Exploring synergies – management of multifunctional agricultural landscapes

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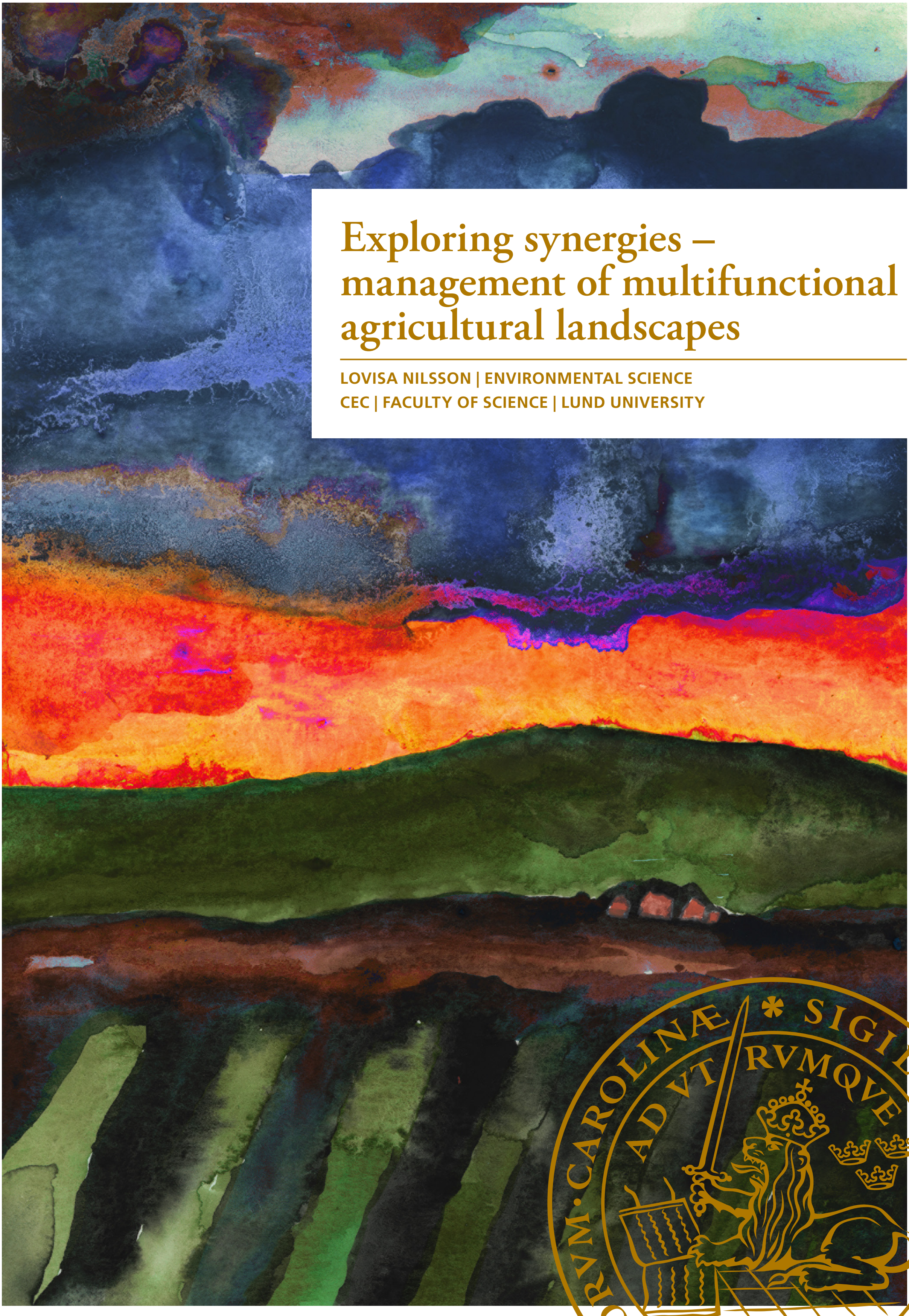

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II Nilsson, L., J. Leventon, M. V. Brady, J. Hanspach, K. Hedlund, P. Olsson, and H. G. Smith. Factors influencing farmers' responses to changes in agri-environmental schemes. Manuscript.

III Nilsson, L., B. K. Klatt, and H. G. Smith. Effects of flower-enriched ecological focus areas on functional diversity across scales. Manuscript.

IV Klatt, B. K., L. Nilsson, and H. G. Smith. Annual flowers strips benefit bumble bee colony growth and reproduction. Submitted to Biological Conservation.

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Exploring synergies – management of multifunctional agricultural landscapes

Lovisa Nilsson

LUND UNIVERSITY

DOCTORAL DISSERTATION

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Abstract

Human ingenuity and activities have resulted in erosion of ecosystems and their capacity to support the sustainable production of goods and functions that we depend on. Biodiversity i.e. the diversity within and between species and of ecosystems, underpins many of the ecosystem functions critical for human well-being and resilience, and is declining faster than at any time in human history. Thus, the ongoing loss of biodiversity and its associated ecosystem functions is one of the most critical challenges we face today. The intensification of agriculture during the last century, including both in-field intensification and loss and fragmentation of habitats, has played a major role in the degradation of biodiversity and ecosystem services world-wide. The intensification of agriculture has resulted in increased production of private goods such as crops but at the expense of public goods like for example regulation of water and climate. In addition, the intensification of agriculture also erodes regulating ecosystem services such as pollination, which ultimately threatens the provision of sustainable crop production. In this thesis I have investigated how to integrate management of ecosystem services in arable farming, to promote multifunctional landscapes that are able to support sustainably both private and public goods. In a conceptual study, framing the thesis, I suggest that the whole 'ecosystem service cascade' needs to be taken into consideration when formulating agri-environmental policies and that by exploiting synergies between private and public goods, it is possible to let public goods hitchhike on private goods. I have investigated the possibilities of and constraints on integrating ecosystem services under current EU agri-environmental policies, how these policies affect farmer behaviour and the consequences of alternative policy formulations for ecosystem services such as pollination and natural pest control. I contribute to the currently weak evidence base on the ecological effect of agri-environmental measures, using the CAP ecological focus areas as a case study. Annual ecological focus areas sown with flower strips had weak effects on natural enemies but positively affected bumblebees up to several 100 m from the strips. Together the two studies showed the potential for networks of annual flower strips to provide complementary resources in intensively managed agricultural landscapes, where late-season resources are often scarce. By investigating the role of farmer attitudes and farm characteristics for decisions to take up a voluntary agri-environmental measure, we showed that uptake of buffer strips is connected to both attitudes and farm size. The results highlight the importance of ensuring positive attitudes among farmers as well as the need to facilitate environmentally friendly management. Using ecological-economic modelling we demonstrated that by restricting ecological focus areas to such with a high quality with optimal placement, they could have positive effects on functional biodiversity. The same study also showed how the current incentives made the ecological focus areas end up in landscapes were their benefits were lowest, and the structural changes that may occur as an effect of agri-environmental policies, for example when higher management costs caused more farms to close down, resulting in the average farm size increasing. The farmers participating in the workshop in this study, perceived the CAP 'greening measures' as complicated and without any environmental benefits. Through the studies in the thesis, I have shown the importance of combining experimental demonstrations of effects of measures across scales, with investigations on what affects the uptake of measures, and combining ecological and economic aspects to use analyses of policy-scenario to account for the complex consequences of policies.

Key words: Multifunctionality, ecosystem services, functional biodiversity, agri-environmental policy, CAP, agri-environmental measures

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List of papers

This thesis is based on the following papers, referred to in the text by their roman numbers.

I. **Nilsson, L.,** G. K. S. Andersson, K. Birkhofer, and H. G. Smith. 2017. *Ignoring ecosystem-service cascades undermines policy for multifunctional agricultural landscapes.* Frontiers in Ecology and Evolution 5:109

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Author contributions

I. HGS originally conceived the idea. LN developed the idea further and wrote the manuscript with significant input from HGS. All other authors contributed to the final manuscript.

II. LN, JL, HGS, and MB designed the study with input from KH. LN and JL designed the questionnaire and LN executed the research. LN and PO performed the spatial analysis. LN analysed the data from the questionnaires with support from JH, JL and HGS. LN wrote the paper with input from all authors.

III. LN, BKK and HGS designed the study. Fieldwork and data collection were done by LN and BKK. LN carried out the statistical analyses with input from BKK and HGS. LN wrote the paper with input from HGS and BKK.

IV. BKK, LN and HGS designed the study. Fieldwork and data collection were done by BKK and LN. All authors conducted the statistical analysis and BKK wrote the paper with input from LN and HGS.

V. This paper is an elaboration on a report which included preliminary results and was commissioned by the Swedish Environmental Protection Agency (Dänhardt et al., 2017). YC and JD initiated the project with DS and KS, and all authors contributed to its preparation. LN developed the ideas from the report into a manuscript with help from HGS, and input from all authors. LN and JD were the main responsible for stakeholder interviews, YC for the ecological modelling, JD and JAO for the farmer workshop where LN, MB and YC participated, and MB and JH for the economic modelling.

Populärvetenskaplig sammanfattning

Det senaste århundradet har den tekniska utvecklingen gått snabbt inom många områden. Jordbruket är ett av dessa. Idag upptas ungefär en tredjedel av jordens landyta av jordbruk och boskapsskötsel. Utvecklingen av jordbruket har inneburit att vi idag kan producera mer mat än någonsin, men den har också inneburit intensivare brukningsmetoder, genom till exempel ökad användning av besprutningsmedel och konstgödsel och allt större fält. Detta har bland annat resulterat i att allt fler naturliga och semi-naturliga habitat, så som åkerholmar, fältkanter, naturbetesmarker och ängar har fragmenterats och försvunnit från våra landskap. Det allt intensivare jordbruket har i sin tur lett till en dramatisk minskning av jordens biologiska mångfald. Faktum är att vår markanvändning är den största orsaken till utarmningen av biologisk mångfald globalt. Detta sätt att använda vår planet utarmar inte bara dess ekosystem och biologiska mångfald, men också många av de ekosystemtjänster som vi människor är beroende av. För att vi långsiktigt ska kunna förse jordens befolkning med mat och andra resurser samtidigt som vi bevarar biologisk mångfald är det därför nödvändigt att hitta lösningar som innebär vi kan göra detta utan att utarma vår natur och dess förmåga att förse oss med materiella och icke-materiella resurser.

I denna avhandling har jag undersökt olika aspekter, både möjligheter och utmaningar, för att möjliggöra dessa multifunktionella jordbrukslandskap. Med multifunktionella landskap menas sådana som kan förse oss med mat och grödor men också bevara biologisk mångfald och ekosystemtjänster som klimat- och vattenreglering. Det är därför landskap där vi integrerar multipla ekosystemtjänster och undviker negativa konsekvenser av intensiva jordbruksmetoder, så som övergödning och utarmning av den biologiska mångfalden. I avhandlingens olika kapitel har jag tillsammans med mina medförfattare använt olika metoder för att söka svar på frågor kring hur en central miljöpolicy i EU:s jordbrukspolitik och andra faktorer påverkar lantbrukares beslut när det kommer till att utföra miljöåtgärder, hur en specifik miljöåtgärd påverkar pollinatörer och naturliga fiender, samt hur utformningen av en policy kan leda till indirekta effekter som strukturella förändringar av jordbruket.

I Sverige och resten av EU regleras miljöfrågor i jordbrukslandskapet främst genom den Gemensamma jordbrukspolitiken (CAP). Alla lantbrukare i EU måste uppfylla vissa krav gällande bland annat hur jordbruksmarken ska skötas. Dessa krav kallas för tvärvillkor vilka utgör en lägsta nivå för EU:s lantbrukares åtagande för att minimera negativa effekter på miljön. Utöver tvärvillkoren finns det så kallade förgröningsstödet som innebär att många europeiska lantbrukare måste odla minst tre olika grödor samt ha så kallade ekologiska fokusarealer på fem procent av sin mark, för att ha rätt till hela sitt arealbaserade gårdsstöd. Det finns dessutom frivilliga miljöåtgärder som lantbrukare kan utföra mot ersättning för förlorad inkomst. En vanlig sådan miljöåtgärd är skyddszoner längs vattendrag, vars syfte är att förhindra näringsläckage från åkermark. Trots dessa olika styrmedel är de flesta forskare överens om att EU:s miljö- och jordbrukspolitik inte är tillräcklig för att stävja den negativa utvecklingen, framförallt när det gäller biologisk mångfald.

Vi behöver hitta hållbara lösningar, där vi kan förse jordens befolkning med mat och andra materiella och icke-materiella resurser utan att samtidigt utarma planeten på dessa. För att göra detta behöver vi veta hur vi på bästa sätt implementerar en hållbar markanvändning. Vi behöver veta hur utformningen av policys påverkar lantbrukares beslut att inkludera miljövänliga metoder i sitt jordbruk men även hur de påverkar jordbruket strukturellt. Denna kunskap behöver kombineras med bevis kring de effekter de resulterande fysiska förändringarna av landskapet har för biologisk mångfald och ekosystemtjänster. För att kunna förutse konsekvenser av olika typer av policys är det med andra ord av största vikt att dessa är underbyggda av solida vetenskapliga bevis.

Multifunktionella jordbrukslandskap

Begreppet multifunktionalitet används på flera olika sätt i diskussioner om ekosystemtjänster och markanvändning. Dessa olika sätt spänner från att beskriva förhållandet mellan antalet arter och funktioner i ett ekosystem till hur landskap förutom att producera mat och foder också utgör habitat för djur och växter och bidrar till arbetstillfällen och en levande landsbygd. I avhandlingens första kapitel argumenterar jag för att miljö- och jordbrukspolitiken i större grad bör länka samman de olika sätt som begreppet multifunktionalitet används inom olika ämnesområden. Effektiva policys för att gynna multifunktionella landskap måste bygga på kunskap om hur markanvändning påverkar de olika tjänster vi människor nyttjar, både direkt och indirekt via påverkan på underliggande ekologiska processer. Jag uppmärksammar också möjligheten att utnyttja potentiella synergieffekter mellan olika typer av ekosystemtjänster; ekosystemtjänster av gemensamt värde kan åka snålskjuts när lantbrukare sköter ekosystemtjänster som är viktiga för den egna produktionen. Detta kan vara ett mer kostnadseffektivt sätt att gynna ekosystemtjänster av allmänt värde än subventioner, men kan inte ersätta behovet av andra åtgärder som miljöstöd i jordbruket.

Vilka faktorer påverkar beslut kring miljöåtgärder?

I avhandlingens andra kapitel kombinerar jag information om förekomst av vattendrag och markanvändning i Södra Götalands slättbygder med en enkätstudie skickad till lantbrukare i samma område. Jag undersöker vilka faktorer som ligger bakom beslut om att ha skyddszoner på åkermark längs vattendrag, under några olika år då miljöstöd funnits för denna åtgärd. Resultaten visar att både positiva attityder kring biologisk mångfald i jordbrukslandskapet och kring skyddszoner specifikt ökar chanserna för att lantbrukare anlägger skyddszoner. Resultaten visar också att lantbrukare med större gårdar i högre grad har skyddszoner men också att de reagerade kraftigare på förändringar i ersättningen. Lantbrukare med mindre gårdar var i högre grad deltidslantbrukare än de med större gårdar. En del av förklaringen skulle därför kunna vara en proportionellt större administrativ börda för dessa lantbrukare. Betydelsen av både gårdsstorlek och attityder visar vikten av att göra det enkelt att delta i miljöåtgärder men också att säkerställa att lantbrukare kan basera sina skötselbeslut på största möjliga kunskapsunderlag för att maximera chanserna till positiva attityder.

Ekologiska fokusarealer

I de tre sista kapitlen i avhandlingen ligger fokus på de ekologiska fokusarealerna, som nämndes ovan. De ekologiska fokusarealerna blev obligatoriska för många europeiska lantbrukare, om de önskade få hela sitt gårdsstöd, när CAP reformerades och 'förgrönades' år 2013. Syftet med fokusarealerna var att gynna biologisk mångfald på de europeiska gårdarna. Ekologiska fokusområden skulle vara enkla att utforma, generella och ettåriga. Den så kallade förgröningen av CAP fick snabbt kritik för att vara för svag för att kunna bidra till att uppnå uppställda mål kring biologisk mångfald.

I kapitel tre och fyra utgick vi från ett antal gårdar där man hade planerat att ha ekologiska fokusarealer i form av så kallade obrukade fältkanter. För att höja kvalitén på dessa sådde vi in dem med en fröblandning bestående av växter som tidigare visat sig attrahera både pollinatörer och naturliga fiender, för att undersöka om vi på så vis kunde gynna dessa organismgrupper i det omgivande landskapet. Gårdarna låg i slättbygden i södra Skåne, ett landskap dominerat av intensivt brukad åkermark. Detta område valdes eftersom de undantag som finns från förgröningsåtgärderna gör att det är främst stora gårdar i denna typ av landskap som behöver ha ekologiska fokusarealer. De ettåriga blomremsorna som etablerades på de ekologiska fokusarealerna, hade dock ingen eller relativt liten effekt på förekomsten av de undersökta naturliga fienderna i närliggande spannmålsfält. Inte heller solitära bin och steklar påverkades positivt av närhet till en blomremsa; istället påverkades de av det omgivande landskapets struktur genom att de blev fler ju mindre andelen jordbruksmark var. Bland blomflugorna, den mest mobila av de studerade organismgrupperna, kunde vi se en svag positiv effekt av förekomsten av blomremsor på mängden larver. Vi placerade även ut humlekolonier på olika avstånd från blomremsorna. Här kunde vi visa en stark positiv effekt för humlornas kolonitillväxt nära blomremsorna, denna effekt avtog sedan med ökat avstånd från remsorna. Nätverk av ettåriga blomremsor skulle därmed kunna leda till positiva populationseffekter både inom och mellan säsonger för humlor. I intensivt brukade jordbrukslandskap med få naturliga habitat kan vi inte förvänta oss att ettåriga blomremsor får samma effekt som om de anläggs i ett småskaligt jordbrukslandskap, där det redan finns mer bo- och födoplatser för nyttodjur som pollinatörer och naturliga fiender. I dessa landskap bör snarare perenna blomremsor övervägas eller möjligen en kombination av perenna och annuella åtgärder.

I avhandlingens sista kapitel undersöker jag följderna av alternativa utformningar av reglerna för de ekologiska fokusarealerna, för både ekosystemtjänster, lantbrukare och jordbrukslandskapet strukturellt. Vi visar bland annat att det inte räcker med att inkludera åtgärder med större potential att gynna biologisk mångfald bland de möjliga fokusarealerna, utan att de dessa också måste begränsas till just åtgärder med hög kvalité.

Multifunktionella landskap – är det möjligt?

I denna avhandling har jag visat på möjligheter att i större utsträckning utnyttja synergieffekter mellan olika typer av ekosystemtjänster för att öka multifunktionaliteten hos våra landskap. Detta kan ske genom att i större utsträckning se till att miljöåtgärder vi utför i jordbrukslandskapet samtidigt gör nytta både för den enskilda lantbrukaren och för samhället i stort. Jag har också visat på hur miljöåtgärders effekt kan utvärderas, så att de underbyggs av vetenskapliga bevis. I en rad studier har jag visat på metoder för hur alternativa policys kan utvärderas, genom att studera effekter på upptag av åtgärder och deras placering i landskapet, ekologiska effekter av åtgärder och strukturella effekter på lantbruket i stort. En heltäckande utvärdering av jordbrukspolitiken kräver naturligtvis fler studier än vad som ryms inom ramarna för en avhandling men studierna här visar betydelsen av ett helhetsgrepp när denna typ av utvärderingar görs och har bidragit till det kunskapsunderlag som behövs.

Om vi tar detta i beaktning och dessutom underlättar för lantbrukare att sköta sin mark på bästa möjliga vis, så ökar möjligheterna för multifunktionella landskap med förmåga att förse jordens befolkning med mat och andra materiella och icke-materiella resurser utan att utarma planeten på dessa samtidigt.

Introduction

"While more food, energy and materials than ever before are now being supplied to people in most places, this is increasingly at the expense of nature's ability to provide such contributions in the future, and frequently undermines nature's many other contributions, which range from water quality regulation to sense of place. The biosphere, upon which humanity as a whole depends, is being altered to an unparalleled degree across all spatial scales. Biodiversity – the diversity within species, between species and of ecosystems – is declining faster than at any time in human history."

From the summary for policymakers for IPBES Global Assessment, 2019

Humans are and have always been dependent on nature. For example, nature provides us with food, feed and fibre, regulates climate and water, and enrichen our lives by providing aesthetic and cultural values. The ability of nature to provide us with these goods and functions, often called ecosystem services (Westman 1977, Ehrlich and Ehrlich 1981), has often been taken for granted. However, during the last centuries, anthropogenic impact on the planet has become larger than ever before. This result of human ingenuity and activities have resulted in erosion of ecosystems and their capacity to support the sustainable production of goods and functions that we depend on (IPBES 2019, IPCC 2019).

Biodiversity, defined in the United Nation's Convention of Biological Diversity (United Nations 1992) as "*The variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems*", plays a special role in this story, by underpinning many of the ecosystem functions critical for human well-being and resilience. Therefore, the human caused, ongoing loss of biodiversity and its associated ecosystem functions is one of the most critical challenges we face today (IPBES 2019) (Box 1).

Our dependence on nature and susceptibility to erosion of critical ecosystem functions have been particularly obvious in agricultural landscapes. As early as 1962, Rachel Carson in *Silent Spring* noted that modern agricultural production methods were a main driver of loss of biological diversity. Today we know that the agricultural intensification of the last centuries, including both in-field intensification and loss and fragmentation of habitats, has resulted in a major decline in biodiversity and ecosystem services worldwide (see e.g. Matson et al. 1997, Krebs et al. 1999, Donald et al. 2001, Robinson and Sutherland 2002, Tscharntke et al. 2005, Geiger et al. 2010, IPBES 2019).

Increased production of private goods such as agricultural products as a result of the intensification of agriculture, has occurred at the expense of many public goods provided by agricultural landscapes. This "tragedy of ecosystem services" (Lant et al. 2008) (alluding to Hardin's *the tragedy of the common* (1968)), is caused by farmers/landowners carrying the costs of supporting public goods while their benefits will be shared with others. There are, in other words, trade-offs between different type of ecosystem services - private goods such as production of food and fibre on one hand, and public goods such as regulation of climate and water on the other, where the production of private goods often are at the expense of public goods. However, in addition agricultural intensification also erodes regulating services underpinning yield, which ultimately threatens the provision of sustainable crop production (Matson et al. 1997, Power 2010). One likely reason for the erosion of yield-enhancing ecosystem services from agricultural landscapes is lack of knowledge on the relationships between ecosystem functions and processes and final ecosystem services and benefits. Nevertheless, pollination and natural pest control are both examples of regulating services underpinning yield, that involves processes occurring on larger spatial scales than within one farm and therefore have some properties of a public good, making them subject to the "tragedy of ecosystem services" (Cong et al. 2014).

The aim of this thesis was to investigate how to integrate management of ecosystem services in arable farming, to promote multifunctional landscapes that are able to support sustainably both private and public goods. To this end, I have investigated the possibilities of and constraints on integrating ecosystem services under current agri-environmental policies, how these policies affect farmer behaviour and the consequences of alternative policy formulations for ecosystem services such as pollination and natural pest control. The focus is on the European Union (EU), through the environmental aspects of the Common Agricultural Policy (CAP), as implemented in Sweden.

Multifunctional agricultural landscapes

"*One basic weakness in a conservation system based wholly on economic motives is that most members of the land community have no economic value*"

From *The Sand County Almanac*, (Leopold 1949)

Agricultural landscapes are intrinsically multifunctional. Beyond producing private goods such as food and fibre, these landscapes also constitute habitats for many species and provide us with public goods such as climate and water regulation (OECD 2001, Huylenbroeck et al. 2007, Mastrangelo et al. 2014). Nevertheless, as summarized well in the quote above from the summary for policy makers for IPBES Global Assessment, the incentive to increase private goods has resulted in an intensification of agriculture and overall land use during the last centuries which has to a large extent occurred at the expense of the environment and its ability to provide contributions apart from crop production (and, as noted above, in the long term also crop production). It is thus urgent to find solutions to avoid trade-offs between the private and public goods provided by agricultural landscapes and to prevent biodiversity loss and other environmental externalities.

In trying to find synergies between the production of private and public goods, a common argument for conserving and restoring biodiversity in agricultural landscapes is its role in contributing to ecosystem services important for crop production, such as pollination and natural pest control. According to this view, integration of biodiversity conservation in agricultural landscapes benefits production goals.

Conservation of biodiversity can be integrated in landscapes at different spatial scales. In the broadest sense different conservation strategies can be divided into either the creation of protected areas separated from agricultural production or into efforts to integrate conservation with agricultural production by making it less adverse to biodiversity, i.e. land sparing versus land sharing (Green et al. 2005, Fischer et al. 2008). Land sparing *sensu stricto* rarely affects yield enhancing ecosystem services as conservation measures needs to be adjacent to crop fields that benefit from these services (Brosi et al. 2008, Smith et al. 2014, Mitchell et al. 2015). Land sharing *sensu stricto,* on the other, has very high costs in terms of yield loss. However, the two conservation strategies do not necessarily represent distinct categories, because land can be spared at different spatial scales and at which scale integration of conservation in agriculture should be regarded as sharing is in the eye of the beholder (Ekroos et al. 2016). In this thesis the focus in on an intermediate level of land sharing, in the EU facilitated through compulsory (cross compliance) and voluntary (agri-environmental schemes) measures, where farmers are either enforced to or compensated for the integration of certain environmentally friendly management practices on their land.

In focusing on the capacity of cross-compliance and agri-environmental schemes to contribute to multifunctional agricultural landscapes, important questions asked in this thesis are about which interventions to use, where they should be placed and at what scales they have effects. Things that we need to know more about, in order to improve agri-environmental policies.

If an intervention, an agri-environmental measure, will have anticipated effects will depend on several things. The spatial and management strategies for managing ecosystem services and for conservation of biodiversity per se are for example often different (Ekroos et al. 2014). The relationship can be asymmetrical and measures aiming to benefit biodiversity per se, will often improve conditions for ecosystem services while measures targeted for ecosystem services do not necessarily improve conditions for rare species/biodiversity (Macfadyen et al. 2012, Kleijn et al. 2015). Further, it is unclear how much biodiversity is needed to provide those ecosystem services that enhance yields. Often a small subset of mostly common species that persist under modern agricultural management visit the crops (Kleijn et al. 2015), while specialist species, if present, prefer other sources of pollen and nectar (Magrach et al. 2018). If, for example, flower strips will contribute to actually increasing farmland biodiversity, or if they only will benefit already common species and the services they provide, will depend on both on the surrounding landscape and what kind of plants that are included in the flower strip (Macfadyen et al. 2012, Wood et al. 2016). In a simple landscape with a high proportion of crop production the chances that an agri-environmental measure will benefit rare species are low (Tscharntke et al. 2002, Tscharntke et al. 2005, Rundlöf and Smith 2006, Concepción et al. 2012, Tscharntke et al. 2012). In landscapes with more available habitat the probability for synergies between biodiversity conservation and ecosystem services are higher (Ekroos et al. 2014). Thus, in order to create synergies between biodiversity conservation and ecosystem service management, a landscape perspective is thus needed for the different agri-environmental policies (Macfadyen et al. 2012). Today this holistic, landscape approach is, to a large extent, missing. In **Paper III** and **IV** the general effects on functional biodiversity of an agri-environmental measure is considered, and in particular at what scales they have effect. The spatial targeting of agri-environmental measures (related to landscape effects) is considered in **Paper V**.

The term *multifunctionality* is often used in the context, of agricultural landscapes (see e.g. OECD 2001, Mastrangelo et al. 2014) and has the potential to be a useful concept for policy regarding sustainable land use, aiming for optimal levels of both private and public goods. Still, agri-environmental policies have so far had limited success in mitigating biodiversity loss and other negative externalities from intensive agricultural management (see e.g. IPBES 2019, Pe'er et al. 2019). In **Paper I**, I explore the use of the concept of multifunctionality in the literature and suggest ways forward in order to better integrate it in agri-environmental policies by considering the ecosystem service cascade and the scales of processes behind final ecosystem services and benefits.

Box 1. Governing biodiversity

The realisation of the seriousness and irreversibility of biodiversity loss has resulted in an array of global initiatives and increased focus on functional aspects of biodiversity. In 1993, the United Nations (UN) Convention of Biological Diversity (CBD), was signed by 168 countries. The CBD recognised the intrinsic value of biological diversity (biodiversity), but also its ecological, genetic, social, economic, scientific, educational, cultural, recreational and aesthetic values (United Nations 1992). In 2011, The EU biodiversity strategy to 2020 was adopted. It aimed to halt loss of biodiversity and ecosystem services in the EU by 2020 (EU 2011). The preservation of biodiversity is also an important part of the sustainable development goals (SDGs), adopted by all 193 UN member states through Agenda 2030 in September 2015 (UN General Assembly 2015). Goals 14 and 15 specifically focus on preserving life on land and below water respectively and it is pointed out that preservation of biodiversity is crucial for sustaining human life. With the objective to strengthen the science-policy interface for biodiversity and ecosystem services, for the conservation and sustainable use of biodiversity, long-term human well-being and sustainable development, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) was established as an independent intergovernmental body in 2012. IPBES has the same role for biodiversity and ecosystem services related questions as The Intergovernmental Panel on Climate Change (IPCC) (established in 1988) has for climate change, in synthesising current state of knowledge. IPBES has produced thematic and regional synthesis reports, and in May 2019, the IPBES Global Assessment Report on Biodiversity and Ecosystem Services (IPBES 2019) was presented and approved at the seventh sessions of the IPBES Plenary, by 132 member states. The report, that was the first global assessment since the Millennium Ecosystem Assessment in 2005 (MEA 2005), highlighted the seriousness of the situation for the state of biodiversity and caught a lot of media attention.

The role of policies in mitigating loss of biodiversity and its functions in farmland

CAP is the major European policy affecting agricultural development. It was launched in 1962 by the EUs founding countries, with the aim to safeguard food production. However, over the years additional policy instruments aiming to support the environment have been incorporated in CAP. The 1992 reform of CAP introduced agri-environmental schemes which aimed to reduce negative externalities of agriculture. In the 2003 CAP reform, direct payments to farmers, that up to this point had been coupled with agricultural production, were de-coupled and instead based on the area of agricultural land. Further, CAP was organised into two so-called pillars. The first pillar addresses the common organisation of the markets (CMO) and includes the direct payments to farmers, which were now linked to the area of agricultural land instead of production. The second pillar is the EU's rural development program, which includes for example the overarching priority to ensure sustainable management of natural recourses. Through Pillar 2, instruments such as payments for voluntary agri-environmental measures and Natura 2000 are funded. Since 2005, all farmers receiving the direct payments of Pillar 1 are subject to compulsory cross-compliance, meaning that to be eligible for direct payments they need to live up to certain standards concerning the environment, food safety, animal and plant health and animal welfare, as well as maintaining their land in good agricultural and environmental condition. Thus, cross-compliance represents a baseline for all EU farmers and is an important tool for integrating certain environmental requirements in CAP.

In the 2013 CAP reform, three so called 'greening measures' were introduced in Pillar 1 and now constitutes 30 percent of the direct payments. The three measures included crop diversification, maintaining permanent grasslands and so-called ecological focus areas (EFA). The requirements for crop diversification meant that farmers needed to grow at least two or three crops on their land, something most farmers already did (for Sweden, see Josefsson et al. (2017)) which meant that this measure had little impact on farming practices. The requirement to maintain permanent grasslands also did not have any effect in practice, as this was regulated on a national or regional level. Hence, the greening measure with best potential to affect farmland biodiversity and associated ecosystem services were the EFAs, which implied that farmers should have areas with an ecological focus on five percent of their arable land. These areas became mandatory for many farmers (to be eligible for the full direct payment). The EFAs were explicitly focused on biodiversity, and their purpose was *"in particular, [...] to safeguard and improve biodiversity on farms"* (Recital 44 of Regulation (EU) No 1307/2013 EU 2013b). Further, the EFAs should be easy to implement and be annual. It is stated that: *"Those practices should take the form of simple, generalised, non-contractual and annual actions that go beyond cross-compliance and that are linked to agriculture, such as crop diversification, the maintenance of permanent grassland, including traditional orchards where fruit trees are grown in low density on grassland, and the establishment of ecological focus areas"* (Recital 37 of Regulation (EU) No 1307/2013 EU 2013b).

The agri-environmental schemes, funded through Pillar 2, in which farmers are financially compensated for carrying out specific voluntary agri-environmental measures that are beneficial for the environment including biodiversity, are together with cross-compliance, the main environmental policy instrument in CAP. Compared to general measures such as EFAs and cross-compliance they are often better conceived to handle the concerns that they are addressing. Due to the voluntary nature of these schemes it is therefore important that, in addition to understanding how they affect biodiversity and prevent negative environmental externalities from agriculture in general, effort is made to understand farmers' motivations in implementing them. The more we know about what factors influence farmer's decision making on environmentally friendly practices, the better conditions we will have for designing policies that can mitigate biodiversity loss and promote farmland ecosystem services. In **Paper II**, I contribute to a growing literature on farmer decision making and the uptake of voluntary agri-environmental schemes, by exploring factors affecting farmer's uptake of buffer strips along water bodies in Sweden.

After being introduced with the 2013 reform, it did not take long until the CAP's 'Greening measures', including the EFAs, received critique for being too weak to be able to fulfil stated biodiversity goals (e.g. Pe'er et al. 2014, Pe'er et al. 2016). The main critique was that the quality requirements were low including their general and annual character, and the fact that exceptions from them being mandatory for full direct payments in many areas made them end up mostly in intensively managed areas. In **Paper III, IV** and **V**, I scrutinise the CAP EFAs, and their effects in the region with the most intensive farming in Sweden. In **Paper III**, based on the existing critiques, I investigated whether improved EFAs can be used to enhance functional biodiversity across scales or if these landscapes already are so depauperated that annual measures like these have no effect. In **Paper III** and **IV** I investigated local and landscape effects of the annual EFAs on pollinators. **Paper V** evaluates the consequences of different EFA policy scenarios for functional biodiversity and ecosystem services, farmers, as well as EFA placement in the landscapes, by investigating the link between policies and uptake of measures.

As a response to the criticism of a lack of a landscape perspective it has been suggested that increased collaboration among actors would increase CAP's efficiency in conserving biodiversity and associated ecosystems services (Leventon et al. 2017). There are several reasons to expect that farmer collaboration could benefit the implementation of policies aiming at preserving biodiversity and ecosystem services in agricultural landscapes (which is highlighted in **Paper I**). Collaboration among farmers could facilitate an improved spatial targeting of measures and be a way to avoid "the tragedy of ecosystem services" when the processes underpinning the service takes place at scales larger than within farms (Lant et al. 2008, Lindborg et al. 2017, **Paper I**). In **Paper V** the role of farmer collaboration in terms of collective implementation of the EFAs is explored.

Thesis aims

Finding ways to meet human demands of material and non-material contributions from nature without depleting biodiversity is one of the biggest societal challenges of today. If in the future, agricultural landscapes shall be able to provide us with food, feed and fibre, as well as other services such as climate mitigation and water regulation, there is a need to manage them in ways that balance the multiple contributions landscapes make. The overarching theme for this thesis is to investigate how to integrate management of ecosystem services in arable farming, with the aim to promote multifunctional landscapes. To this end, I have investigated how to best use and incentivise agri-environmental measures on field borders to benefit functional biodiversity and ecosystem services.

Overview of Papers

Paper I explores the concept of multifunctionality, in particular potential synergies between private and public goods generated by agri-environmental measures, and argues for an integrated approach accounting for the entire ecosystem service cascade when formulating agri-environmental policies.

Paper II investigates the role of farmer attitudes and farm characteristics for decisions to take up a voluntary potentially multifunctional agri-environmental measure - buffer strips along water bodies.

Paper III investigates the effect of EFAs, managed as annual flower strips, on organisms providing biological control of pests and pollination of crops and wild plants across scales.

Paper IV studies the effect of flower strips on the performance of bumblebee colonies across scales, to understand how to implement flower strips spatially to benefit their populations.

Paper V evaluates multiple ecosystem service benefits of ecological focus areas under alternative policy formulations using a multi-method approach able to capture both uptake of agri-environmental measures and structural effects on farming.

Methods

Pursuing this thesis in environmental science, aiming to investigate how to integrate management of ecosystem services in arable farming, by pursuing questions on both ecological relationships and farmer uptake of agri-environment measures, made a multi-method approach a necessity. The main methods are described in this section.

Paper I is a conceptual paper, framing my thesis. Based on analyses of current literature on multifunctionality and ecosystem services in agricultural landscapes, I propose a conceptual framework that serves as a framework when designing and analysing subsequent studies. In **Paper II** and **V**, a questionnaire, interviews and a decision game were used to explore farmers' attitudes and decisions regarding agri-environment measures under Pillar 2 and 1 of CAP, respectively. **Paper V** was based on a cross-disciplinary collaboration, including natural and social scientists, to be able to combine interviews, workshop methodology, economic and ecological modelling. In **Paper III** and **IV**, the effects of annual flower strips on natural enemies, a pest and pollinators were studied in an experimental field-study.

In **Paper II**, we used both a questionnaire, sent by post to over 1800 famers in 2015, spatial analyses of the potential buffer strip uptake for each farm using land cover GIS data of streams and water bodies from the Swedish cadastral surveyor (© Lantmäteriet), and spatial analysis of buffer strip uptake using IACS panel data on land use for all crop land in Sweden from the Swedish Board of Agriculture, to explore factors potentially influencing farmer's decision making on participating in the buffer-strip scheme. We explored the opportunity arising from the payments for buffer strips changing two times during the first ten years after the scheme was introduced in Sweden in 2001. It was already known that when the payment decreased, also the total area of buffer strip did. Using this as a point of departure for this study, I wanted to explore what factors influenced farmers' decision making on buffer strips. Hence, I asked if farmers that decreased their area have something in common, if some farmers were more likely to have a buffer strip and if some farmers were more likely to opt out of the scheme?

By using a novel mixed methods approach, combining spatially explicit information on land use (crop land) and land cover from multiple sources, we could not only see if a farmer had buffer strips in a given year or not, but also how much of the theoretically potential area that was enrolled in the buffer strip scheme. To investigate the role of factors such as farmer's attitudes towards buffer strips and farmland biodiversity in general, as well as socio-economic variables such as farm size, farm productivity and education, in buffer strips decision making, we sent out a questionnaire to farmers with cropland close to water. The questionnaires were sent to farmers in the most productive area of Sweden, i.e. the area were buffer strips in general have the best potential to mitigate eutrophication (Johansson and Bång 2014, Sidemo-Holm et al. 2018). We used an exploratory approach with regression models and model selection based on Akaike Information Criteria (AICc) to investigate if farm and farmer characteristics could explain the variation in uptake of buffer strips.

In **Paper III**, **IV**, and **V** the Ecological Focus Areas (EFAs) of the European Union's Common Agricultural Policy (CAP) are under scrutiny. Since the 2013 CAP reform, EFAs are mandatory for many farmers in the EU in order to get the full direct payment. The EFAs were introduced as a "greening" of the CAP but have been criticised for having too low quality requirements to be able to fulfil stated biodiversity goals (see e.g. Pe'er et al. 2014, Pe'er et al. 2016).

Figure 1. Top left, one of the flower strips in the study leading up to Paper III and IV (Photo: Albin Andersson). Lower left, weighing of bumble bee hives for Paper IV (Photo: Albin Andersson). Picture to the right: the author with tiller samples for Paper III (Photo: William Sidemo Holm).

In **Paper III** and **IV**, we designed studies to experimentally evaluate the consequences of high quality EFAs on multiple ecosystem services. By high quality EFAs we mean such that in contrast to the current regulation not only are strips of bare soil but contain vegetation that is thought to benefit biodiversity in landscapes. To explicitly relate it to current implementation of the "greening" of the CAP, we improved the habitat in already planned EFAs at large arable farms, by sowing annual flower strips in them. In total eleven annual flower strips were sown on areas already planned to be managed as EFAs in the form of uncropped field borders, in 2016 (Figure 1). The strips were sown in a landscape with a relatively high proportion of agricultural land (approximately 75-95 percent crop land within 1000 m from the strip). This selection of study design was based on the fact that that, due to exemptions from the mandatory EFAs, it is in these types of landscapes ecological focus areas are found. These landscapes are also dominated by annual crops (in contrast to leys and pastures) that potentially benefit from functional biodiversity and the ecosystem services of biological control and crop pollination. Our intent in **Paper III** and **IV** was to investigate if the annual EFAs could have a positive effect on natural enemies and pollinators in landscapes with a high proportion of agricultural land. If so, we wanted to know if these effects extend out in the landscape.

In **Paper III** we studied potential effects of annual flower strips on natural enemies and aphids in adjacent cereal fields, and on solitary bees and wasps up to approximately 1000 meters from the strip. For natural enemies, we used suction sampling, pitfall traps and tiller counts to estimate their abundance, and for aphids we used tiller counts. These measurements took place in winter wheat in fields close to the flower strip, at different distances from the flower strip (up to 40 m). For the solitary bees and wasps, we used trap nests (artificial nesting holes) at different distances from the flower strip (up to ca 1000 m) to estimate reproductive output as the number of cells with larvae.

In **Paper IV,** we studied the effect of annual flower strips on bumble bee colony development and reproduction at different spatial scales. This was done by placing commercial bumble-bee hives of the native species *B. terrestris* at different distances from the flower strips and studying average growth rate (colony weight), production of reproductives (drones and queens) and colony foraging activity (rate of incoming workers with pollen) during the summer.

Paper V was a cross-disciplinary study where we used both economic and ecological modelling as well as interviews and a decision game with farmers, to evaluate current and alternative policy for CAP EFAs. We devised six policy scenarios differing in quality requirements of the EFAs and whether implementation was collective or not. These scenarios were used to assess alternative policies on functional biodiversity, farmer livelihoods and the feasibility of their implementation in Sweden. We did this in three steps; first, using agent-based economic modelling, we predicted how profit maximising farmers take up available EFA measures and adapt their farm and overall land use to the new policy. In the next step, this knowledge was integrated into ecological models and we predicted how these changes affect the ecosystem services pollination and natural pest control. Last, the modelling was complemented with a farmer workshop, including a decision game to better understand factors affecting real farmers, and interviews with officials at administrative and advisory bodies concerning their expectations connected to the different scenarios. In this way, we could identify barriers and opportunities perceived by both farmers and administrative and advisory bodies regarding the different EFA scenarios.

Results and Discussion

The overarching theme of this thesis is that of multifunctional agricultural landscapes, in particular agri-environmental measures and policies aiming to promote such multifunctionality. Agricultural policies, technological development and farmers' strive to increase farm profits have resulted in a focus on intensified production of food, feed and fibre, often at the expense of the many public goods produced by agricultural landscapes. As a result, there has been a loss of multifunctionality in agricultural landscapes. In spite of major changes to the CAP, often with the aim to improve its ability to reduce agriculture's environmental externalities and benefit the production of public goods, this trend has not been reversed. Furthermore, it is now realised that this development is not only threatening public goods, but also sustainable crop yields, by eroding regulating and supporting ecosystem services that depends on biodiversity in a wide sense (Matson et al. 1997, Power 2010). Reversing this development, constitutes one of the greatest challenges globally today. In this thesis, I have focused on the EUs CAP, and more precisely on its implementations in Sweden.

There is a plethora of studies identifying key weaknesses of current EU agri-environmental policies, explaining why they are not successful in mitigating loss of biodiversity and associated ecosystem services, and suggesting improvements (see e.g. these resent papers: Gawith and Hodge 2019, Pe'er et al. 2019, Simoncini et al. 2019, but also e.g. Plieninger et al. 2012, Dicks et al. 2014). Some of the main aspects of this criticism are outlined here.

The effects of agri-environmental measures on biodiversity and ecosystem services will to a high degree depend on how and where they are implemented. Accordingly, a reason for that policies do not give anticipated effects may be that they are not sufficiently spatially targeted (Smith et al. 2010, Batáry et al. 2015, Pe'er et al. 2019). For example, it has been suggested that it is in landscapes with intermediate levels of semi-natural habitats that a measure aiming to promote biodiversity will be most successful. In contrast, in a too simple landscape there will be no source habitats from which organisms to be benefitted can colonise, and in a complex landscape the marginal benefit of a measure will be small since the landscape can already sustain biodiversity (Tscharntke et al. 2002, Tscharntke et al. 2005, Rundlöf and Smith 2006, Concepción et al. 2012, Tscharntke et al. 2012, Tschumi et al. 2015). A policy that fails in incorporating a landscape perspective may thus fail in reaching its aims.

Spatial targeting is complicated by biodiversity being a multifaceted concept, such that which measures are best will depend on which aspects of biodiversity is to be protected. If the target of the policy is conservation per se and then often rare habitat specialists with limited mobility, agglomerated and permanent habitats may be needed (Drechsler et al. 2010). In contrast, to optimise agri-environmental measures for functional biodiversity and intermediate ecosystem services like pollination and natural pest control, measures should ideally be spread in the landscape and be implemented close to cash crops that benefit from these services (Brosi et al. 2008, Smith et al. 2014, Mitchell et al. 2015). A common critique of agri-environmental policies is that there is a lack of incentives for spatially arranging agri-environmental measures to achieve larger benefits for biodiversity and associated ecosystem services (Rundlöf and Smith 2006, McKenzie et al. 2013, Pe'er et al. 2014).

One suggestion to better coordinate and spatially target biodiversity and ecosystem services management in agricultural landscapes is through increased collaboration among actors (Leventon et al. 2017). Collaboration among farmers could allow for agri-environmental measures to be placed in the landscape where their biodiversity and ecosystem service benefits are largest regardless of farm boundaries (Kuhfuss et al. 2016, Lindborg et al. 2017). For ecosystem services such as pollination, where the scale of processes underpinning the service may be such that farmers implementing measures also benefit their neighbours (Cong et al. 2014), farmer collaboration could be a way to overcome 'the tragedy of ecosystem services' (Lant et al. 2008, Lindborg et al. 2017, **Paper I**). Further, farmer collaboration may create synergies, such as improved knowledge dissemination, higher flexibility and lower costs for farmers as well as lower administrative transaction costs (Franks 2011, Prager et al. 2012, McKenzie et al. 2013, Prager 2015, van Dijk et al. 2015).

Finally, and equally important, agri-environmental policies not only need to lead to measures being implemented in the right places, but also to that farmers actually implement them. Today farmers enrolling in agri-environmental schemes are compensated for profits forgone or for management costs. If the payments are not closely adjusted to these costs it may result in a heterogenous uptake quite different from the optimal one in terms of effects. Nevertheless, also other factors than profit maximisation may affect farmers' decisions. Therefore, it is vital to understand the full range of factors influencing farmer's uptake of agri-environmental measures and their pro-environmental behaviour in general.

A holistic approach to evaluating agri-environmental policies

In this thesis, I have explored the main challenges in restoring multifunctionality in contemporary agricultural landscapes. I theoretically explored how a combined focus on intermediate and final services, may be used to identify synergies between multiple services (**Paper I**). In a series of studies, I investigated how agri-environmental policies can foster multifunctionality, by using multiple methods to study how EFAs can be used to benefit biodiversity and associated ecosystem services (**Paper III**, **IV**, and **V**). Empirical and model studies investigated implications of the placement of agri-environmental measures and the relation to policy (**Paper III**, **IV**, and **V**). I also investigated what drives the uptake of measures and thus the effectiveness of policies to benefit biodiversity and ecosystem services (**Paper II**), but also how the direct consequences interact with structural change, to affect the flow of ecosystem services (**Paper V**).

In the thesis, I have used a holistic approach, by studying the different aspects of the chain from policy to effects. I have studied uptake of agri-environmental schemes (**Paper II**), but also how policies may result in non-intended effects through structural change (**Paper V**). I have used empirical studies (**Paper III** and **IV**) and models (**Paper V**) to link the measures, as well as the more general outcome of alternative policies, to the outcomes in terms of functional diversity.

Multifunctionality – the overarching framework

EU environmental policies have traditionally been focused on benefitting biodiversity and reducing environmental externalities. Lately there has been an increasing focus on promoting multifunctional landscapes that sustain private and public goods as well as rural livelihoods (see e.g. EU 2011, 2013a, b), but it has been suggested that current policies are failing to achieve this (see e.g. Gawith and Hodge 2019, Pe'er et al. 2019). In **Paper I**, I suggested how the different definitions of multifunctionality (used in the context of ecosystem services and agricultural landscapes) could be joined into a coherent framework that could be used to analyse and propose policies for sustaining agricultural landscapes that provide both private and public goods. I suggest that the different multifunctionality concepts can be linked to different parts of 'the ecosystem service cascade' (sensu Haines-Young and Potschin 2010, Potschin and Haines-Young 2011) and that to improve multifunctionality of agricultural landscapes we need to take the whole 'ecosystems service cascade' into consideration when formulating agri-environmental policy (**Paper I**). In the paper, we argue that: *"A cascade perspective on multifunctionality simultaneously focuses on the underlying drivers and processes that* *provide ecosystem functions (i.e., intermediate ecosystem services; Pasari et al. 2013), the joint supply of ecosystem services, and the capacity of a landscape or management practices to simultaneously support multiple benefits to society (i.e., final ecosystem services; Mastrangelo et al. 2014)"* (**Paper I**). With a better knowledge of the underlying intermediate functions/services we can for example exploit synergies between private and public goods and target several ecosystem services in the same agri-environmental measure and/or policy and thus let public goods hitchhike on private goods (**Paper I**). Further, we argue that agri-environmental policies need to acknowledge that ecosystem services occur at different spatial scales. Intermediate services such as pollination might for example occur at scales larger than a farm, even if the final service they benefit in the form of crop production is a private good. We argue that "*the "tragedy of ecosystem services" to some extent can be overcome if policy considers both the private and public goods that are generated through agri-environmental measures"* and suggest that for this collaboration among neighbouring farmers might be required (**Paper I**).

The case of the ecological focus areas

It has been argued that the 'greening' of the CAP has failed to meet its aims (e.g. Pe'er et al. 2014, Pe'er et al. 2016). In this thesis, I investigated why agri-environmental policies sometimes fail to meet their stated environmental aims, by using EFAs and their intended effect on farmland biodiversity as a case study. In **Paper V**, I suggest that the problem might be that the reform was not well thought out in relation to the chain from policy – over uptake – to ecological effects. In **Paper V**, the farmers participating in the study perceived the CAP 'greening measures' as complicated and without any environmental benefits and they requested EFAs (as well as measures targeted by agri-environmental schemes) to be more flexible and easily integrated into both long-term planning on the farm as well as in every-day activities (**Paper V**). One important aspect of the 'greening' was to maintain a low administrative burden for farmers (EU 2013b), the result became a "greening" policy with measures with little to no effect on farmland biodiversity (Pe'er et al. 2014), that at the same time undermines the farmers trust in the policy, as well as their motivation to perform agri-environmental measures (**Paper V**). By using agent-based modelling we, in **Paper V**, could also show how different quality requirements of mandatory measures such as the EFAs lead to different structural changes, where for example higher management costs led to more farms closing down and the remaining farms on average increasing in size. This shows how seemingly small policy changes can result in unintended consequences for the agricultural landscapes.

The aim of the EFAs was to "*safeguard and improve biodiversity on farms*", nevertheless there was also a priority on them being simple, because they should be easily integrated into commercial farming. This led to a selection of measures that had little proven benefits (Dicks et al. 2014). Further, the EFAs, due to vast exemptions, mostly have ended up at relatively big farms in intensively managed agricultural landscapes. In intensively managed landscapes there are only small founding populations of organisms to be benefited by measures and annual measures - the only alternative under present EFA regulations - can only benefit/boost these populations during a limited amount of time. Since, under the current regulation, the quality of EFAs also tend to be low (such as the in Sweden commonly occurring uncropped field borders with bare soil), their effect on biodiversity may be very small.

In **Paper III**, I investigated if an alternative formulation of the EFA measure would have consequences for functional biodiversity, by sowing annual flower strips on the EFA type *uncropped field borders.* The experimental annual high-quality EFAs were implemented as flower strips in intensively managed landscapes were benefits from improved functional biodiversity may be large. We found that they had no to little effect on natural enemies and aphids and for solitary bees and wasps in general. However, we did find a positive, but small, effect of the flower strips on the abundance of hoverfly larvae, which suggest that they may improve biological control since these larvae may act as natural enemies of pests such as aphids. The effect we found may be explained by adult hoverflies being the most mobile organism group included in the study, with a life history (e.g. not being central place foragers (Covich 1976)) allowing them to be opportunistic and take advantage of newly established habitats, also in intensively and fragmented agricultural landscapes (Jönsson et al. 2015). Thus, adult hoverflies may be attracted to and utilize the flower strips and lay eggs in their surroundings. In contrast, less mobile species (e.g. spiders) or species which are central-place foragers (e.g. solitary bees), did not benefit from the annual strip, possibly because of a lack of sufficient founding populations. Alternatively, these species are limited by the lack of overwintering habitats and would rather benefit from other type of measures (Landis et al. 2000). In the study, we investigated the use of EFAs, and any improvement of quality *therefore* had to be annual. However, if the regulations on EFAs instead encouraged multi-annual measures, there might be better measures such as perennial or multi-annual flower strips (Jönsson et al. 2015). Nonetheless, in **Paper IV** we showed that the annual flower strips had a positive effect on bumble bee colony growth and reproduction. Since bumble bees are important pollinators of crops and wild plants, this demonstrates that annual flower strips on EFAs can provide an opportunity to benefit an important ecosystem service in agricultural landscapes. However, given that the effect on bumble bees decreased with distance from the flower strip, flower strips needs to be implemented at a high enough density.

In **Paper V**, we formulated alternative policy scenarios for EFAs which included different quality requirements as well as demands for spatial targeting. Using ecological-economic modelling we were able to demonstrate that by restricting EFAs to such with a high quality with optimal placement, they could have positive effects on functional biodiversity, and ultimately on pollination and natural pest control (**Paper V**).

However, here the assumptions of the ecological models need to be mentioned, as they highlight an important risk when evaluating policy using a modelling approach when lacking sufficient empirical data. In the ecological models in **Paper V**, we assumed that the EFA flower strips had a positive effect on natural enemies up to 50 meters into the adjacent fields (based on, at the time of the study, available data in e.g. Tschumi et al. 2015). However, in **Paper III**, when exploring the effects of flowering EFAs empirically in the same type of landscapes as the modelled ones, we were not able to show any strong positive effect of flowering EFAs (although hoverfly larvae were affected as expected in the model). This may be because of the exact placement of EFAs, which was determined by farmers' choice of which crop to place them in (for practical reasons), but also different prerequisites in Swiss (Tschumi et al. 2015) and Swedish landscapes. The assumption in **Paper V** of a positive effect of EFA flower strips on pollinators was on the other hand confirmed in **Paper IV**, where bumble bees were positively affected by the strips.

The results from **Paper III**, also highlights that polices needs to consider that measures have different values in different types of landscapes (see e.g. Rundlöf and Smith 2006, Pe'er et al. 2014). Annual flower strips have successfully been implemented and been able to contribute to natural pest control in Switzerland (Tschumi et al. 2015, Tschumi et al. 2016). The landscape there was dominated by a mosaic of small fields, providing plenty of habitat for beneficial arthropods (Martin et al. 2019) and the annual flower strips thus became a complement to existing habitats (Tschumi et al. 2015). One of the main conclusions on the mandatory EFAs evaluated in **Paper III**, was that annual agri-environmental measures needs to be implemented with care in intensively managed agricultural landscapes. Bumble-bee colony development and reproduction, studied in **Paper IV**, in the same landscapes as for **Paper III**, was nevertheless positively affected up to 600 m from the annual strips. Taken together, the results from **Paper III** and **IV** show that annual flower strips have the potential to provide valuable complementary resources in intensively managed agricultural landscapes were the availability of late season resources (after the early mass-flowering of crops such as oil-seed rape) is often low (see e.g. Westphal et al. 2009, Rundlöf et al. 2014). However, in these type of landscapes (where the availability of semi-natural habitats is low) annual flower strips is likely most efficient if combined with multi-annual or perennial measures since a measure with longer duration will allow populations to build up over time and subsequently spread in the landscape (Jonason et al. 2011, Jönsson et al. 2015).

Mandatory measures, enforced through the direct payments in CAP's Pillar 1, such as the EFAs, could facilitate networks of potential habitat for farmland biodiversity. However, for them to actually mitigate biodiversity loss, they need to have a high enough quality. With the current flexible and low requirements on quality of EFAs this is not likely to happen (Pe'er et al. 2014, **Paper V**). This was one of the main conclusions in **Paper V**, where we suggest that a first step to more potent EFAs is to increase quality requirements (both of measures and their placement) and exclude measures with little or no potential to benefit biodiversity. This will be the case when measures of lowest ecological quality also generate the lowest costs to farmers and thus will be preferred over more expensive options with higher environmental benefits (under the assumption of that the farmers profit-maximise). The incentives also for the same reason resulted in a sub-optimal spatial targeting of *functional* biodiversity, with EFAs being placed in landscapes were their benefits were lowest. Interestingly, this effect worsened over time as a result of structural change of agriculture. The sub-optimal spatial targeting was worsened by farmer collaboration (**Paper V**), because this allowed farmers to utilize the variation in implementation costs across multiple farms. Nevertheless, as we, like others before us, show in **Paper II**, also non-pecuniary factors such as attitudes, occupation rate, and farm size, influence farmers decisions on environmentally friendly management. This demonstrates that it is not only important to consider evidence on the effect of agri-environmental measures (Dicks et al. 2014) in the menu of options, but also important to acknowledge the importance of the farmers attitudes and consequently the access to information on the value of measures (**Paper V**).

Farmer collaboration - challenges and possibilities

In **Paper V**, we evaluated the possibility for farmers to implement EFAs collectively, as this is something that the EU policy on EFAs makes possible (but that only The Netherlands and Poland have implemented). Coordinated biodiversity management through collaboration between farmers (and other actors) has, as mentioned above, been suggested as one way of increasing the CAP's potential to conserve biodiversity and associated ecosystem services (Leventon et al. 2017). Coordinated agri-environmental measures could allow for a landscape approach, allowing measures to be placed where the biodiversity benefits are largest (Kuhfuss et al. 2015, Lindborg et al. 2017). In addition, it may create synergies such as knowledge dissemination, higher flexibility and lower costs for farmers (Prager et al. 2012, McKenzie et al. 2013, Prager 2015). For voluntary agri-environmental measures in the Netherlands (Pillar 2), farmer collectives have proven to increase participation in schemes and reduce transaction costs (Franks 2011). However, there is one important difference between the farmer collaboration in the studies mention above, and collaboration on implementation of EFAs – the EFAs are mandatory for the farmers in order for them to get full direct payments. The farmers are thus enforced rather than enticed to have EFAs which may affect their motivation. As stated in the paper: *"This in itself is an incentive rather for a "better being safe than sorry" approach to EFAs than for creating meaningful measures, collaborative or not, that would have a positive effect on farmland biodiversity."* (**Paper V**). The results of the modelling in **Paper V**, showed that to incentivise profit maximising farmers to place effective EFA types where it is environmentally optimal in a landscape perspective, instead of placing them where they have least cost, would provide added environmental benefits. While to allow collective implementation, and at the same time give farmers great flexibility in placement and types of EFAs, did not provide incentives for the profit maximising model farmers to best benefit the environment, but only to reduce their costs even further. In **Paper V**, we thus demonstrate the importance of incentivising collaboration but only when combined with a landscape perspective for where to implement measures. A potential added benefit of collaboration between farmers could occur if the policy instead just allowing a reduction of opportunity costs (as a result from the farmers managing EFAs together), also utilized the ability of collaboration to overcome the tragedy of the commons for ecosystem services such as pollination an natural pest control were the ecological processes may takes place on scales bigger than individual farms (Stallman 2011, Lindborg et al. 2017, **Paper I**). In this way collaboration could be of joint benefit to the participating farmers and then the main challenge would only be to help farmers overcome potential resistance to collaborate (Riley et al. 2018).

Altogether, the potential for collaboration to overcome the 'tragedy of ecosystem services' (Stallman 2011, Lindborg et al. 2017, **Paper I**), the willingness to collaborate demonstrated among the farmers participating in the decision game in **Paper V**, the positive examples showed in for example Franks (2011), and the potential in positive synergy effects such as knowledge dissemination among farmers (Prager et al. 2012, McKenzie et al. 2013, Prager 2015), suggest that farmer collaboration have great potential to provide positive environmental effects for agricultural landscapes. In contributing to knowledge dissemination among farmers, collaboration may also induce a positive chain reaction, as both positive attitudes towards biodiversity (as demonstrated in **Paper II**) and greater knowledge about it (Kelemen et al. 2013, Power et al. 2013), have been suggested to positively affect both willingness to apply biodiversity friendly farming as well as on farm biodiversity (Power et al. 2013).

Uptake of environmentally friendly practices

The results from **Paper V**, demonstrate the challenges in devising mandatory measures aiming to improve biodiversity and associated ecosystem services. The EFAs are a part of the direct payments, in practice this makes them mandatory. As a result, it becomes necessary that they are fairly easy for authorities to administrate. In the case of the EFAs, it unfortunately led to a selection of measures that had little proven benefits (Dicks et al. 2014). As they are a part of the direct payment, it means that there is a large incentive to implement the EFAs, whether or not farmers are interested in their effects. That opportunity and management costs drives the uptake of agri-environmental measures is a generic problem in the CAP. Through Pillar 2, the agri-environmental schemes are activity- and not result-based, meaning that the farmer gets compensated regardless of the result of the agri-environmental measures (Herzon et al. 2018, Sidemo-Holm et al. 2018). While result based payments in theory have great potential, there are particular challenges when it comes to biodiversity and ecosystem services since it is difficult to quantify these benefits (Burton and Schwarz 2013).

In **Paper II**, the focus is on the voluntary agri-environmental measures in Pillar 2. Even if the design of these schemes often could be improved, for example by being result- instead of activity-based (Herzon et al. 2018, Sidemo-Holm et al. 2018), as shown in **Paper II** the fact that they are voluntary increases the chances that the farmers enrolling in the schemes actually care about the results (compared to the EFAs). This may lead to higher quality and thus better outcomes for biodiversity and ecosystem services (Power et al. 2013).

In order to meet the aims for the agri-environmental schemes it is, nevertheless, essential to have sufficient levels of uptake of the agri-environmental schemes among farmers. In **Paper II**, we focus on the uptake of buffer strips, a relatively common scheme in Sweden and many other EU member states. Buffer strips are grass-sown strips placed on agricultural fields along water bodies to prevent nutrients from entering the water and thus preventing eutrophication (see e.g. Jansson et al. 1994, Zedler 2003). They have a high potential to go beyond preventing eutrophication, to also promote biodiversity (see e.g. McCracken et al. 2012, Stutter et al. 2012, Josefsson et al. 2013), and improve conditions for both pollination and natural pest control (Gill et al. 2014, Cole et al. 2015). Using a novel mixed methods approach where we combined panel data on agricultural land use, land cover maps and a farmer questionnaire, we could explore factors affecting farmers' uptake of buffer strips.

Our results in **Paper II**, showed that farm size and attitudes were the most important predictors for buffer strip uptake. Positive attitudes and larger farms increased the chances of enrolling in the scheme, and importantly the larger farms reacted more strongly to changes in the scheme/payment level compared to smaller farms. That larger farms were more sensitive to changes than smaller farms can possibly be explained by the administrative burden of the schemes being relatively higher for the smaller farms, especially since the smaller farms also were more likely to be managed by farmers that also had other jobs. The difference in uptake between farmers with different attitudes and prerequisites suggests that learning more about how different type of farmers perceive enrolling in agri-environmental schemes could facilitate changes that could increase scheme uptake levels. Future research should aim to increase our understanding on how different farmers perceive enrolling in agri-environmental schemes and how factors such as lifestyle and family situation can impact the uptake of environmentally friendly management and participation in schemes. The positive impact of positive attitudes also highlights the importance of ensuring that farmers have access to the best possible information when they make decisions on participating in an agri-environmental scheme or environmentally friendly practices in general.

Conclusions and future perspectives

There is a strong need to evaluate consequences of agri-environmental policies on biodiversity and ecosystem services to be able to base choice of policies on comprehensive scientific evidence. Nevertheless, it is not straightforward to evaluate consequences of agri-environment policies on ecosystem services, since they may affect interlinked intermediate and final services, but at different spatial scales. We therefore need to understand the consequences of policies along the ecosystem service cascade – from the ecosystem functions and processes to the final ecosystem services and benefits. With the papers in this thesis, I have been able to contribute to a conceptual framework usable to evaluate agri-environmental policies. (**Paper I**).

Current approaches to evaluate agri-environmental policies tend to depend largely on simple methods based on uptake or time-series of indices (Smith et al. 2016). However, policy evaluation requires that we understand the effects of the policies on uptake as well as non-intentional consequences of policies (e.g. structural change) and that we then combine this knowledge with evidence of effects the resulting physical changes of the landscape (e.g. agri-environmental measures, abandonment) have on biodiversity and ecosystem services. In this thesis, I have demonstrated the value of a mixed method approach to evaluate agri-environmental policies. I show the importance of combining experimental demonstrations of effects of measures across scales (**Paper III and IV**), with investigations on what affects the uptake of measures (**Paper II**), and combine ecological and economic aspects to use analyses of policy-scenario to account for the complex consequences of policies (**Paper V**).

I contribute to the currently weak evidence on the ecological effect of agri-environmental measures (Dicks et al. 2014). When experimentally testing the effects of annual EFAs sown with flower strips in southern Sweden, we only found weak positive effects on hoverfly larvae in adjacent fields (**Paper III**). However, for bumblebees, we found a positive effect up to several 100 m from the strips (**Paper IV**). Together, the studies showed the potential for networks of annual flower strips to provide complementary resources in intensively managed agricultural landscapes, where late-season resources are often scarce. In intensively managed and ecologically simple agricultural landscapes, where perennial habitat is scarce, the annual flower strips would most likely have a better effect if combined with more permanent agri-environmental measures (Krimmer et al. 2019). This type of management planning is something that future research needs to study more specifically. The consequences of policies will also depend on how they affect farmer behaviour. In investigating factors influencing uptake of agri-environmental schemes we could show how uptake of voluntary buffer strips is connected to both attitudes and farm size, highlighting the importance of ensuring positive attitudes among farmers as well as the need to facilitate environmentally friendly management (**Paper II**). I have also shown the importance of co-developing agri-environmental policies with farmers, by demonstrating how farmers perceived the CAP EFAs as impractical and without environmental effects (**Paper V**). The same paper also showed structural changes that may occur as an effect of agri-environmental policies, for example when higher management costs caused more farms to close down, resulting in the average farm size increasing. This shows how seemingly small changes in policies can have far-reaching consequences for agricultural landscapes and their ability to sustain public goods.

This thesis focuses on agri-environmental measures integrated with arable farming and with a focus primarily on functional biodiversity. In addition to what the studies here have focused on, there also exists possibilities to exploit synergies between mitigation of biodiversity loss and climate change (IPBES 2019, IPCC 2019). Moreover, while I focused on functional biodiversity, this is only one aspect of biodiversity. The measures I have been studying may be important for functional biodiversity, but they may fail to conserve all species we want to conserve, for example rare habitat specialist. Thus, although not included as part of this thesis it is important to acknowledge that to exploit synergies between private and public goods as a way to mitigate biodiversity losses and negative environmental externalities from modern agricultural practices, cannot be the only strategy (see e.g. Macfadyen et al. 2012, Kleijn et al. 2015). To use a combination of approaches is probably the most realistic way to conserve biodiversity and sustain ecosystem services in agricultural landscapes (Lescourret et al. 2015), i.e. land also needs to be spared for the sole purpose of conservation (e.g. Grass et al. 2019). To be able to do this, changes beyond improved farming practices are most likely needed. Today, more than one third of the terrestrial surface of our planet is used for crop production and animal husbandry (IPBES 2019). By making changes in our food systems, and in our diets, it has been suggested that the agricultural area could be significantly reduced (see e.g. Alexander et al. 2019), which then would allow larger areas to be dedicated to conserving biodiversity and ecosystem services.

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