K., Margallo, M., Kahhat, R., & Aldaco, R. (2021). Climate action and food security: Strategies to reduce GHG emissions from food loss and waste in emerging economies. *Resources, Conservation and Recycling*, *170*, 105562. https://doi.org/10.1016/j.resconrec.2021.105562

Vera, I., Wicke, B., Lamers, P., Cowie, A., Repo, A., Heukels, B., Zumpf, C., Styles, D., Parish, E., Cherubini, F., Berndes, G., Jager, H., Schiesari, L., Junginger, M., Brandao, M., Bentsen, N. S., Daioglou, V., Harris, Z., & van der Hilst, F. (2022). Land use for bioenergy: Synergies and trade-offs between sustainable development goals. *Renewable & Sustainable Energy Reviews*, *161*, Article 112409. https://doi.org/10.1016/j.rser.2022.112409

Werling, B. P., Dickson, T. L., Isaacs, R., Gaines, H., Gratton, C., Gross, K. L., Liere, H., Malmstrom, C. M., Meehan, T. D., Ruan, L. L., Robertson, B. A., Robertson, G. P., Schmidt, T. M., Schrotenboer, A. C., Teal, T. K., Wilson, J. K., & Landis, D. A. (2014). Perennial grasslands enhance biodiversity and multiple ecosystem services in bioenergy landscapes. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(4), 1652-1657. https://doi.org/10.1073/pnas.1309492111

Wu, F., & Pfenninger, S. (2023). Challenges and opportunities for bioenergy in Europe: National deployment, policy support, and possible future roles. *Bioresource Technology Reports*, *22*, 101430. https://doi.org/10.1016/j.biteb.2023.101430

Xu, Y., Zhou, J., Feng, W., Jia, R., Liu, C., Fu, T., Xue, S., Yi, Z., Guillaume, T., Yang, Y., Peixoto, L., Zeng, Z., & Zang, H. (2022). Marginal land conversion to perennial energy crops with biomass removal enhances soil carbon sequestration. *Global Change Biology Bioenergy*, *14*(10), 1117-1127. https://doi.org/10.1111/gcbb.12990

Öckinger, E., & Smith, H. G. (2007). Semi-natural grasslands as population sources for pollinating insects in agricultural landscapes. *Journal of Applied Ecology*, *44*(1), 50-59. https://doi.org/10.1111/j.1365-2664.2006.01250.x

DOCTORAL THESES PUBLISHED IN ENVIRONMENTAL SCIENCE, LUND UNIVERSITY

1. Georg K.S. Andersson (2012) Effects of farming practice on pollination across space and time. Department of Biology/Centre for environmental and climate research

2. Anja M. Ödman (2012) Disturbance regimes in dry sandy grasslands – past, present and future. Department of Biology/Centre for environmental and climate research

3. Johan Genberg (2013) Source apportionment of carbonaceous aerosol. Department of Physics/Centre for environmental and climate research

4. Petra Bragée (2013) A palaeolimnological study of the anthropogenic impact on dissolved organic carbon in South Swedish lakes. Department of Geology/Centre for environmental and climate research

5. Estelle Larsson (2013) Sorption and transformation of anti-inflammatory drugs during wastewater treatment. Department of Chemistry/Centre for environmental and climate research

6. Magnus Ellström (2014) Effects of nitrogen deposition on the growth, metabolism and activity of ectomycorrhizal fungi. Department of Biology/Centre for environmental and climate research

7. Therese Irminger Street (2015) Small biotopes in agricultural landscapes: importance for vascular plants and effects on management. Department of physical geography and ecosystem science/ Department of Biology/Centre for environmental and climate research

8. Helena I. Hanson (2015) Natural enemies: Functional aspects of local management in agricultural landscapes. Department of Biology/Centre for environmental and climate research

9. Lina Nikoleris (2016) The estrogen receptor in fish and effects of estrogenic substances in the environment: ecological and evolutionary perspectives and societal awareness Department of Biology/Centre for environmental and climate research

10. Cecilia Hultin (2016) Estrogen receptor and multixenobiotic resistance genes in freshwater fish and snails: identification and expression analysis after pharmaceutical exposure. Centre for environmental and climate research

11. Annika M. E. Söderman (2016) Small biotopes: Landscape and management effects on pollinators. Department of Biology/Centre for environmental and climate research

12. Wenxin Ning (2016) Tracking environmental changes of the Baltic Sea coastal zone since the mid-Holocene. Department of Geology/Centre for environmental and climate research

13. Karin Mattsson (2016) Nanoparticles in the aquatic environment, Particle characterization and effects on organisms. Department of Chemistry/Centre for environmental and climate research

14. Ola Svahn (2016) Tillämpad miljöanalytisk kemi för monitorering och åtgärder av antibiotika- och läkemedelsrester I Vattenriket. School of Education and Environment, Kristianstad University/Centre for environmental and climate research

15. Pablo Urrutia Cordero (2016) Putting food web theory into action: Local adaptation of freshwaters to global environmental change. Department of Biology/Centre for environmental and climate research

16. Lin Yu (2016) Dynamic modelling of the forest ecosystem: Incorporation of the phosphorous cycle. Centre for environmental and climate research

17. Behnaz Pirzamanbein (2016) Recontruction of past European land cover based on fossil pollen data: Gaussian Markov random field models for compositional data. Centre for Mathematical Sciences/Centre for environmental and climate research

18. Arvid Bolin (2017) Ecological interactions in human modified landscapes –Landscape dependent remedies for the maintenance of biodiversity and ecosystem services. Department of Biology/Centre for environmental and climate research

19. Johan Martinsson (2017) Development and Evaluation of Methods in Source Apportionment of the Carbonaceous Aerosol. Department of Physics/Centre for environmental and climate research

20. Emilie Öström (2017) Modelling of new particle formation and growth in the atmospheric boundary layer. Department of Physics/Centre for environmental and climate research

21. Lina Herbertsson (2017) Pollinators and Insect Pollination in Changing Agricultural Landscapes. Centre for environmental and climate research

22. Sofia Hydbom (2017) Tillage practices and their impact on soil organic carbon and the microbial community. Department of Biology/Centre for environmental and climate research

23. Erik Ahlberg (2017) Speeding up the Atmosphere: Experimental oxidation studies of ambient and laboratory aerosols using a flow reactor. Department of Physics/Centre for environmental and climate research

24. Laurie M. Charrieau (2017) DISCO: Drivers and Impacts of Coastal Ocean Acidification. Department of Geology/Centre for environmental and climate research

25. Kristin Rath (2018) Soil salinity as a driver of microbial community structure and functioning. Department of Biology/Centre for environmental and climate research

26. Lelde Krumina (2018) Adsorption, desorption, and redox reactions at iron oxide nanoparticle surfaces. Department of Biology/Centre for environmental and climate research

27. Ana Soares (2018) Riverine sources of bioreactive macroelements and their impact on bacterioplankton metabolism in a recipient boreal estuary. Department of physical geography and ecosystem science/Centre for environmental and climate research

28. Jasmine Livingston (2018) Climate Science for Policy? The knowledge politics of the IPCC after Copenhagen. Centre for environmental and climate research

29. Simon David Herzog (2019) Fate of riverine iron over estuarine salinity gradients. Department of Biology/Centre for Environmental and Climate Research

30. Terese Thoni (2019) Making Blue Carbon: Coastal Ecosystems at the Science-Policy Interface. Centre for Environmental and Climate Research

31. Lovisa Nilsson (2019) Exploring synergies – management of multifunctional agricultural landscapes. Centre for Environmental and Climate Research

32. Zhaomo Tian (2019) Properties and fungal decomposition of iron oxide-associated organic matter. Centre for Environmental and Climate Research

33. Sha Ni (2020) Tracing marine hypoxic conditions during warm periods using a microanalytical approach. Department of Geology/Centre for Environmental and Climate Research

34. Julia Kelly (2021) Carbon exchange in boreal ecosystems: upscaling and the impacts of natural disturbances. Centre for Environmental and Climate Science

35. William Sidemo Holm (2021) Effective conservation of biodiversity and ecosystem services in agricultural landscapes. Centre for Environmental and Climate Science

36. John Falk (2021) Ice out of Fire: Ice and cloud condensation nucleation of aerosol particles emitted from controlled soot generation and combustion of renewable fuels. Department of Physics/Centre for Environmental and Climate Science

37. Maria Blasi i Romero (2021) Wild bees in agricultural landscapes: Modelling land use and climate effects across space and time. Centre for Environmental and Climate Science

38. Ivette Raices Cruz (2021) Robust analysis of uncertainty in scientific assessments. Department of Biology/Centre for Environmental and Climate Science

39. Adrian Gustafson (2022) On the role of terrestrial ecosystems in a changing Arctic. Department of Physical Geography and Ecosystem Science/Centre for Environmental and Climate Science

40. Klas Lucander (2022) Direct and indirect pressures of climate change on nutrient and carbon cycling in northern forest ecosystems – Dynamic modelling for policy support. Department of Physical Geography and Ecosystem Science/Centre for Environmental and Climate Science

41. Johan Kjellberg Jensen (2023) Understanding the urban ecosystem – interactions between plants, animals, and people. Department of Biology/Centre for Environmental and Climate Science

42. Paola Michaela Mafla-Endara (2023) Encounters at the microscale: Unravelling soil microbial interaction with nanoplastics. Department of Biology/Centre for Environment and Climate Science.

43. Dmytro Perepolkin (2023) Scientific methods for integrating expert knowledge in Bayesian models. Centre for Environment and Climate Science

44. Karlsson, Melanie (2024) Developing organic farming – Agroecological challenges for sustainable intensification. Centre for Environment and Climate Science.

45. Rosero, Pedro (2024) Conservation biological control in agricultural landscapes at the interface between ecology and evolution – The importance of land-use-mediated bottom-up ecological effects and eco-evolutionary dynamics. Centre for Environment and Climate Science.

Centre for Environmental and Climate Science
Faculty of Science

ISBN 978-91-8104-147-7