Inter-annual landscape planning for pest and pollinator management in faba beans

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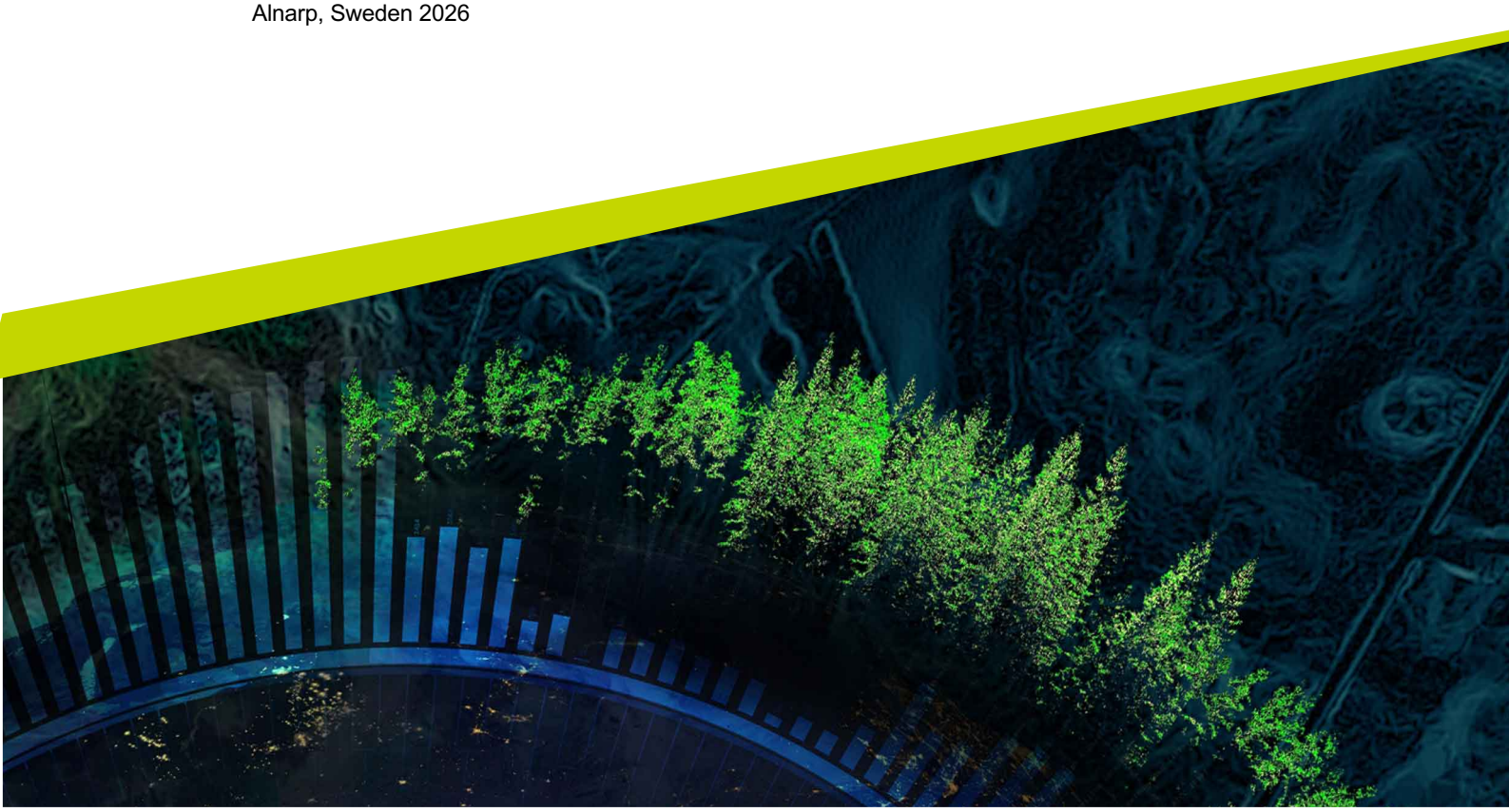

Interannual Landscape Planning for Pest and Pollinator Management in Faba Bean

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Abstract

An overwhelming body of evidence shows that our modern intensive agricultural practices are no longer compatible with a sustainable future for humanity. Therefore, the question becomes: how can we maintain the high yields necessary to feed our growing population in a manner which is sustainable? Here, agroecology and integrated pest and pollinator management (IPPM) offer a potential solution. Agroecology is a scientific study, an agricultural practice and a social movement. In all its forms, agroecology aims to understand, utilize and promote biodiversity and ecosystem services in farmland to create a more socially, economically and environmentally sustainable food production system. IPPM is a decision-making framework which builds on two previous frameworks: integrated pest management (IPM), and integrated crop-pollination (ICP). Both of these previous frameworks suggest the utilization of multiple strategies in concert. IPM focuses on reducing pest pressure with the minimal usage of pesticides. Similarly, ICP aims to increase pollination ecosystem services with minimal use of managed bee hives. IPM has often been critiqued for (among other things) failing to recognize the substantial impact of pollinators in its research or methods. IPPM's goal is to address this failure and to balance the benefits of pollination ecosystem services with the need for crop protection.

The composition of the agricultural landscape surrounding a farm is known to have impacts on both pollinator abundance, diversity and pollination services and on insect pest pressure. Meta-population dynamics, insect dispersal distance, and the habitat composition of a landscape can all affect populations of both insect pests and pollinators within a given field.

In this study, we used faba bean (*Vicia faba*) as a model crop to examine how landscape factors both within the same year and interannually affected pest pressure and pollination services. Fourteen fields in Östergötland, Sweden, were selected to be studied. Two transects were constructed in each field, one 10 m from the field edge and the other 50 m from the field edge. Pollinators and flower surveys were conducted along each transect to determine the number of flower visitations by honeybees and bumblebees, along with the abundance of flowers. The same transects were then used to determine the number of eggs laid by the broad bean beetle (*Bruchus rufimanus*) and the subsequent proportion of beans that were damaged by the beetle. The surrounding landscape composition of each field was analyzed at 3 different spatial scales (1, 2 and 3 km from the focal field). The proportion of faba bean in the landscape in the previous year, the proportion of faba bean in the landscape in the current year, and the proportion of pasture in the landscape were all determined. This data was then used to create 12 general linear mixed models (GLMM).

The models revealed that the number of faba bean fields in the landscape in the previous year increased the number of honeybee observations, but not bumblebees. Bumblebee observations were significantly higher in the transect 50 m from the field edge when compared to the transect 10 m from the field edge. The number of beetle eggs and the proportion of bean damage increased with the proportion of pasture in the landscape and the proportion of faba bean in the landscape in the current year. All of these effects changed with the spatial scale at which they were observed.

Our findings suggest that mass-flowering crops (MFCs) do not provide consistent enough floral resources to increase the reproductive fitness of wild pollinator populations, but may benefit managed honeybee populations. An increase in landscape heterogeneity, crop diversity and semi-natural habitat (SNH) is suggested to provide a more steady supply of floral resources to wild pollinators. Our research also highlights both the importance and complexity of ecological

interactions and their effects on pest pressure and pollination at the landscape scale. In order to implement landscape-scale IPPM strategies along with many other agroecological methods that rely on biodiversity and ecosystem services, we will need further research to better understand these complexities. However, further research will not be enough. Unprecedented cooperation and communication among farmers, researchers, governing bodies and agricultural extension personnel will be required. To achieve this level of communication and cooperation, radical change will have to occur in the social, political, economic and ecological systems that govern the composition of our agricultural landscapes.

Keywords: Agroecology, biodiversity, ecosystem services, integrated pest management (IPM), integrated pest and pollinator management (IPPM), landscape ecology, pest management, pollination, sustainability.

Table of contents

List of tables

List of figures

Abbreviations

Abbreviation	Description
ANOVA	Analysis of Variance
EBD	Edge-biased Distributions
EFN	Extrafloral Nectary
GLMM	General Linear Mixed Model
IACS	Integrated Administration and Control System
ICP	Integrated Crop Pollination
IPM	Integrated Pest Management
IPPM	Integrated Pest and Pollinator Management
MFC	Mass flowering crop
OSR	Oilseed Rape
SNH	Semi-natural habitat
VIF	Variance Inflation Factor
VOC	Volatile Organic Compounds

Foreward

If you had asked anyone who knew me throughout my entire childhood and early adolescence what I wanted to be when I grew up, they would have undoubtedly told you that I wanted to be a marine biologist and that I loved sharks more than anything else. Every year for Christmas and my birthday, I would ask for new books about sharks; my obsession was borderline concerning. Now I am in Sweden, studying agroecology, spending my time walking through rows of faba bean, looking for bees, counting the holes in dried beans and losing my phone in a field somewhere about an hour east of Norrköpping. As you can imagine, since I ended up here and not in shark-infested water, things did not go as young Nathan planned.

In my teen years before attending university, despite not knowing exactly what I wanted to do with my life, I was certain I wanted to be a scientist. Of what kind, I was unsure, but some sort of scientist nonetheless. My memory is fuzzy of those years, but sometime in my late teens, I became more and more aware of the dire state of the environment, of anthropogenic climate, pollution, the destruction of ecosystems and the massive losses in biodiversity. At 17, I read a quote by the author George Orwell. I don’t remember the exact words, nor will I spend the time to try and find them; it is only their sentiment that matters. To paraphrase, Orwell explained that he really had no interest in writing dystopian and political prose. He would have much rather written fantasy books like J.R.R Tolkien. But he felt that he had a duty. To use his knack for writing, to address and combat the greatest issues of his time. After I read this, I decided I would become a scientist who would study ecology and climate science, so I could make a difference in what I saw as the greatest issues of my time.

I entered university, as many before me, scared for the future, but believing that what I was doing was something that would someday make a difference. That belief was then summarily crushed and ground down into nothingness by the overwhelming mountain of evidence before me. Evidence which spelled out humanity's inevitable doom. Still, I continued to study (despite being objectively and biologically designed not to do so). Partially because I just wanted to learn even if it was depressing, and because I figured if I became a professor, I could learn for the rest of my life (while also forcing a whole classroom of intelligent young students to listen to me rant about all the depressing facts I had learned) and partially because despite the best efforts of life and the aforementioned mountain of evidence, I still held on to a minute flicker of hope that I could make things better.

I discovered and then entered into the field of agroecology through a series of more or less serendipitous circumstances, still with the goal of becoming a professor. And, despite my better judgment, there were times during this degree when I had a small amount of genuine optimism for our future on this planet. However, as I mentioned before, I was not biologically designed to be a student, and soon found myself facing the seemingly insurmountable challenge of writing this thesis, while any previously acquired optimism quickly evaporated. Somewhere between the three-hour drive back to Linköping with no phone for directions and the third or fourth all-nighter, I began to question why I was putting so much effort into something that I genuinely did not think would make any appreciable difference and was bringing me no discernible joy or fulfilment anymore. I began to feel that becoming a researcher and a professor, essentially repeating what I was already doing, but with less supervision, was not something I was meant to do. Once again, I felt rudderless, perhaps more than I had ever felt in my (now slightly longer but still relatively short) life.

After I had already presented my thesis, I was working on revisions, something I was especially dreading, as I never want to look at my own work after it has been submitted. For me, as soon as an assignment is finished, it should ideally immediately disappear from my consciousness. Nevertheless, driven by some enigmatic forces, I continued revising my thesis. Then, while reading the ten thousandth paper of my academic career, I was struck by an idea. If staying in academia and doing research wasn't meant for me, I didn't have to! For a long time, I had known that conducting primary scientific research was not what interested me. What I really wanted to do was just learn things and then have a semi-captive audience to heap all of my newfound thoughts and knowledge onto, all while somehow having that positively impact society and the planet. The 9,998th, 9,999th and and ten thousandth papers I had read/ was reading were all about how changing social structures and policy around agriculture was necessary for real change. I realized perhaps instead of academia, education and policy-making was a better fit for me!

I am a long way from shark-infested waters and George Orwell. I have no idea if this new course of direction will be the right fit. I am certain that in the pursuit of reaching this new goal, I will inevitably come across new challenges that feel just as insurmountable as writing this thesis. And, I still have very little hope that my actions (even when combined with every other person who is desperately trying to keep us alive on this tiny blue marble) will stop the oncoming apocalypse. But, still, that flicker of hope persists, and for the first time in what feels like a long time, I am excited about the direction I am headed, and that has to count for something.

1. Introduction

Modern agriculture faces the challenge of increasing food production while simultaneously reducing its environmental impacts. Over the past century, agricultural intensification has greatly improved crop yields through the expansion of cultivated land, mechanization, and the widespread use of synthetic fertilizers and pesticides (Matson et al., 1997; Tilman et al., 2001). However, these developments have also contributed to biodiversity loss, habitat homogenization, soil degradation, and declines in ecosystem services that are essential for sustainable food production (Tscharntke et al., 2005). Agricultural intensification has also transformed large areas of complex natural ecosystems into simplified and highly managed agricultural landscapes, losing semi-natural habitats (SNH). Because agricultural land occupies a substantial proportion of terrestrial ecosystems, its management is critically important for biodiversity conservation and the maintenance of ecosystem services (Tscharntke et al., 2005). Among the most affected organisms are insect pollinators and natural enemies of crop pests, both of which play fundamental roles in maintaining agricultural productivity and ecological stability (Klein et al., 2007; Egan et al., 2020).

Agroecology is an umbrella term which represents a scientific study, a set of practices, and a social movement (Wezel et al. 2009; Gliessman 2018); all of which are guided by principles which aim to create a more sustainable future for agriculture and the broader food system (Wezel et al. 2009; Gliessman 2018; Tittonell et al. 2020). Agroecology focuses not only on the environmental sustainability of food production, but also on social and economic sustainability and includes a broad lens which involves food transportation, consumption and all other facets of the food system. Agroecology recognizes that social, ecological and economic processes are complex and interconnected, and that they have emergent properties that can only be seen when assessing the system as a whole. Therefore, agroecology encourages complex, multidisciplinary systems thinking and cooperation to tackle the challenges faced by modern agriculture and food systems (Wezel et al. 2009; Gliessman 2018; Tittonell et al. 2020).

Concurrent to and interrelated with agroecology, Integrated Pest Management (IPM) has emerged as one of the central frameworks for promoting sustainable agriculture while maintaining economically viable crop production (Smith et al., 1959). IPM emphasizes the integration of multiple pest control strategies rather than relying solely on chemical applications. IPM has its origins in “supervised control,” which focused primarily on pest monitoring and the use of economic injury thresholds to guide pesticide applications and reduce unnecessary spraying, which was leading to pesticide resistance (Bueno et al. 2021; Deguine et al. 2021).

Supervised control was combined with the use of biological control methods to create IPM (Naranjo & Ellsworth 2009; Deguine et al. 2021). Since then, the concept of IPM has expanded beyond pesticide reduction to incorporate preventative and ecosystem-based management practices. Modern IPM frameworks include not just biological control but crop rotation, resistant cultivars, habitat management, and landscape diversification to suppress pest populations more sustainably. By promoting ecological processes and supporting populations of natural enemies, IPM aims to reduce dependence on agrochemicals while improving the long-term resilience and sustainability of agricultural systems. More recently, the concept of Integrated Crop Pollination (ICP) is based on the understanding that effective crop pollination cannot rely on a single strategy or a single pollinator species. Instead, it is increasingly recognized that "the use of managed pollinator species in combination with farm management practices that support, augment, and protect pollinator populations" provides more reliable and sustainable pollination services for crops (Isaacs et al. 2017). In this context, the guiding idea that "the pollination optimum depends on a diverse system of pollinators and the agricultural landscape" reflects a growing body of ecological evidence showing that wild pollinators and managed bees often complement each other. This diversity enhances not only pollination efficiency but also the stability of crop yields across different environmental conditions and years (Winfree et al., 2011; Garibaldi et al., 2013). Despite its benefits, implementing IPM can involve important ecological trade-offs, particularly in systems where pollination services are essential for crop production. Some pest management practices may negatively affect pollinators, while measures designed to enhance pollinator abundance may also benefit crop pests (Egan et al., 2020). These interactions have contributed to the development of Integrated Pest and Pollinator Management (IPPM), an emerging framework that seeks to jointly optimize pest suppression and pollination services through coordinated ecological management (Egan et al., 2020; Lundin et al., 2021).

Landscape-scale analysis is fundamental in arthropod ecology because their abundance and population dynamics are not determined solely by local field conditions, but also by the composition and configuration (Priyadarshana et al. 2024) of the surrounding agricultural landscape across multiple spatial scales, which can influence both colonization and survival of pest populations. Understanding how landscape composition and land-use practices influence ecological communities is therefore essential for developing more sustainable agricultural systems (Tscharntke et al., 2005, Bianchi et al., 2006). However, despite increasing recognition of the importance of integrating pest and pollinator management, there is still limited understanding of how specific landscape composition and configuration simultaneously affect pest and pollinator dynamics across spatial scales.

2. Research objectives

As mentioned previously, landscape factors can have effects both on pest pressure and pollination services. Recent research has shown that a greater proportion of a host crop in the surrounding landscape in the previous year(s) can lead to an increase in the pest infestation rate of the current year's crop (Hausmann et al. 2024). However, it remains unclear whether pollinators may also benefit from the same inter-annual landscape composition.

In this study, we will use faba bean *(Vicia faba*), as a model crop to explore the interplay between pests and pollinators as a result of interannual landscape factors. To determine the effects of the previous years' agricultural landscape composition on faba bean pollination services, we will measure the number of flower visitations from honeybees and bumblebees in faba bean fields with varying proportions of faba bean in the nearby landscape. To assess pest pressure, using the same fields, we will measure the number of broad bean beetle eggs laid on faba bean pods and the proportion of damaged bean seeds to determine pest pressure, using the same fields as for the pollinator surveys. We will also measure landscape composition within three buffer sizes (1, 2 and 3 km around each focal field). Each field will be surveyed at two different distances from the edge of the field (10 and 50 m) to identify differences in field and landscape spatial scales.

We expect to find that both the number of flower visits and eggs laid, along with the proportion of damaged beans, will increase with the proportion of faba bean in the surrounding landscape in the previous year. We also expect to find an increase in pollinators, pest eggs and pest damage with increasing pasture in the landscape. As every species has a unique dispersal distance and foraging range (Tscharntke et al. 2005; Lepais et al. 2010; Veres et al. 2013; Hausmann et al. 2024), we expect to find differences in the effects of the three spatial scales on our three insect classes (Bumblebees, Honeybees and *Bruchus rufimanus*). Finally, because of their increased habitat heterogeneity and floral resources, among other factors, arthropod abundance and diversity are generally greatest at or near field edges (Dauber & Wolters 2004; Nguyen & Nansen 2018a), therefore, we expect to find greater pollinator flower visits and pest pressure closer to field edges in comparison to deeper into the crop field.

3. Background

3.1 IPM, ICP and IPPM

As recognition of the harmful effects of pesticide use has increased, many substances have been prohibited. However, there is still a need for effective management of pests in agriculture as global food demand continues to rise and farmers are reliant on consistent yields (Hillocks 2012; Storck et al. 2017; Kaila et al. 2022). In order to ensure high yields while reducing pesticide usage, IPM was developed (Deguine et al. 2021). IPM is a decision support framework for farmers. When it began, IPM was largely focused on encouraging restraint in pesticide application by switching from calendar spraying (spraying on regularly scheduled dates throughout the season) to using monitoring and modelling to determine when spraying was required to prevent significant economic injury (Sousa et al. 2020; Lundin et al. 2021; Van Helden et al. 2022). Since then, IPM has evolved and broadened its scope, advocating for the use of multiple methods of control, prioritizing the use of preventive measures and utilizing ecosystem services over reactive measures and agrochemical usage (Egan et al. 2020; Lundin et al. 2021). These new methods include creating habitats that support pest natural enemies: predators, parasites or parasitoids of crop pests.

More recently, with a growing understanding of the importance of pollination and pollinators, ICP was developed. Like IPM, ICP encourages a multi-pronged, holistic approach to ensure crop pollination, focused on creating conditions which support wild pollinators and their ecosystem services (Lundin et al. 2021). IPPM has emerged only in the past few years and aims to combine the goals and decision-making frameworks of both IPM and ICP (Egan et al. 2020; Lundin et al. 2021).

It may be assumed by some that the goals and methods of IPM and ICP would naturally be aligned because pesticides are known to be harmful to pollinators and, therefore, a reduction in pesticide use should lead to an increase in pollinators and pollination services. And while a reduction in the use of pesticides is beneficial to pollinators, this does not, in turn, mean that all the methods utilized by IPM practitioners are inherently pollinator-friendly. By the same token, practices which can be used to increase pollinator abundance can lead to increases in pest infestation (Egan et al. 2020). Because insect pests, pollinators and pest natural enemies share a common phylogeny and therefore have similar ecologies, they have many shared drivers (Egan et al. 2020; Lundin et al. 2021). Also, insects which are considered

pollinators and/or pest natural enemies in their adult life stage may be considered a pest in their juvenile life stage (Lundin et al. 2021). This can lead to challenges in reconciling the goals of IPM and ICP, but also creates potential for synergistic solutions (Egan et al. 2020; Lundin et al. 2021). IPPM aims to maximize pollination services while minimizing pest pressure by studying these shared ecologies and drivers and creating a joint decision-making framework (Egan et al. 2020; Lundin et al. 2021).

IPM often uses a pyramid to represent how decisions on pest management should be prioritized. IPPM borrows this model. At the bottom of the pyramid lies preventative landscape management. This includes increasing landscape heterogeneity by crop rotation, diversifying crop production and preserving or restoring SNH. At the second tier are crop field-level management strategies. Extending field edges/buffer zones, preserving or restoring hedgerows, implementing flower strips, companion cropping and changes to sowing or irrigation regimes can all be utilized to boost pollinator and pest natural enemy abundance. IPPM also encourages shifting the focus of cultivar selection away from yield alone to also consider pest resistance and pollinator attraction (Egan et al. 2020; Lundin et al. 2021). At the top of the pyramid lie more reactive measures, such as the application of pesticides and the use of managed honeybee hives. These are recommended if monitoring reveals that there will potentially be a significant economic loss from either pest infestation or a pollinator deficit, respectively (Egan et al. 2020; Lundin et al. 2021).

Because of the complex and interconnected ecologies of pollinators, pests and their natural enemies, IPPM solutions can be highly specified and must be tailored to each unique situation. Interactions among different crop and cultivar types, unique species traits and the nature of the surrounding landscape must all be taken into consideration. Therefore, more research is required so that ecosystem services can be utilized and economic losses minimized in an effective and sustainable manner.

3.2 Agroecology and IPPM

3.2.1 Definition and evolution of agroecology

The term agroecology was first used by Basil Benson in 1928. In its earliest iterations, agroecology referred specifically to the scientific study of crops and the use of ecological methods in their production (Wezel et al. 2009). Since then, the use of the term agroecology has increased exponentially, and its definition has broadened significantly as well.

The foundational concepts of modern agroecology first formed in the 1970's and 80's as a response to the so-called "green revolution", the period in which agriculture began to rapidly intensify in many nations (Wezel et al. 2009; Gliessman 2018b). This intensification led to a substantial increase in yield, but it has created and neglected to address many of the issues surrounding sustainability in our agricultural and food systems (Gliessman 2018a; Tittonell et al. 2020). Agroecology expanded beyond simply a scientific study to include a global community of practitioners, utilizing more sustainable methods of farming and a social movement which aims to empower farmers to take part in the agroecological transition and to create a more just and equitable food system (Wezel et al. 2009; Gliessman 2018a).

Initially, the agroecology movement simply aimed to encourage the replacement of industrial inputs, such as inorganic fertilizers and pesticides, with more sustainable and efficient alternatives on a farm level. However, it became clear that this strategy would be insufficient for remedying the sustainability issues inherent to large monoculture farming. Instead, the movement began to focus on encouraging increased biodiversity to support ecosystem services in place of external inputs (Duru et al. 2015; Gliessman 2018a). By the end of 20th century, this movement had expanded its view again to focus beyond the farm level and to the agriculture and food system, to address issues beyond simply food production(Wezel et al. 2009; Gliessman 2018a). Agroecology now represents a scientific study, a farming practice and a social movement, all of which work together on spatial scales from the crop to the landscape to the entire food system to encourage sustainability through the use of biodiversity and ecosystem services and aims to create a more just, equitable and sustainable form of food production and consumption (Wezel et al. 2009; Duru et al. 2015; Gliessman 2018a; Tittonell et al. 2020; Deguine et al. 2021).

3.2.2 Connections between IPPM and agroecology

Plant protection and the reduction of pesticide use have long been associated with the agroecology movement (Wezel et al. 2009). As early as 1950, the term agroecology was being used to refer to ecological methods of pest management (Wezel et al. 2009). The environmental movement of the 1960's which arose in opposition to the Green Revolution, was particularly focused on the reduction of pesticide use. This can be seen in the book Silent Spring by Rachel Carson, which has been highly influential to agroecology and the broader environmental movements and largely centers on the environmental issues of pesticide use (Wezel et al. 2009). The social movement and practice of agroecology was also initially focused (and still has a large contingent focused) on the reduction or elimination of

pesticide use and an opposition to large agrochemical companies, which rose to prominence in the 1970's and 80's (Wezel et al. 2009).

IPM aims to protect crops from disease and pest infestation with minimal use of pesticides so as to protect the agroecosystem, human and environmental health (Deguine et al. 2021). As such, IPM can be an effective tool for those aiming to practice agroecological methods and an area of scientific research for those in the field of agroecology (Gliessman 2018a; Tittonell et al. 2020; Deguine et al. 2021; Petit et al. 2023). IPM has been criticized for its focus on the field and crop scale as well as for ignoring the importance of beneficial arthropods such as pollinators and pest natural enemies (Deguine et al. 2021). A larger focus on beneficial arthropods and the effects of landscape scales in agroecosystems has been cited both by leaders in the field of agroecology and proponents of IPPM, highlighting their interconnectedness (Egan et al. 2020; Tittonell et al. 2020; Lundin et al. 2021)

3.3 Faba bean

Faba bean *(Vicia faba*), also known as the field bean or the broad bean, is a leguminous crop that is cultivated all over the world, including in Sweden (Dhull et al. 2022; Dell'Aglio & Tayeh 2023). Faba bean produces seeds which can be consumed and are rich in protein, fibre and other essential nutrients (Gailis et al. 2022; Dell'Aglio & Tayeh 2023). It is produced both for human consumption and for use in animal feed. Cultivation of faba bean in Europe is important in particular because it allows Europe to be less reliant on imports of soybean for plant protein and animal feed (Raderschall, et al. 2025). As a legume, growing faba beans can be highly beneficial as part of a crop rotation. Faba beans' symbiotic relationship with soil bacteria allows for the fixation of atmospheric nitrogen into the soil (Peoples et al. 1995). It can also help to dissolve insoluble phosphorus and improve the soil's structure and microbiome (Gailis et al. 2022). These factors allow for better uptake of nutrients, both for the faba bean and also for successive crops sown within the same field. These services can allow farmers to reduce inorganic fertilizer applications without sacrificing yield (Segers *et al.*, 2021; Raderschallet al. 2025).

Faba beans are a self-fertile flowering crop, meaning they are not reliant on insect vectors for pollination. However, insect pollination has been shown to produce significantly higher yields in faba bean crops (Raderschall *et al.*, 2021). The faba bean flowers can also provide resources (pollen and nectar) to insect pollinators. Faba bean may be of particular of value to certain pollinators at certain times of the year, because although faba bean flowers produce relatively little nectar, their pollen is very protein-rich (Raderschall *et al.*, 2021).

Despite its widespread cultivation and its potential benefits for growers, consumers, and the environment, the faba bean is not without its issues. The crop is strongly affected by abiotic stressors such as frost and drought, as well as biotic stressors such as fungal infections, weed competition, and pest herbivory; all of which can reduce potential crop yields (Segers *et al.*, 2021; Dell'Aglio and Tayeh, 2023). To deal with biotic stressors in their crops, most farmers employ the use of pesticides. However, many pesticides have been banned in the EU in recent years, owing to their detrimental effects on humans and environmental and ecological health (Boetzl *et al.,* 2026). Pesticide use in faba bean fields can also be limited in its effectiveness because the leaf canopy of the bean stalks can shield lower regions of the plant, where the pesticide application is most needed (Segers *et al.,* 2021). These issues have hampered the spread of faba bean production throughout Europe. Research on how to sustainably mediate the challenges of faba bean production will be necessary to further realize its economic, agronomic and environmental benefits.

3.4 Broad bean beetle

The broad bean beetle (*Bruchus rufimanus*), also known as the bruchid beetle or broad bean weevil, is a major pest in faba bean production and can be found wherever faba bean is grown (Segers et al. 2021; Gailis et al., 2022; Dell'Aglio & Tayeh 2023). Broad bean beetles are univoltine, meaning they complete one life cycle per year (Segers et al., 2021; Dell'Aglio & Tayeh 2023). The beetles emerge from their hibernation after overwintering in the bark of trees or in leaf litter (Dell'Aglio & Tayeh 2023; Raderschall et al.,2025) to feed on the flowers. They begin feeding before their host plant has begun flowering (Segers et al., 2021). Broad bean beetles are oligophagous, meaning they feed on several different plant species. However, the beetles are still heavily dependent on the phenology of their host plant(s). The beetles utilize volatile organic compounds (VOCs) released by their host plant, combined with sex pheromones, to find their host plant and mates (Segers et al. 2021). Adult males become sexually mature when the photoperiod reaches 16 h per day, and temperatures reach around 15 ºC (Segers et al. 2021; Dell'Aglio & Tayeh 2023). Females, on the other hand, reach sexual maturity after feeding on the faba bean (or one of the 10 other suitable hosts) pollen. The ideal temperature for broad bean beetle reproduction is between 20 and 25 º C (Segers et al. 2021). The mating period lasts approximately 2 to 3 weeks (Segers et al. 2021). After mating, the female beetles begin to lay their eggs on the newly forming faba bean pods, and the egg-laying period can last 4 to 6 weeks (Segers et al. 2021; Gailis et al. 2022). Females can lay up to 100 eggs when they are sexually active, and in cases of severe infestation, there can be upwards of 30 eggs laid on a single pod (Gailis et al. 2022; Dell'Aglio & Tayeh 2023). Once the eggs hatch, they burrow through the exterior of the bean pods and into the developing seeds, consuming the

endosperm (Segers *et al.*, 2021; Dell'Aglio and Tayeh, 2023; Raderschallet al., 2025). The beetles' larvae then develop and pupate within the seeds before cutting a hole through the seed and pod and migrating into the surrounding landscape to find suitable overwintering habitat, completing the lifecycle (Dell'Aglio & Tayeh 2023). Of note, in certain cases, broad bean beetles have been known not to emerge from the seeds and instead overwinter inside them before emerging when the seeds are sown in the field the next season (Segers et al. 2021; Gailis et al. 2022).

Broad bean beetles represent a significant issue for faba bean producers across Europe (Segers *et al.*, 2021; Gailis *et al.*, 2022; Dell'Aglio and Tayeh, 2023; Raderschallet al., 2025). The beetles do cause a loss in yield; however, this loss is relatively minor. The main concerns are their effects on seed aesthetics and reproductive quality (Dell'Aglio and Tayeh, 2023; Raderschall, et al. 2025). Not only do emerging beetles leave substantial holes in the seeds, but some beetles do not successfully emerge, being then found by a potential consumer. Naturally, the presence of holes and insects makes the beans less desirable, especially for human consumption, where their sale can fetch a higher price (Raderschall et al. 2025). Seed lots to be exported on the international market cannot have greater than 3% infested seeds or greater than 10% infested seeds if they are intended to be sold for animal feed (Dell'Aglio & Tayeh 2023). Broad bean beetle infestation also significantly affects the efficacy of seeds that are sown, reducing both the germination rate as well as the plants' health and growth. This problem can be compounded as the holes left by the beetles can increase the rate of fungal infections (Raderschall, et al. 2025). As such, broad bean beetle infestation can lead to substantial economic losses for faba bean sellers and producers (Segers et al., 2021; Gailis et al., 2022; Dell'Aglio and Tayeh, 2023; Raderschall et al., 2025).

Management of broad bean beetles in faba production can be a challenge due to the limited availability and effectiveness of pesticides, as stated above. The use of biological control methods has also not been shown to be a promising measure, at least in isolation (Dell'Aglio & Tayeh 2023). Broad bean beetle eggs experience higher mortality due to rain and low temperatures (Segers et al. 2021). Unfortunately, warming temperatures due to anthropogenic climate change mean that beetle infestations of faba bean are expected to worsen in the coming years (Segers et al., 2021; Adler et al. 2022)). However, broad bean beetles have been shown to have cultivar preferences and differing larval survival rates in different cultivars and genotypes. In particular, late flowering cultivars were seen to have significantly lower infestation rates than earlier flowering cultivars (Dell'Aglio & Tayeh 2023). In this thesis, I explored the potential effects of inter-annual landscape composition on beetle infestation.

3.5 Honeybees and wild bees as pollinators of faba bean

In the past few decades, we have seen a drastic decline in both wild and managed pollinator populations in agricultural landscapes as a result of changes in farming practices and agricultural land management known as agricultural intensification (Couvillon et al. 2014; Dicks et al. 2021; Raderschall et al. 2021b)). Agricultural intensification includes increased agricultural inputs such as pesticides and inorganic fertilizers, a reduction in the variety of crops grown in a given landscape, an increase in tillage, and expansion of crop lands and field size through the reduction of SNH (Tscharntke et al. 2005). This reduction of SNH takes several forms: crop area on fields has increased by reducing semi-natural field edges and hedgerows, and Europe, in particular, has also seen a massive conversion of historic pasture and meadows to cropland. Agricultural intensification has been credited with increasing food production; however, it has led to habitat homogenization, which in turn has drastically reduced species abundance and richness in agroecosystems, threatening the ecosystem services these organisms provide (Benton et al. 2003). Of particular importance to pollinators, SNH provides essential nesting habitat for wild pollinators and is a source of various wildflowers, which ensure a consistent source of nectar and pollen (Couvillon, Schürch and Ratnieks, 2014; Rotheray et al., 2017). Pesticides can also have lethal and sublethal effects on non-target organisms such as pollinators (Ward et al. 2022). Europe has seen a decline in 46% of its bumblebee species since 2014, while the demand for crops relying on pollination has risen (Couvillon et al. 2014; Marja *et al.*, 2018). Globally, the pollination services provided by insect pollinators are valued between 215 and 529 billion U.S. dollars annually (Marja et al. 2018). More than 75% of the world's major crops could face a pollination deficit where yields suffer from insufficient pollination (Klein et al. 2006).

4. Methods

4.1 Study area

Östergötland County (58N, 15E) is a region located in the south of Sweden and borders the Baltic Sea. The county has an area of almost 10.000 square kilometres (Garrido et al. 2017). The landscape is primarily forested (59% land cover). Arable land covers just 19% of the region's land area, and another 4% is dedicated to pasture lands. Only 4% of the region consists of urban areas (Garrido et al. 2017). The major crops of Östergötland are ley, winter and spring wheat, spring barley, potatoes, oats, triticale, winter oilseed rape (OSR), rye, faba bean, peas and linseed (De Toro et al. 2015).

4.2 Landscape data and field selection

To determine which fields would be selected, we contacted the landscape consulting companies HS Konsult and Lovanggruppen Lantbrukskonsult to provide us with the contact information for faba bean farmers in the 2025 growing season in Östergötland County. We aimed to collect data from 20 different faba bean fields within Östergötland, 10 with low proportions of faba bean in the nearby landscape and 10 with high proportions. Landscape data describing field size and crop type of the fields in Östergötland (for 2024 and 2025) was provided by the European Union's Integrated Administration and Control System (IACS), which is managed by the Swedish Board of Agriculture within Sweden. We extracted the data using QGIS version 4,0.1 and R version 4.5.3. We then used this data to determine the proportion of faba bean fields in 2024 (by land area) in the surrounding area (for 1, 2 and 3 km buffers) of each faba field in the year our study was conducted (2025). The 10 fields with the highest and the 10 fields with the lowest proportions of faba bean within the 3 km buffer zone of each field were selected. Unfortunately, we were only able to get approval to conduct our research from 14 of these farmers (Fig. 1). It is worth noting that at two locations we had fields with buffer zones that overlapped. However, based on the limited overlap, we believe that this did not significantly impact our results (Fig. 1) (Boetzl et al. 2026b).

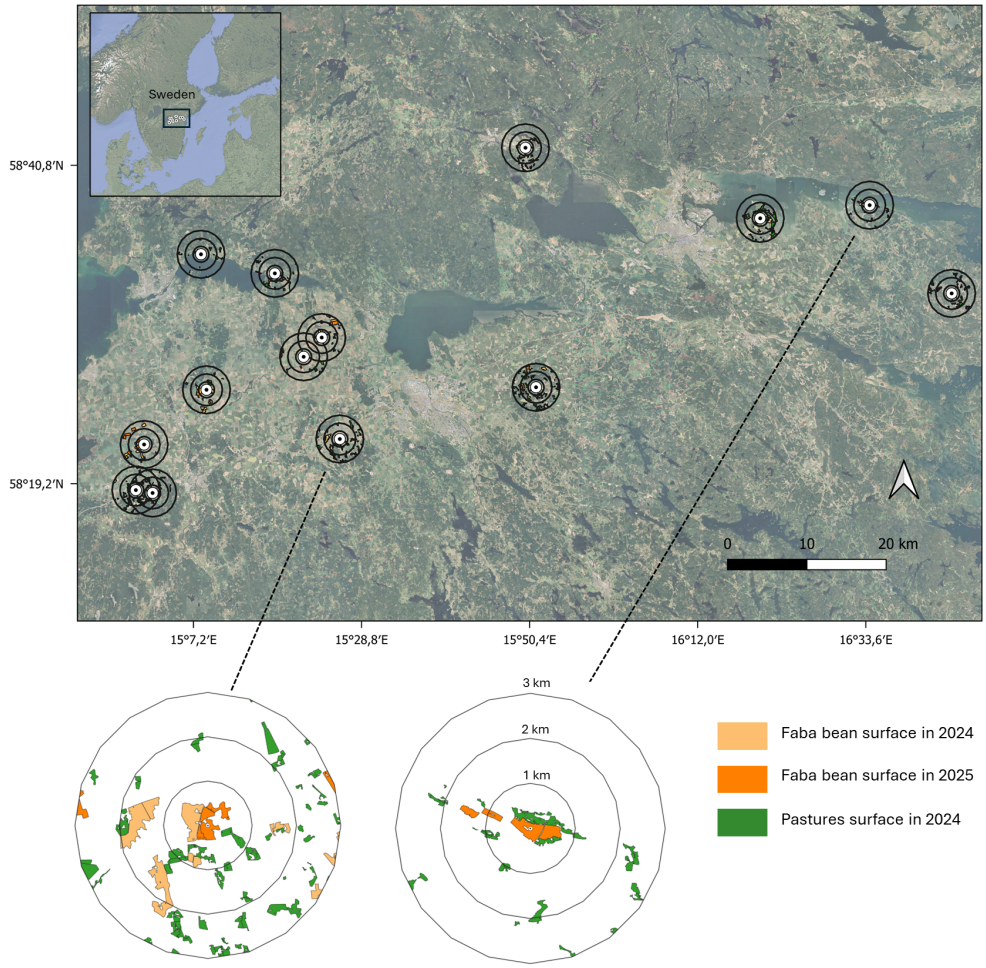

Figure 1. Study area and buffer radius. Location of the study area and spatial extent of the analytical buffers used to characterize landscape composition around sampling sites. Buffers represent the spatial scales at which surrounding land-use was quantified to assess potential landscape effects on pest and pollinator species.

4.3 Measuring pollinator and flower abundance

4.3.1 Pollinator surveys

In each of the 14 selected fields, two 50 m long transect lines were established, one 10 m away from the field edge, the other 50 m away from the field edge. Due to the irregular shape of some of the fields, these two transects could not always be placed near each other. Fields were observed to determine when a substantial portion of the faba bean plants had begun to bloom. Once a field was sufficiently in bloom, pollinator surveys were conducted along each of the transect lines within the field. Pollinator surveys only took place when weather conditions were suitable for bee foraging. Surveys were not performed when the temperature was below 15 °C, when wind speeds were above 8 m/s or within 1 hour of rain. Surveys were also

only conducted when skies were clear or with a light overcast. A researcher would slowly walk the length of the transect, scanning 1 m to either side of the transect line, looking for pollinating insects visiting a faba bean flower or extrafloral nectary. To ensure an even survey effort between transect surveys and within each individual transect survey, researchers would use a stopwatch, aiming to complete each 50 m survey in 10 minutes while walking at a consistent pace. The researchers also only focused on what was in front of them as they walked. When a pollinator was spotted on a faba bean flower or extra floral nectary (EFN), the timer was momentarily stopped, and the pollinator's species and behaviour (whether it was legitimately pollinating, nectar robbing or visiting an extra floral nectary) was recorded. If a bee could not be identified to species level by sight, it was captured and placed in a sealed container so that it could be examined in the lab under a microscope. Due to difficulties distinguishing between *B. lucorum, B. terrestris*, *B. cryptarum* and *B. magnus,* these species were grouped together (*B. terrestirs aggr.*). Because keeping track of every pollinator moving between the rows of faba bean plants was not feasible, unless a pollinator was seen flying from one flower or extra floral nectary to another, it was assumed that each visitation was from a unique individual. We aimed to complete at least three surveys per transect. However, due to adverse weather conditions, we could not perform surveys for a significant portion of the flowering period of the faba bean fields. As a result, some transects were surveyed only twice.

4.3.2 Flower surveys

After each pollinator transect survey was completed, a second survey was conducted to estimate the number of flowers in each field. A researcher would randomly select four locations along each transect to place a quadrat measuring 0.6 m by 0.6 m. The number of faba bean stalks within the quadrat was counted, and then every flower was counted on five stalks chosen at random within the quadrat. This was then used to calculate an average number of flowers per square metre for each transect. This allowed us to account for differences in the number of pollinators observed based on differences in the number of flowers present in each field.

4.4 Measuring pest pressure

To determine the extent of pest infestation by *Bruchus rufimanus,* we used two measures: the number of eggs laid on faba bean pods and the percentage of faba bean seeds that incurred damage from broad bean beetles.

4.4.1 Broad bean beetle egg surveys

After flowering had finished, we observed the formation of bean pods in each field. When the pods had developed enough (BBCH 75) to become suitable for broad bean beetle females to have begun oviposition, 50 bean pods were collected along the length of each of the previously established transects. As the number of eggs laid on a pod likely varied depending on where in the field each stalk was situated, each pod was harvested from a different bean stalk dispersed evenly over the length of the transect. The number of eggs deposited on each pod may also differ based on where along the bean stalk it is grown. Therefore, one third of all beans collected were harvested from the top third of the stalk, one third from the middle of the bean stalk, and one third were harvested from the bottom third of the bean stalk. The pods were then inspected, and the number of broad bean beetle eggs was counted. Each pod was examined within 24 hours of collection to ensure that the eggs had not hatched before inspection.

4.4.2 Broad bean beetle damage surveys

To measure the proportion of beans damaged by broad bean beetles in each field, we waited until one week before the bean pods were to be harvested by farmers and then repeated the same collection methods above, except 75 pods were collected per transect instead of 50. Unfortunately, one farmer began harvesting before expected, and we were therefore unable to collect samples from one edge transect. The pods were then opened, and each bean was counted and inspected for the exit holes left by the emerging adult broad bean beetles.

4.5 Data analysis and modelling

To assess how the proportion of faba bean present in the landscape in the previous year affected pollinators and pest infestation, the data collected from the field were analyzed using general linear mixed models (GLMM). Twelve separate models were fitted using the "glmmTMB" package in R version 4.5.3. The four response variables used were: the number of honeybee flower (or EFN) visits, the number of eggs counted per 50 pods and the proportion of damaged beans. The explanatory variables we chose for the model were: the proportion of faba bean in the 2024 landscape, the proportion of faba bean in the 2025 landscape, the proportion of pasture in the 2024 landscape, the number of flowers per square meter, and the distance of the transect from the field edge (computed as either edge or centre). We chose to include the proportion of faba bean in the 2025 landscape in all our models, as we hypothesized that landscapes with a higher proportion of faba bean would attract a greater number of both broad bean beetles and pollinators

because the higher proportion of faba beans would produce a more concentrated chemical signal in the form of VOCs. We also included the proportion of pasture in the 2024 landscape because both pests and pollinators are known to benefit from the presence of pasture land and other SNH. It was assumed that pasture land is semi-permanent and therefore any variation between years would be insignificant. To check for any correlation between the explanatory landscape variables, a Pearson's correlation test was employed. We also used the variance inflation factor (VIF) to check all the variables for collinearity. As a random variable, we included the field identification. To account for differences in survey effort between fields in the pollinator surveys, we added an offset to the honeybee and bumble models using the natural log of the number of survey rounds per field. Each of the four explanatory variables was assessed with three different GLMMs, using the different proportions of each landscape type found within the three different buffer sizes. Also, an analysis of variance (ANOVA) for each of the explanatory variables was conducted using a type II ANOVA. For the three models examining the effects on honeybee visitations, a Poisson distribution was used as the response variable consisted of count data. For the bumblebee visitation models and the egg models, we used a negative binomial distribution was used to account for overdispersion in the count data. Finally, a beta distribution was used to model bean damage, as this response variable represented proportions bounded between 0 and 1. Finally, the "DHARMa" package was used to check that our models fit all our assumptions.

5. Results

5.1 Pollinator and flower abundance

5.1.1 Pollinator surveys

In total, 68 pollinator transect surveys were conducted. Over these 68 surveys, 621 pollinators were observed; six different species (in descending order of frequency: *Bombus terrestris aggr., Apis mellifera, Bombus hortorum, Bombus subterraneus, Bombus lapidarius,* and *Bombus pratorum)* and 5 taxa (*Bombus*, *Apis*, Syrphidae, Apocrita, and Diptera), were identified. Unidentified *Bombus* spp. and solitary bees were also observed. Of the 621 pollinators observed, just over half were of the genus *Bombus* (51.5% of total observations), with the vast majority being *Bombus terrestris aggr.* It was also the most abundant species overall with 301 observations (48.4% of total observations). The second most observed species was *Apis mellifera,* which accounted for 36.7% (228 observations) of all observations.

The most common behaviour observed amongst all species was legitimate pollination (39.3% of observations). However, nectar robbing was spotted almost as often (30.1% of observations). There were only 15 confirmed observations of species considered to be long-tongued bees (*Bombus hortorum* and *Bombus subterraneus*). However, notably, long-tongued bees were always observed performing legitimate pollination.

The results of the GLMMs showed that the proportion of faba bean found in the landscape in the previous year had a significant positive effect on the number of *Apis mellifera* observed at the 2 (Fig. 2, Table 1 , see also Appendix 1, Table 1.1) and 3 km spatial scales (Fig. 3, Table 2, see also Appendix 1, Table 1.2) but no significant effect at the 1 km spatial scale. All other factors concerning *Apis* m*ellifera* were found to be non-significant at all spatial scales. At all three spatial scales, the transect's distance from the edge of the field was found to have a significant effect on the number of observations of *Bombus* spp. (Fig. 4, Table 4 to 6, see also Appendix 1, Table 1.4 to 1.6), with fewer observations closer to the field edge. The average number of flowers per square meter in the field also positively affected the number of bumblebees observed at the 1 and 2 km spatial scales (Fig. 5 and 6, Table 4 and 5, see also Appendix 1, Table 1.4 and 1.5). All other factors had non-significant effects on *Bombus* spp. observations.

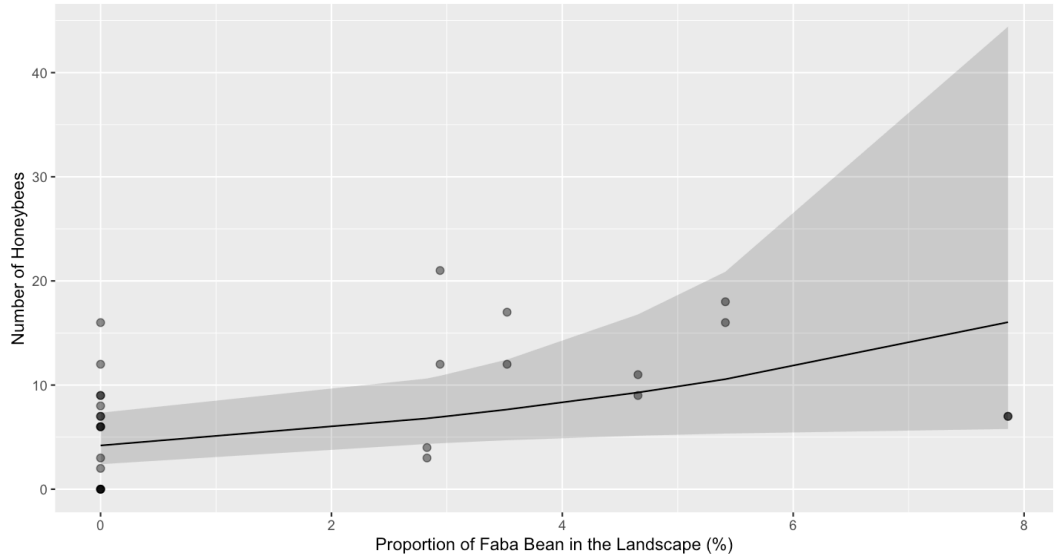

Figure 2. The number of honeybees observed visiting flowers or EFN in faba bean fields in 2025 increased with the proportion of faba bean in the landscape (% area of the buffer zone) in 2024, at the 2 km spatial scale. Dots represent observations per transect and the shaded area represents the 95% confidence interval.

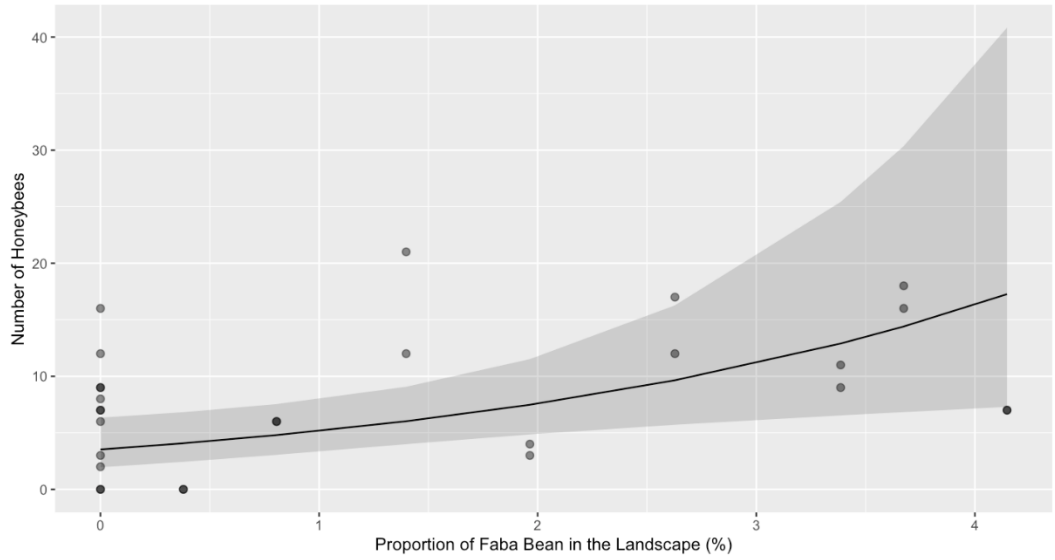

Figure 3. The number of honeybees observed visiting flowers or EFN in faba bean fields in 2025 increased with the proportion of faba bean in the landscape (% area of the buffer zone) in 2024, at the 3 km spatial scale. Dots represent observations per transect and the shaded area represents the 95% confidence interval.

*Table 1. Results of Type II ANOVA show the effects of landscape factors at a 2 km spatial scale on the number of visits to faba bean by honeybees. Significant p-values are shown in bold ($\alpha = 0.05$). Level of significance: $p < 0.001$ = "***", $p < 0.01$ = "**", $p < 0.05$ = "*", $p < 0.1$ = ".".*

Variable	χ^2	Df	P-value
Pasture	0.014	1	0.905
Faba Bean 2024	4.255	1	**0.039***
Faba Bean 2025	0.087	1	0.768
Transect	0.526	1	0.468
Avg. Flowers per m^2	0.603	1	0.437

*Table 2. Results of Type II ANOVA show the effects of landscape factors at a 3 km spatial scale on the number of visits to faba bean by honeybees. Significant p-values are shown in bold ($\alpha = 0.05$). Level of significance: $p < 0.001$ = "***", $p < 0.01$ = "**", $p < 0.05$ = "*", $p < 0.1$ ".".*

Variable	χ^2	Df	P-value
Pasture	0.825	1	0.364
Faba Bean 2024	6.984	1	**0.008****
Faba Bean 2025	2.702	1	0.100
Transect	0.525	1	0.469
Avg. Flowers per m^2	0.548	1	0.459

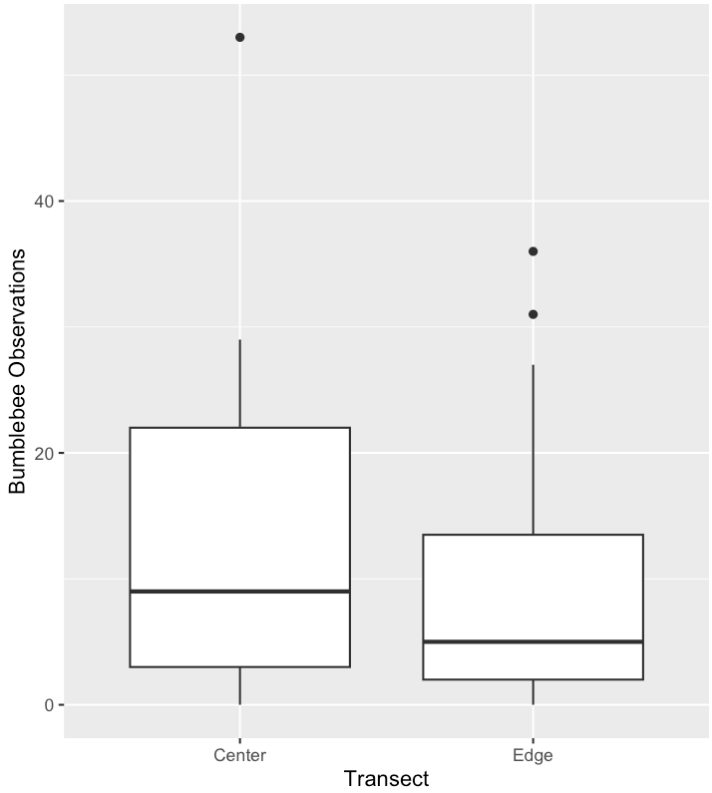

Figure 4. Boxplot depicting the number of bumblebees observed visiting flowers or EFN in faba bean fields based on the transect's distance from the field edge (Edge = 10 m, Center = 50 m).

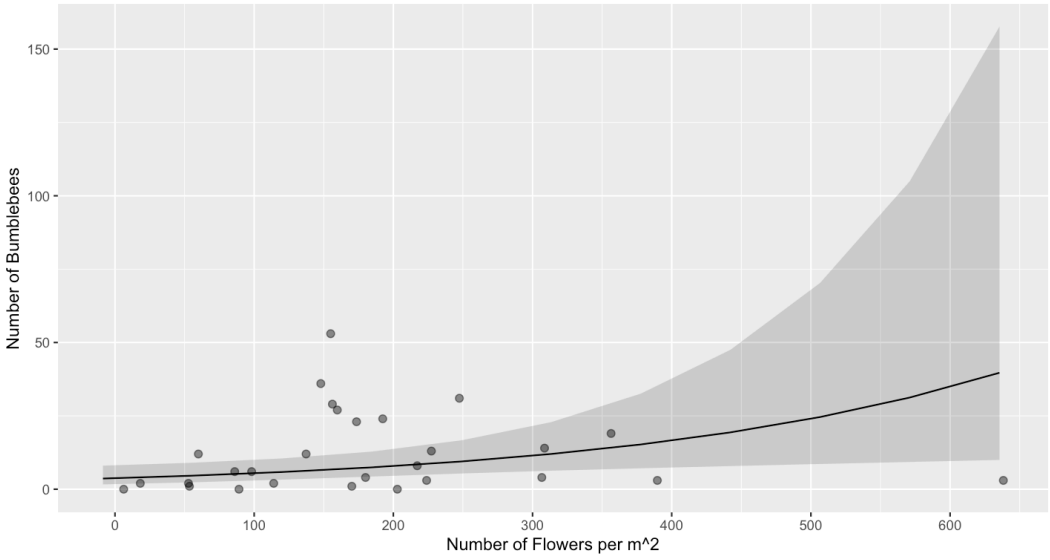

Figure 5. The number of bumblebees observed visiting flowers or EFN in faba bean fields in 2025 increased with the average number of flowers per m2 at the 1km spatial scale. Dots represent observations per transect, and the shaded area represents the 95% confidence interval.

*Table 3. Results of Type II ANOVA show the effects of landscape factors at a 1 km spatial scale on the number of visits to faba bean by bumblebees. Significant p-values are shown in bold ($\alpha = 0.05$). Level of significance: $p < 0.001$ = "***", $p < 0.01$ = "**", $p < 0.05$ = "*", $p < 0.1$ = ".".*

Variable	χ^2	Df	P-value
Pasture	1.064	1	0.302
Faba Bean 2024	3.612	1	0.057 .
Faba Bean 2025	1.132	1	0.287
Transect	5.620	1	**0.018***
Avg. Flowers per m^2	6.446	1	**0.011***

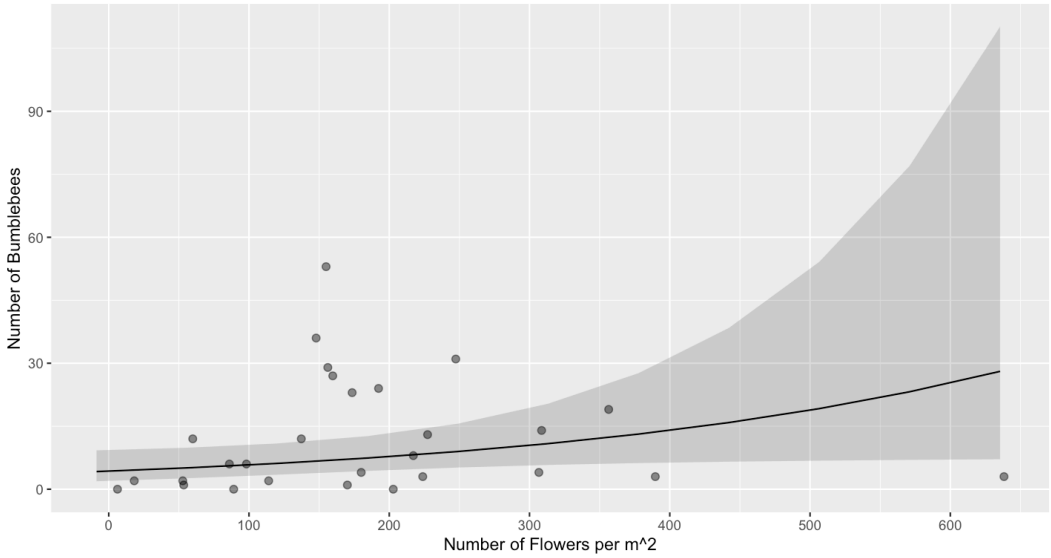

Figure 6. The number of bumblebees observed visiting flowers or EFN in faba bean fields in 2025 increased with the average number of flowers per m2 at the 2 km spatial scale. Dots represent observations per transect, and the shaded area represents the 95% confidence interval.

*Table 4. Results of Type II ANOVA show the effects of landscape factors at a 2 km spatial scale on the number of visits to faba bean by bumblebees. Significant p-values are shown in bold (α = 0.05). Level of significance: p < 0.001 = "***", p < 0.01 = "**" , p < 0.05 = "*" , p < 0.1= ".".*

Variable	χ^2	Df	P-value
Pasture	0.049	1	0.825
Faba Bean 2024	3.766	1	0.052 .
Faba Bean 2025	0.922	1	0.337
Transect	5.321	1	**0.021***
Avg. Flowers per m^2	4.073	1	**0.044***

*Table 5. Results of Type II ANOVA show the effects of landscape factors at a 3 km spatial scale on the number of visits to faba bean by bumblebees. Significant p-values are shown in bold (α = 0.05). Level of significance: p < 0.001 = "***", p < 0.01 = "**" , p < 0.05 = "*" , p < 0.1 = ".".*

Variable	χ^2	Df	P-value
Pasture	0.366	1	0.545
Faba Bean 2024	2.940	1	0.086 .
Faba Bean 2025	0.434	1	0.510
Transect	4.919	1	**0.027***
Avg. Flowers per m^2	2.513	1	0.113

5.2 Pest pressure

5.2.1 Broad bean beetle eggs

Out of the 1400 pods collected, 567 eggs were counted, giving an average of 40.5% of all faba bean pods with an egg laid on them.

At all three spatial scales, the proportion of pasture in the surrounding landscape was found to increase the number of *Bruchus rufimanus* eggs observed on the faba bean pods (Fig. 7, 8 and 9; Table 6 to 8, see also Appendix 1, Table 1.6 to 1.8). The proportion of faba bean in the landscape at the two larger spatial scales also led to an increase in the number of eggs observed according to our models (Fig. 10 and 11; Tables 7 and 8). All other factors were not found to be significant in the models.

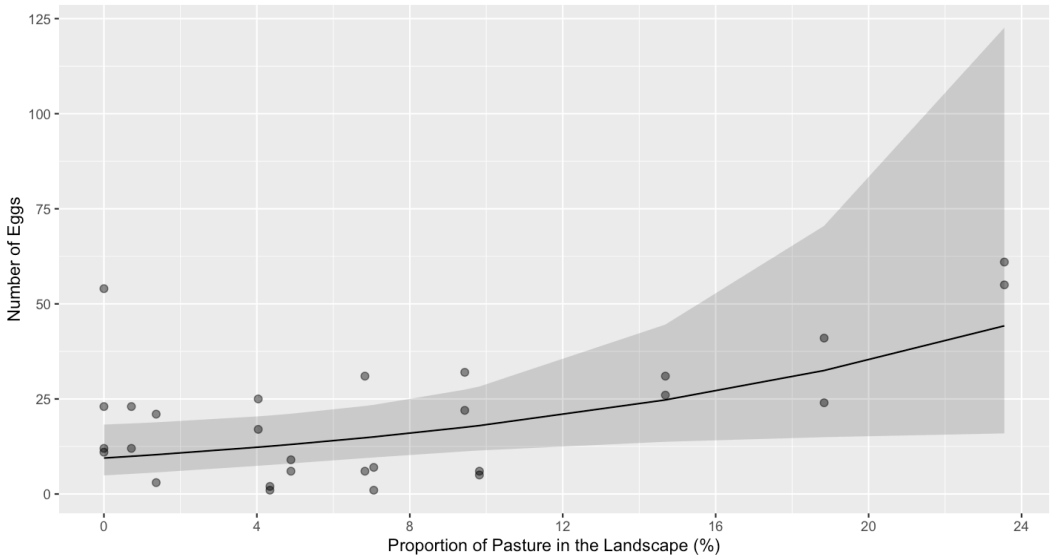

Figure 7. The total number of Bruchus rufimanus eggs counted on the 50 pods collected in each transect increased with the proportion of pasture in the landscape (% area of the buffer zone) at the 1 km spatial scale. Dots represent the number of eggs per transect, and the shaded area represents the 95% confidence interval.

*Table 6. Results of Type II ANOVA show the effects of landscape factors at a 1 km spatial scale on the number of eggs laid by Bruchus rufimanus on faba bean pods. Significant p-values are shown in bold ($\alpha = 0.05$). Level of significance: $p < 0.001$ = "***", $p < 0.01$ ="*", $p < 0.1$ = "." .*

Variable	χ^2	Df	P-value
Pasture	4.607	1	**0.032***
Faba Bean 2024	2.036	1	0.154
Faba Bean 2025	2.120	1	0.145
Transect	0.027	1	0.869
Avg. Flowers per m^2	0.027	1	0.869

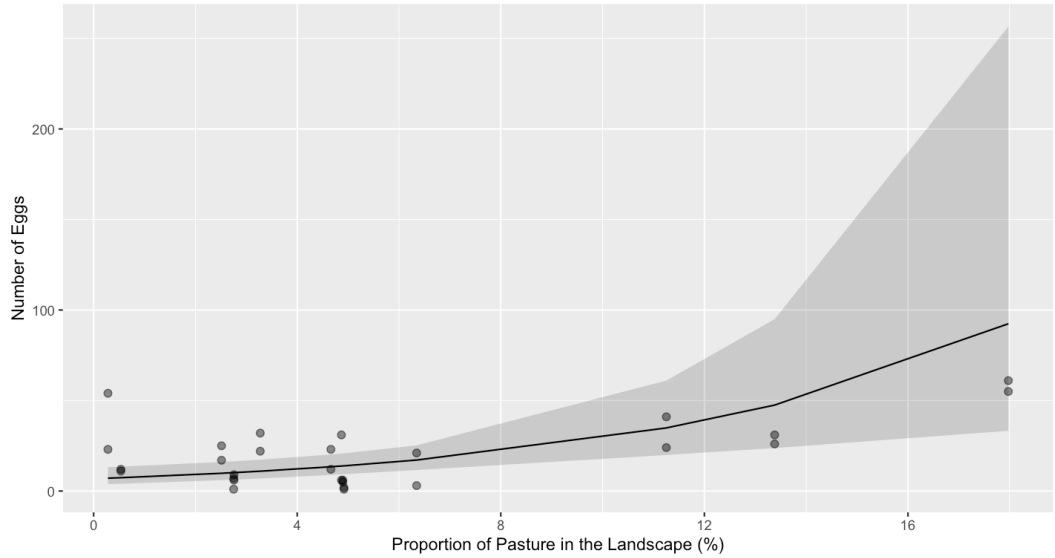

Figure 8. The total number of Bruchus rufimanus eggs counted on the 50 pods collected in each transect increased with the proportion of pasture in the landscape (% area of the buffer zone) at the 2 km spatial scale. Dots represent the number of eggs per transect, and the shaded area represents the 95% confidence interval.

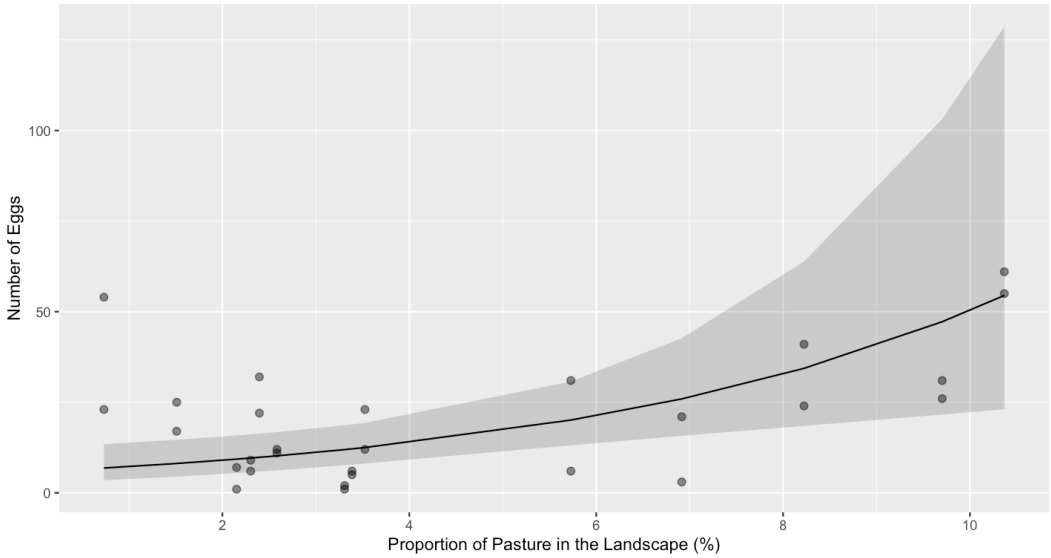

Figure 9. The total number of Bruchus rufimanus eggs counted on the 50 pods collected in each transect increased with the proportion of pasture in the landscape (% area of the buffer zone) at the 3 km spatial scale. Dots represent the number of eggs per transect, and the shaded area represents the 95% confidence interval.

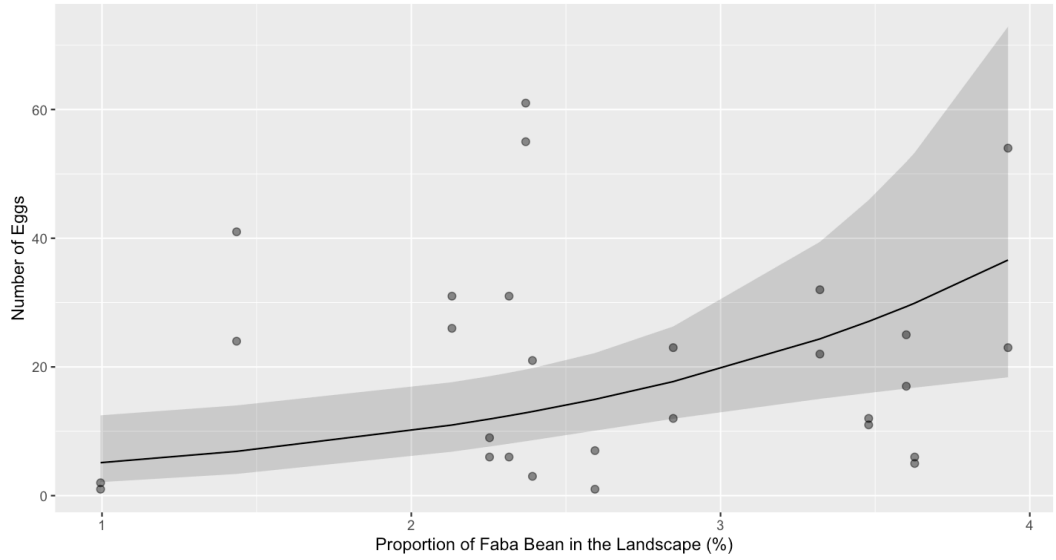

Figure 10. The total number of Bruchus rufimanus eggs counted on the 50 pods collected in each transect increased with the proportion of faba bean in the landscape (% area of the buffer zone) in the current year at the 2 km spatial scale. Dots represent the number of eggs per transect, and the shaded area represents the 95% confidence interval.

*Table 7. Results of Type II ANOVA show the effects of landscape factors at a 2 km spatial scale on the number of eggs laid by Bruchus rufimanus on faba bean pods. Significant p-values are shown in bold ($\alpha = 0.05$). Level of significance: $p < 0.001$ = "***", $p < 0.01$, $p < 0.1$ = "."*

Variable	χ^2	Df	P-value
Pasture	12.450	1	**< 0.001*** **
Faba Bean 2024	2.140	1	0.143
Faba Bean 2025	7.935	1	**0.005** **
Transect	0.013	1	0.910
Avg. Flowers per m^2	0.001	1	0.976

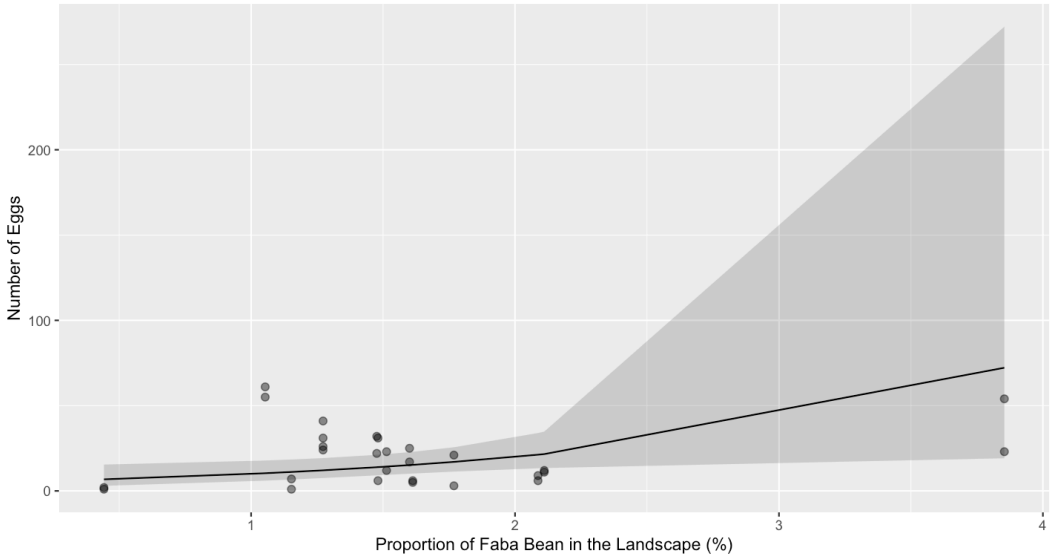

Figure 11. The total number of Bruchus rufimanus eggs counted on the 50 pods collected in each transect increased with the proportion of faba bean in the landscape (% area of the buffer zone) in the current year at the 3 km spatial scale. Dots represent the number of eggs per transect, and the shaded area represents the 95% confidence interval.

*Table 8. Results of Type II ANOVA show the effects of landscape factors at a 3 km spatial scale on the number of eggs laid by Bruchus rufimanus on faba bean pods. Significant p-values are shown in bold ($\alpha = 0.05$). Level of significance: $p < 0.001$ = "***", $p < 0.01$ = "*", $p < 0.1$ = ".".*

Variable	χ^2	Df	P-value
Pasture	9.812	1	**0.002****
Faba Bean 2024	0.444	1	0.505
Faba Bean 2025	5.484	1	**0.019***
Transect	0.168	1	0.682
Avg. Flowers per m^2	0.002	1	0.962

5.2.2 Broad bean beetle damage

Overall, 1902 faba bean pods were collected, containing 6594 seeds. On average, only 15.2% of faba bean seeds were seen to have exit damage from *Bruchis rufimanus*, although many seeds without damage from the beetles exiting did show signs of damage from larvae entering the seeds. Similar to the beetle eggs counted,

field 3 had the greatest proportion of damaged seeds per field and the transect with the greatest proportion of damaged seeds (32.8 and 41.0% respectively). However, the field with the lowest proportion of damaged seeds was not field 16 but field 11, with field 16 as the second lowest (5.3% and 6.0% respectively).

At the 1 km spatial scale, no factors were found to have a significant effect. However, the proportion of pasture in the landscape was very close to being significant ($p = 0.05$). The proportion of pasture at the 2 km (Fig. 12, Table 9) and 3 km (Fig. 13) spatial scales did have a positive effect on the proportion of damaged seeds observed according to the models. The effect of the proportion of faba bean in the landscape in the current year was also shown to be significant and positive, but only at the 2 km spatial scale (Fig. 14, Table 9). No other factors were found to be significant in the models.

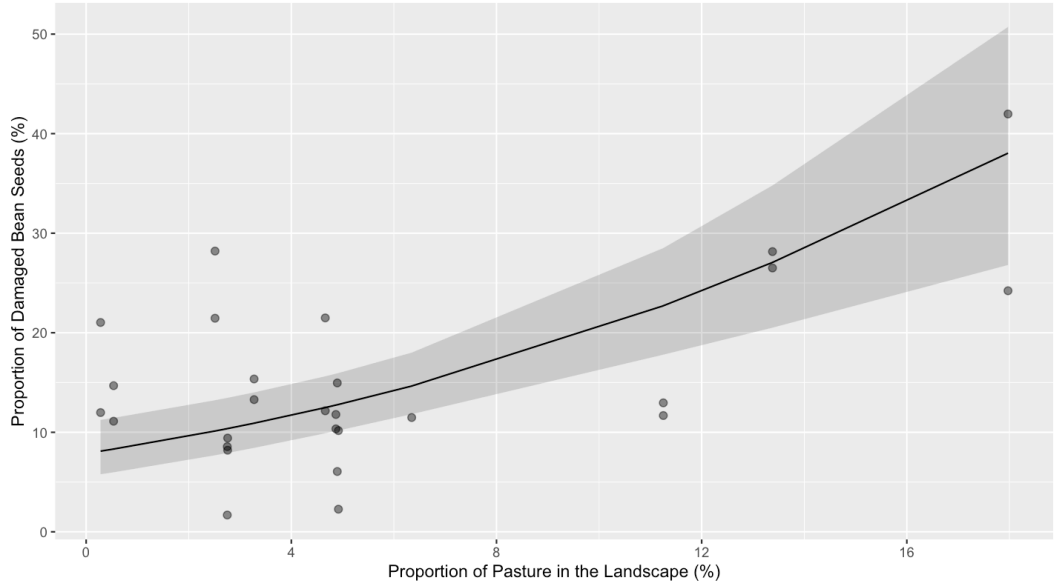

Figure 12. The proportion of faba bean seeds damaged by Bruchus rufimanus (% of seeds damaged) in each transect increased with the proportion of pasture in the landscape (% area of the buffer zone) at the 2 km spatial scale. Dots represent the percentage of damaged seeds per transect, and the shaded area represents the 95% confidence interval.

*Table 9. Results of Type II ANOVA show the effects of landscape factors at a 2 km spatial scale on the proportion of damaged faba bean seeds. Significant p-values are shown in bold (α = 0.05). Level of significance: p < 0.001 = "***", p < 0.01 = "**" , p < 0.05 = "*", p < 0.1 = ".".*

Variable	χ^2	Df	P-value
Pasture	27.943	1	**< 0.001*** **
Faba Bean 2024	2.310	1	0.129
Faba Bean 2025	12.155	1	**< 0.001*** **
Transect	0.010	1	0.921
Avg. Flowers per m^2	0.044	1	0.833

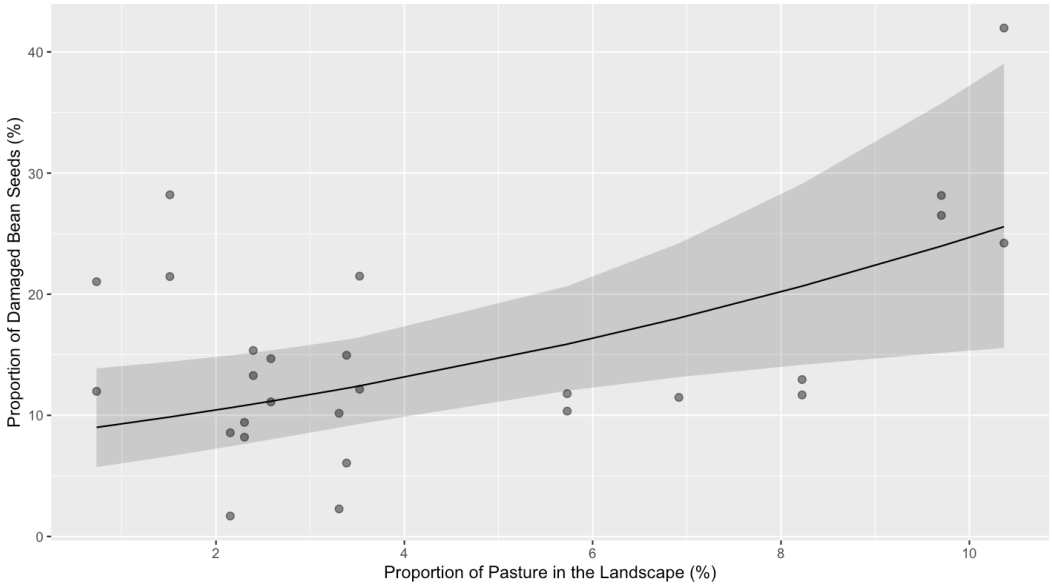

Figure 13. The proportion of faba bean seeds damaged by Bruchus rufimanus (% of seeds damaged) in each transect increased with the proportion of pasture in the landscape (% area of the buffer zone) at the 3 km spatial scale. Dots represent the percentage of damaged seeds per transect, and the shaded area represents the 95% confidence interval.

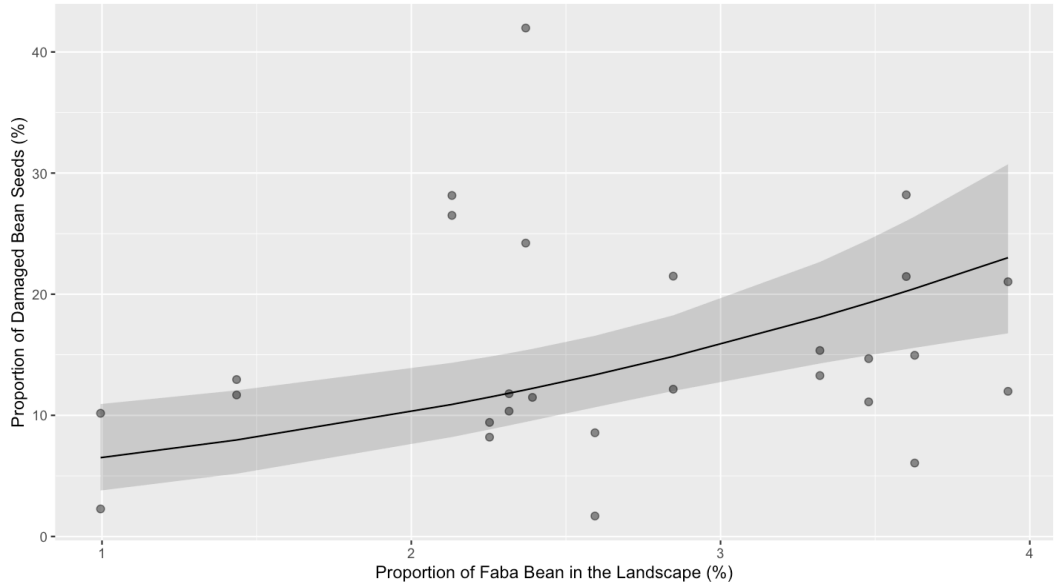

Figure 14. The proportion of faba bean seeds damaged by Bruchus rufimanus (% of seeds damaged) in each transect increased with the proportion of faba bean in the landscape (% area of the buffer zone) in the current year at the 2 km spatial scale. Dots represent the percentage of damaged seeds per transect, and the shaded area represents the 95% confidence interval.

*Table 10. Results of Type II ANOVA show the effects of landscape factors at a 3 km spatial scale on the proportion of damaged faba bean seeds. Significant p-values are shown in bold ($\alpha = 0.05$). Level of significance: $p < 0.001$ = "***", $p < 0.01$ = "**", $p < 0.05$ = "*", $p < 0.1$ = ".".*

Variable	χ^2	Df	P-value
Pasture	7.021	1	**0.008****
Faba Bean 2024	0.888	1	0.346
Faba Bean 2025	1.349	1	0.246
Transect	0.002	1	0.961
Avg. Flowers per m^2	0.046	1	0.830

6. Discussion

6.1 Effects of landscape factors on pollinator observation in faba bean

6.1.1 Proportion of faba bean in the landscape in the previous year

Initially, we expected to find that both honeybee and bumblebee observations would be higher in landscapes where faba bean made up a higher proportion of the surrounding landscape in the previous year. However, we only found this to be true for honeybees at the 2 and 3 km spatial scales and not for bumblebees at any spatial scale. These results were counterintuitive, as it was believed that bumblebees would receive a greater fitness benefit from a higher proportion of faba bean in the landscape in the previous year, when compared with honeybees, and as a result, we would see a greater effect on the number of bumblebee observations than on the number of honeybee observations. This result has also been reported in a recent study. Although both *Apis mellifera* and *Bombus* spp. are central-place foragers which produce colonies, *A. mellifera* is a managed species in agricultural landscapes and generally lives in perennial colonies established in locations by humans. In comparison, *Bombus* spp. live in wild, seasonal colonies (Mallinger, 2017; Borchardt *et al.*, 2025). Therefore, at the end of the season, each year, new queens and male drones are produced. These new queens, after mating, must forage and then find a suitable habitat to hibernate until the next season (Svensson, 2000; Westphal et al., 2009).

Steffan-Dewenter and Tscharntke (2009) further highlighted that only the largest colonies produce females, medium-sized colonies produce only male drones, and the smallest colonies produce neither. They also found that bumblebee colonies near mass flowering crops (MFCs) are found to be greater in size. Thus, it would be assumed that bumblebee colonies near faba bean fields would produce a greater amount of both queens and males, resulting in more fertilized queens hibernating in the nearby landscape and then producing colonies the next year. Additionally, the new queens produced would be expected to be attracted by the immense amount of floral resources provided by faba bean or other MFCs and therefore choose to hibernate in these fields or the nearby landscape. In comparison, as a managed species, *A. mellifera* in agricultural landscapes has colonies placed almost exclusively by humans where it is advantageous to them, not to the bees. These perennial colonies will not shift location with the availability of floral resources, like the annual colonies of bumblebees would be expected to.

Although these results are initially confounding, they potentially highlight an important factor in pollinator landscape ecology. As mentioned, the presence of MFCs in the landscape has been shown to increase colony size, which is linked to the production of queens and males (Westphal et al. 2009). And, especially in combination with SNH, MFCs have also been shown to increase the abundance of pollinators within the same year (Riedinger et al. 2014; Grab et al. 2017). This is likely because, as central place foragers, the ready abundance of floral resources nearby to the colony reduces the flying distance required for foraging worker bees. A reduced travel distance for worker bees means more of the calories from the nectar and pollen they collect can be allocated to producing and rearing new workers, males and/or queens (for both *A. meliffera* and *Bombus* spp.) (Couvillon et al. 2014; Danner et al. 2016). However, MFCs being of all the same species, only bloom for a relatively small portion of the bumblebee or honeybee foraging season. This means that the massive amount of floral resources provided by these crops is only available for a short amount of time. This can lead to a temporary spike in pollinator abundance; however, the pollinator colonies may not be able to support these enlarged populations once the MFCs in the landscape stop blooming (Westphal et al., 2009; Hanley *et al.*, 2011; Grab *et al.*, 2017; Osborne and Goulson, 2017; Marja *et al.*, 2018). Indeed, Couvillon, Schürch and Ratnieks, (2014) found that honeybee foraging distances changed throughout the season, depending on whether or not nearby MFCs were in bloom. Westphal, Steffan-Dewenter and Tscharntke (2009) also found that although bumblebee nests in close proximity to OSR fields were initially found to weigh more than nests without nearby OSR, nest weight among the two groups converged once the OSR bloom was finished. Therefore, the population of pollinators over a season and the fitness of a colony may be more likely to be linked to the average supply of floral resources in the landscape during the pollinator foraging season than to the peak levels of available resources. This would mean that pollinator populations and fitness are favoured in landscapes with a higher proportion of SNH to support a variety of wild flowering plants that produce a more consistent supply of nectar and pollen throughout the foraging season, rather than landscapes with a high proportion of MFCs producing large spikes in the amount of available floral resources (Schürch and Ratnieks, 2014; Rotheray, Osborne and Goulson, 2017; Vaughan and Memmott, 2019).

Although the development of both honeybee and bumblebee colonies is expected to be affected by the scarcity of floral resources at certain times throughout the season, honeybee colonies may experience less of a detrimental effect from this scarcity because they store large quantities of nectar within their hives, while *Bombus* species store relatively little nectar (Westphal et al., 2009; Danner *et al.*, 2016; Rotheray, Osborne and Goulson, 2017; Timberlake, Vaughan and Memmott, 2019). We predict that for the same reason that honeybees experience less of an impact from food scarcity during so-called “hunger gaps” (Couvillon et al. 2014;

Timberlake et al. 2019), they are also able to capitalize on the high quantity of floral resources provided by faba bean fields and convert this into an increased population in the subsequent year, while bumblebees cannot. The large amount of nectar collected from these faba bean fields can be stored within their perennial hives and utilized both when other resources are scarce within the current season and to keep the population higher during the winter, for the next season. Whereas, because the bumblebee colonies do not store these large quantities of nectar, their size and reproductive fitness are not substantially improved by the mass flowering of faba bean fields.

The specific flowering period of faba bean may also contribute to the lack of an effect of the previous year's proportion of faba bean found on the number of *Bombus spp.* pollinators observed. New *Bombus terrestris* and *Bombus lucorum* (the most common bumblebee species observed during our surveys) queens emerge from hibernation in mid-April (Svensson et al. 2000). This is well before we observed the faba bean fields to be in bloom. Thus, the faba bean fields neither act as an attractant and source of forage for new queens looking for a suitable nesting site, nor as a source of floral resources to support a newly established colony in the critical period of development at the beginning of the season. These same species do not usually produce new queens until the end of summer/ beginning of fall (Timberlake et al. 2019), when faba bean fields have been finished blooming for several weeks. Therefore, faba bean also does not act to attract recently mated queens looking for pollen and nectar, along with overwintering habitat. Dispersal distances of bumblebee queens can also range from around 3 km to tens of km, depending on the species and landscape factors (Knight et al. 2005; Lepais et al. 2010), meaning they can potentially travel far beyond the spatial scales we explored to find suitable habitat for overwintering or colony establishment.

In summation, *A. mellifera's* storage of large quantities of nectar may allow it to benefit from the presence of faba bean in the landscape in the previous year, producing a greater abundance in the next season, whereas *Bombus* spp. colonies likely experience no increase in fitness from faba bean in the landscape, and the flowering timing of faba bean in particular likely does not attract new or old queens.

6.1.2 Proportion of pasture in the landscape

Because SNH is known to provide a significant and more stable supply of floral resources (Danner et al. 2016; Marja et al. 2018; Raderschall et al. 2021b), we would expect that the abundance of both *A. mellifera* and *Bombus* spp. in landscapes with a greater proportion of SNH would be higher. However, none of our models found any effect of the proportion of pasture in the landscape on the number of pollinators observed of either group. It is possible that other landscape factors

and/or species interactions concealed or counteracted its effects. Due to the limited data used in our models, we were only able to test for the effect of pasture on the abundance of pollinators. Our dataset also only included data on arable land and not other landscape types, such as forests. The dataset and models also did not include information on the size or presence of SNH within fields, such as field margins and hedgerows, which are considered crucial for supporting pollinators with consistent floral resources (Timberlake et al. 2019). Field size could also have played a role, as agricultural landscapes with smaller fields are believed to contain a greater abundance and diversity of pollinators (Raderschall et al. 2021a).

6.1.3 Distance of the transect from the field edge

It was expected that the number of pollinators observed during the pollinator transect surveys would be greater in the transects located closer to the field edge due to edge-mediated effects (Dauber & Wolters 2004) or, more specifically, edge-biased distributions (EBDs) (Nguyen & Nansen 2018b). Edge -mediated effects, or simply edge effects, refer to any ecological phenomena caused by the meeting of two different habitat types (Dauber & Wolters 2004). EBDs refer specifically to a greater occurrence of an organism within or near the border between two habitats (the edge) that decreases with increasing distance from the edge. EBDs have been noted in many arthropod species in agricultural landscapes, including in pollinators in orchards (Tuell et al. 2009; Blitzer et al. 2012; Nguyen & Nansen 2018b). However, we could not find strong evidence of EBDs for pollinators in MFCs. Killewald et al. (2025) state they found evidence of a spill-over effect (where a population that is high in a habitat because of ideal or suitable conditions spreads out into the area surrounding that habitat) of bees from edge flower strips into nearby OSR fields both when blooming and not blooming. Yet the authors found no such effect at field edges without flower strips. The authors also only seem to find this increase within the flower strip itself and not in the transects 15 and 50 m into the field. Killewald et al. find no difference between the abundance of bees at the transects 15m from the field edge and 50m from the field edge.

In our study, we found the opposite of what we expected. There was a significantly greater number of bumblebees observed 50 m into the field when compared to 10 m from the field edge (Fig. 6). The reasons for this result are unclear. It may be that fields of MFCs do not experience the same EBDs for pollinators that we find in other crop types. Generally, the reason for EBDs of arthropods in agricultural land is considered to be from factors like increased habitat heterogeneity and plant species richness and abundance in field edges that provide both shelter and floral resources to many species (Dauber & Wolters 2004; Hanley et al. 2011; Nguyen & Nansen 2018b). However, in the case of MFCs like faba

bean, food resources are likely much greater within the fields than at the field edge during blooming. Hanley et al. (2011) surveyed field margins of faba bean fields and wheat fields and found that the faba bean field margins had a greater number of pollinators while the faba bean crop was blooming, but that this difference disappeared just two weeks after it had stopped blooming. Several other studies have also found a spillover effect of pollinators into natural habitats next to MFCs (Hanley et al. 2011). This suggests that perhaps in faba bean and other MFCs, the distribution of pollinators follows the opposite pattern of other crops when the field is in bloom. Killewald et al. (2005) also found that there were species differences concerning the spillover effect. *Apis meliffera* were most commonly found in field edges, whereas two wild bumblebee species were most commonly collected within the fields. This may suggest that honeybees stay closer to field edges and bumblebees may be more likely to venture further into faba bean fields while foraging. This theory is also supported by evidence from Raderschall et al. (2022), who found that in MFC fields *A. mellifera* pushed wild bumblebee foragers deeper into the field.

6.2 Effects of landscape factors on pest pressure in faba bean

6.2.1 Proportion of pasture in the landscape

It was expected that the proportion of pasture in the landscape would be positively correlated with the amount of *Bruchis rufimanus* eggs and the proportion of damaged bean seeds. Broad bean beetles are known to overwinter in the surrounding landscape of faba bean fields (Raderschall et al. 2021b; Dell'Aglio & Tayeh 2023), and several other studies have shown that SNH can offer suitable overwintering sites for pests (Rusch et al. 2010; Santoiemma et al. 2018; Laterza et al. 2023). SNH has been shown to increase pest pressure in some studies and reduce pest pressure in others (Veres et al. 2013; Alarcon-Segura et al. 2025). Several studies have pointed out that SNH can offer alternative host plants for polyphagous insects (Veres et al. 2013), but this is unlikely to be a cause of the increase in pest pressure we saw with increased pasture in the landscape. Broad bean beetles are oligophagous; they do consume multiple plants, but their diet is limited to only a few (Segers et al. 2021). Arable fields may also be hostile to insect pests because of practices like insecticide use and tillage. A greater proportion of pasture or other SNHs could offer refuge from the pest management strategies used within fields (Veres et al. 2013).

Many studies have shown that pest natural enemy populations and predation and/or parasitism of pests increase with the proportion of SNH in the landscape

(Holland et al. 2017; Alarcon-Segura et al. 2025). Therefore, it would be assumed that we would find a decrease in *Bruchus rufimanus* pest pressure when the proportion of pasture in the landscape increased. However, as several reviews have pointed out, most papers looking at pest natural enemies assume that an increase in the rate of predation and/or parasitism will directly correlate to a decrease in pest pressure. These authors rarely look at direct effects on pest damage or yield (Veres et al. 2013; Holland et al. 2017; Santoiemma et al. 2018; Alarcon-Segura et al. 2025). Far fewer studies have demonstrated a negative correlation between pest natural enemy abundance, predation or parasitism and reduced pest pressure. Pest pressure as it relates to SNH has shown to have a negative correlation in some studies but also a positive correlation in other studies, or no correlation at all in still more studies (Alarcon-Segura et al. 2025). Effects of the proportion of SNH in the landscape likely vary greatly based on species ecologies and interactions and other landscape factors.

6.2.2 Proportion of faba bean in the landscape in 2024

We expected to see that the proportion of faba bean in the landscape in the previous year (2024) would be positively correlated with the observed pest pressure in the current year (2025). It is generally accepted that if crop rotation is not performed, the pest pressure in a field will increase over time, from all forms of pests (fungi, nematodes, bacteria etc.), not just insects (Le Féon et al. 2013). We hypothesized that a lower proportion of faba bean in the landscape in the previous year would mean that pests would have a greater distance to travel between the previous year's host crop and the current year's host crop, and that there would be fewer sources of pests in the nearby landscape, meaning that few broad bean beetles would make their way to the current year's fields. Hausmann et al. (2024) found that the distance from the previous year's crop did reduce the pest pressure in OSR from some species of insect pest, but not all. They also found that a change in the proportion of OSR in the landscape from low to high reduced pest pressure from some pests but not others. It is theorized that with little host crop in the previous year, there are fewer pests to spread to the new host crop in the current year, and the greater host crop area results in a dilution of the pest in the landscape. We found no relation between the proportion of faba bean in the landscape in the previous year and the pest pressure in the current year's faba bean fields. Hausmann et al. (2024) looked at scales of up to 10 km and only found effects of distance on pest pressure in certain species. They state that the long dispersal distances of some OSR pests prevent standard crop rotation from having any measurable effect on pest pressure. The long-distance dispersal potential of *Bruchus rufimanus* is not known (Segers et al. 2021), so it is possible that the dispersal distance of the broad bean beetle was too great for us to find any landscape effects at the scales we measured.

Hausmann et al. (2024) also used the change in the proportion of their host crop in the landscape, whereas we used absolute proportions, and we found no correlation between the proportion of faba bean in the landscape in 2024 and the proportion in 2025, meaning landscapes with a high proportion of faba bean in 2024 could have had a high or low proportion of faba bean in 2025.

6.2.3 Proportion of faba bean in the landscape in 2025

In our study, the proportion of faba bean in the landscape in the current year had a significant positive effect on pest pressure. Some studies have found the opposite effect in certain pests or similar effects in other pests. Different studies have found conflicting results for the same insect pest species (Zaller et al. 2008a; b; Hausmann et al. 2024). As described above, it is postulated that high levels of a host crop in the landscape in the current year dilute the number of pests as they spread out into the large area of the current year's host crop (Zaller et al. 2008b; a; Hausmann et al. 2024). We argue that the reasoning for the increase in pest pressure with an increased proportion of faba bean in the landscape in the current year could be caused by a high dispersal distance in *Bruchus rufimanus* combined with an increased concentration of VOCs in what is referred to as the odorscape (Leppik & Frérot 2014; Conchou et al. 2019). The odourscape describes the spatial distribution, concentration and proportions of different VOCs and semiochemicals in the air throughout a specific landscape. It is known that different landscape types (i.e. forest and agricultural land) produce different odourscapes (Leppik & Frérot 2014) and that the atmospheric distribution and composition of VOCs in space and time can alter the behaviour of insects (Conchou et al. 2019). Therefore, we theorize that a higher proportion of faba in the current landscape could create a stronger concentration of faba bean VOCs in the odourscape, increasing the attraction of broad bean beetles from both within and outside of our measured landscape buffer zones to the faba bean fields within our landscape. How VOCs interact with each other and the atmosphere and how long they last in the atmosphere depends both on the properties of the chemical and the environment (Leppik & Frérot 2014). Therefore, more research would need to be done into the specific odourscapes produced in agricultural landscapes and specifically on the semiochemicals produced by faba bean and broad bean beetles to determine whether or not this could be a reason for the increased pest pressure we saw in landscapes with a greater proportion of faba bean in 2025.

6.3 Implications of research findings

6.3.1 Effects on the environment and social welfare

From a cost-benefit analysis, when looking directly at farmers, modern pesticide use can often be the most economically viable option. However, the direct cost to farmers of purchasing pesticides is still very high (Pimentel 2005; Deguine et al. 2021). There are also many costs which are not borne by the farmers and that do not appear at any stage in the chain of food production and consumption, and instead are often borne by society as a whole (Pimentel 2005; Pretty & Bharucha 2015; Kaur et al. 2024). These costs are referred to as negative externalities and can be economic, social and/ or environmental in nature. Externalities derived from pesticide use and other agricultural practices are difficult to detect and account for, and often affect disenfranchised communities the most. As a result, negative externalities are often underrepresented in data and undervalued in economic and policy decisions (Pretty & Bharucha 2015).

Heavy usage of pesticides pollutes the air, water and soil (Pretty & Bharucha 2015; Deguine et al. 2021; Kaur et al. 2024). Pesticide pollution of the environment leads to detrimental effects for all living organisms. This pollution has led to decreases in the abundance and biodiversity of wild plants, birds and insects (Geiger et al. 2010). Human health is also deeply affected by pesticide pollution. High levels of pesticide use are linked with cardiovascular disease, endocrine system dysfunction, psychiatric problems and several forms of cancer, among other health issues (Pimentel 2005; Pretty & Bharucha 2015; Kaur et al. 2024). Farmers, farm workers and those who live in rural landscapes usually face the worst of these health risks (Pretty & Bharucha 2015; Lamichhane et al. 2016). Those living in developing nations are also more strongly affected due to less strict regulations around the available pesticides and their application, as well as a lack of access to more modern, safer pesticide formulations (Pretty & Bharucha 2015). Societies must therefore pay for pesticide use economically by investing in infrastructure like water filtration systems and through increased healthcare costs. But societies also pay social costs with the lives and health of their citizens, something which can be difficult to weigh against economic gains (Pimentel 2005; Pretty & Bharucha 2015). Biodiversity loss, in turn, also leads to economic losses as ecosystem services such as pollination, soil nutrient cycling and biotic pest control decline (Pimentel 2005; Tscharntke et al. 2005; IPBES 2016). These declining ecosystem services lead to “lock-in” effects, where farmers are now even more reliant on inorganic fertilizers, pesticides and managed bees as they can no longer rely on natural pest enemies for crop protection or soil microbes and insect pollinators for increased yields (Pimentel 2005; Geiger et al. 2010; Pretty & Bharucha 2015; Gliessman 2018b).

There is no dispute that the use of pesticides has enabled a massive increase in crop yields worldwide. Along with other practices instituted as part of agricultural intensification, pesticide use has allowed for more people to be fed, at a lower financial cost than ever before (Pimentel 2005; Pretty & Bharucha 2015; Vasileiadis et al. 2017). However, the question is not whether agricultural intensification and specifically pesticide use have been beneficial, but whether these practices are sustainable. Here also, there can be no dispute. Modern intensive agricultural practices, including heavy pesticide use, cannot be sustained (Pimentel 2005; Geiger et al. 2010; Pretty & Bharucha 2015; IPBES 2016; Gliessman 2018b; Kaur et al. 2024). Here, agroecological strategies such as IPM (and IPPM) offer a potential solution as they have been shown to reduce pesticide use significantly while maintaining yields (Pretty & Bharucha 2015; Vasileiadis et al. 2017; Deguine et al. 2021).

6.3.2 Impacts on the agroecological transition

Although there have been many cases in which IPM has been effectively utilized to reduce pesticide applications and their adverse effects while maintaining high yields, the system is not without its flaws. Many farmers have chosen not to adopt IPM, and among those who have, there are many instances in which IPM has failed to meaningfully improve the sustainability of their production systems (Vasileiadis et al. 2017; Deguine et al. 2021). There are many reasons why this is the case, and our study can help to address some of these reasons.

It has been observed that many farmers choose not to adopt IPM strategies as they see it as a risky endeavour compared to the proven short-term efficacy of calendar pesticide applications. Spraying pesticides is a tangible solution for farmers, whereas biodiversity and ecosystem services are less visible or concrete solutions that are not as well understood (Deguine et al. 2021). IPM has also been criticized for focusing too much on pest economic thresholds and monitoring programs (both in research and application) while ignoring the importance of landscape factors and pest natural enemies for pest control. Furthermore, IPM in general fails to consider the effects on pollinators and their ecosystem services as a result of implementing certain strategies (Cumming & Spiesman 2006; Deguine et al. 2021; Petit et al. 2023).

Using IPPM (instead of IPM) as a framework, our study adds to the body of research that highlights the importance of landscape-scale factors on both pest pressure and pollination services (Holland et al. 2017; Raderschall et al. 2021b; Laterza et al. 2023; Priyadarshana et al. 2024; Alarcon-Segura et al. 2025; Boetzl et al. 2026b), thus encouraging their consideration in future pest and pollinator management strategies. The findings of this study can also help to create more

effective IPPM decision-making frameworks, which can, in turn, increase confidence amongst farmers in the merits of strategies of both IPM and IPPM.

6.4 Challenges with implementing IPPM strategies at a landscape scale

Many of the studies researching the effects of landscape factors on pest pressure and pollinators have found mixed or contradictory results (Zaller et al. 2008b; Raderschall et al. 2021a; Hausmann et al. 2024; Boetzl et al. 2026a). Agroecosystems at the landscape scale rely on a complex web of interacting factors, which are often highly variable, such as individual species, landscape composition, crop and pest management practices, to name a few (Marja et al. 2018; Segers et al. 2021; Killewald et al. 2025; Nezhadkheirollah & Drechsler 2025). This means that for IPPM methods to be effective, they have to be highly tailored to the problems faced in a specific context. Therefore, IPPM requires a vast amount of knowledge and research to be effectively utilized (Egan et al. 2020; Lundin et al. 2021).

Landscape-scale implementation of IPPM is especially difficult because it requires not only a rigorous understanding of the ecosystem at multiple scales, but also the coordination of multiple farm operations to accomplish a complex goal (Cumming & Spiesman 2006; Cong et al. 2014; Duru et al. 2015; Prager 2015; Landis 2017; Deguine et al. 2021). These same issues apply to many other agroecological practices that rely on biodiversity and ecosystem services to support agricultural production. Therefore, implementing these strategies will require communication and cooperation between researchers, farmers, political bodies and extension workers on a level which currently does not exist in many places (Prager 2015; Petit et al. 2023). Social and political structures currently in place focus on creating change in agroecosystems through top-down market adjustments and subsidies, which act on the individual farm level (Prager 2015; Landis 2017). They are not equipped for pest and pollinator management and other agroecological strategies that are complex, context-specific and adaptive and that operate on the landscape scale (Cong et al. 2014; Duru et al. 2015; Prager 2015; Stallman & James 2015; Landis 2017).

To implement landscape-scale IPPM and other agroecological practices, new social and political institutions which operate at the local and regional scale and coordinate the management of agricultural landscapes will likely be required. These institutions will have to support the participation, education, and empowerment of local stakeholders and both build and rely on local social capital. These measures will undoubtedly take a great amount of both time and political will to be realized (Cumming & Spiesman 2006; Cong et al. 2014; Duru et al. 2015; Prager 2015;

Stallman & James 2015; Landis 2017; Petit et al. 2023; Nezhadkheirollah & Drechsler 2025).

7. Conclusion

In this thesis, we examined the effects of landscape factors within and between years on both pest pressure and pollinator services. As outlined in Egan et al. (2020) and Lundin et al. (2021), because insect pests share a recent common ancestry, they also exhibit similar ecological traits and respond to common drivers across multiple spatial scales, including the landscape scale.

We found that an increase in the proportion of faba bean in the landscape in the previous year increased faba bean flower visits by honeybees, while bumblebees were not affected. This effect was likely due to honeybees' ability to better capitalize on the spikes of floral resources from MFCs because of their storage of large quantities of nectar (Westphal et al., 2009; Danner *et al.*, 2016; Rotheray et al., 2017; Timberlake et al., 2019). Our models also showed that within faba bean fields, bumblebees were more likely to be found further into the field than honeybees. This finding suggests that blooming MFCs may experience different edge effects than other crops (Hanley et al. 2011; Killewald et al. 2025).

The proportion of pasture in the landscape was linked with an increase in pest pressure from broad bean beetles. Many studies have shown that pollinator and natural enemy abundance and diversity increase with the proportion of SNH in the landscape; however, the effects on actual pest pressure and yield can be highly variable (Holland et al. 2017; Alarcon-Segura et al. 2025). These results confirm one of the main ideas of IPPM that pests, pollinators and natural enemies can benefit from the same landscape drivers (Egan et al., 2020; Lundin et al., 2021). Our initial hypothesis that the proportion of faba bean in the landscape in 2024 would increase pest pressure in faba bean fields in 2025 was not supported by the data. However, the proportion of faba bean in the current year was positively associated with pest pressure. When compared with results from other studies, it becomes clear that the effects of landscape factors on pest pressure are highly context-specific and that further study is necessary to disentangle the complex interactions among factors operating across multiple spatial and temporal scales (Zaller et al. 2008b; a; Hausmann et al. 2024).

Our research adds to the findings of other researchers that show both pest pressure and pollination services are affected by factors at scales ranging from the crop and field to the broader landscape (Zaller et al. 2008a; Veres et al. 2013; Riedinger et al. 2014; Marja et al. 2018; Deguine et al. 2021; Hausmann et al. 2024). Planning landscapes that can improve ecosystem services, such as pollination, and diminish ecosystem disservices like pest damage represents a major challenge in IPPM and the broader agroecological movement (Prager 2015; Stallman & James

2015; Landis 2017; Gliessman 2018a; Egan et al. 2020; Lundin et al. 2021; Nezhadkheirollah & Drechsler 2025). Not only is there a need for much more knowledge surrounding the utilization of ecosystem services in specific, local contexts, but also how this knowledge is created, shared, and employed will likely have to change. This will require drastic alterations to the social, ecological, economic and political structures which currently compose our food system (Cong et al. 2014; Landis 2017; Deguine et al. 2021; Tittonell et al. 2022; Petit et al. 2023). These measures are drastic, however, given the scale and severity of the socio-ecological problems we currently face (Pimentel 2005; Tscharntke et al. 2005; Geiger et al. 2010; IPBES 2016; Dicks et al. 2021; Tang et al. 2021; Kaur et al. 2024), nothing short of a radical departure from the norm seems to be an appropriate solution.

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Popular Science Summary

Many of the modern agricultural practices used today allow for the production of vast quantities of food that are needed to support the growing human population. However, an abundance of research has shown that these practices are not environmentally sustainable or socially or economically just and equitable. New ways of food production, distribution and consumption will be needed to remedy these serious and challenging problems.

Agroeocology is a broad term which encompasses a scientific study, an agricultural practice and a social movement. All three of these aspects aim to make agriculture and food systems more sustainable, equitable and just. The study and practice of agroecology includes the research and use of integrated pest and pollinator management (IPPM). IPPM is a decision-making framework which can be used by farmers. IPPM encourages the use of multiple techniques at once to protect crops from pest damage and increase the presence of pollinators in fields.
Over three-quarters of all major crops grown globally depend on pollinators to maximize yields, and pollination is valued at between 215 and 577 billion USD annually. Despite their clear and substantial importance to agriculture, pollinator populations are declining globally. This is in large part due to modern agricultural practices that have reduced valuable pollinator habitat and employ pesticides, which are detrimental to both to the livelihood and pollinating abilities of many pollinators.

In this study, we looked at faba bean (*Vicia faba*) in Sweden. It is an important crop because it can increase the availability of nitrogen, a vital plant nutrient, in the soil. Using faba in crop rotations can reduce the need for fertilizer use. Faba bean is also high in protein and fibre, meaning it can be a good plant protein alternative to soy, which is often imported into Europe, largely for animal feed but also for human consumption. Faba bean is a mass flowering crop (MFC), meaning it produces a large number of flowers in a field at one period of time. Although faba bean does not require pollination, there are significant yield benefits to faba bean from pollination.

A major pest of faba bean is the broad bean beetle (*Bruchus rufimanus*). It lays its eggs on the bean pods. The beetle larvae then burrow into the beans, where they pupate, and then the adults cut their way out of the beans. These beetles cause significant aesthetic damage to the beans, preventing them from being sold for human consumption or even animal consumption if the amount of beetle damage is too significant. The damage caused by the beetles also reduces the ability of the

beans to grow new healthy plants. Therefore, the broad bean beetle represents a major economic threat to faba bean growers.

We looked at how the composition of the landscape surrounding a particular faba bean field in previous and the current year affected the number of honeybee and bumblebee visits to faba bean flowers, the number of broad bean beetle eggs laid on the bean pods, and the proportion of beans damaged by the broad bean beetle. Specifically, we looked at the effects of the proportion of faba bean in the landscape in the previous year, the proportion of faba bean in the landscape in the current year, and the proportion of pasture in the landscape.

Using data from the transect surveys we conducted, along with data from EU and Swedish agricultural governing agencies, we created 12 statistical models to look at the effects of these landscape factors at 3 different spatial scales (1, 2 and 3km from the study field). These models showed that the proportion of faba bean in the landscape in the previous year had a significant positive effect on the abundance of honeybees we observed, but not the number of bumblebees we observed. The models also showed that the number of beetle eggs and proportion of beetle damage increased with the proportion of pasture and faba bean in the landscape in the current year. Finally, the models showed that the effects of these landscape factors differed based on the spatial scale at which they were observed.

Our results show that honeybees may be able to use MFCs like faba bean to increase their colony size between years, whereas bumblebees likely cannot. This is because mass-flowering crops produce a large amount of nectar and pollen in a landscape for a short period of time. This creates a spike in the available food for pollinators, but then a large drop-off when the crop finishes blooming. This drop-off of available food resources in the landscape is called a “hunger gap”. Because honeybees store large quantities of nectar in their hives and bumblebees do not, it is possible that the honeybees can weather these hunger gaps better than bumblebees and therefore see more benefits from MFCs.

Our results also showed that pasture, which is generally considered to be highly beneficial to wild pollinators, can increase the number of broad bean beetle eggs in a field and the damage these beetles cause. This confirms what other studies have found, that landscape factors can be both beneficial to pollinators and cause increased pest problems for farmers.

Some studies have theorized that MFCs may be beneficial to wild pollinators. However, our study suggests that they may not be able to increase the wild pollinator population. We suggest that an increase in the variety of habitats within agricultural landscapes, and especially an increase in natural habitats that provide a more steady supply of pollen and nectar to wild pollinators such as bumbles to

support their populations. We also recognize that both pests and pollinators are significantly affected by the composition of the landscape surrounding a field at both different spatial and temporal scales, which are in turn part of a complex web of social and ecological factors. If we want to effectively implement IPPM and many agroecological practices on a landscape scale, we will need further research into the functions and causes of these complex webs. But we will also need new ways of creating, disseminating and using this information that increase the coordination of farmers, researchers, agricultural extension workers, policy makers and other stakeholders at a local and regional scale. This will likely require the creation of new social, economic and political institutions. All of these changes to our food production systems will be complicated and challenging, but ultimately necessary to create food in a more sustainable, just and equitable manner.

Appendix 1 – Supplementary Tables

*Table 11. Results of GLMM show the effects of landscape factors at a 2 km spatial scale on the number of visits to faba bean by honeybees. Significant p-values are shown in bold (α = 0.05). Level of significance: p < 0.001 = "***", p < 0.01 = "**", p< 0.05 = "*", p <0.1 = ".".*

Variable	Estimate	Std. Error	χ^2	P-value	Conf. Low	Conf. high
(Intercept)	1.042	0.451	NA	**0.021***	0.158	1.925
Pasture	-0.153	0.809	0.905	0.364	-1.740	1.433
Faba Bean 2024	-0.374	0.411	0.039	**0.008****	-1.180	0.433
Faba Bean 2025	1.268	0.480	0.768	0.100	0.328	2.209
Transect	-1.682	1.023	0.468	0.469	-3.688	0.323
Avg. Flowers per m^2	0.096	0.133	0.437	0.459	-0.165	0.357

*Table 12. Results of GLMM show the effects of landscape factors at a 3 km spatial scale on the number of visits to faba bean by honeybees. Significant p-values are shown in bold (α = 0.05). Level of significance: p < 0.001 = "***", p < 0.01 = "**" , p < 0.05 = "*", p < 0.1 ".".*

Variable	Estimate	Std. Error	χ^2	P-value	Conf. Low	Conf. high
(Intercept)	-0.153	0.809	NA	0.850	-1.740	1.433
Pasture	-0.374	0.411	0.825	0.364	-1.180	0.433
Faba Bean 2024	1.268	0.480	6.984	**0.008****	0.328	2.209
Faba Bean 2025	-1.682	1.023	2.702	0.100 .	-3.688	0.323
Transect	0.096	0.133	0.525	0.469	-0.165	0.357
Avg. Flowers per m^2	0.114	0.154	0.548	0.459	-0.188	0.416

*Table 1.3. Results of GLMM show the effects of landscape factors at a 1 km spatial scale on the number of visits to faba bean by bumblebees. Significant p-values are shown in bold ($\alpha = 0.05$). Level of significance: $p < 0.001$ = "***", $p < 0.01$ = "**", $p < 0.05$ = "*", $p < 0.1$ = ".".*

Variable	Estimate	Std. Error	χ^2	P-value	Conf. Low	Conf. high
(Intercept)	-0.153	0.809	-0.189	0.850	-1.740	1.433
Pasture	-0.374	0.411	-0.909	0.364	-1.180	0.433
Faba Bean 2024	1.268	0.480	2.643	**0.008****	0.328	2.209
Faba Bean 2025	-1.682	1.023	-1.644	0.100 .	-3.688	0.323
Transect	0.096	0.133	0.724	0.469	-0.165	0.357
Avg. Flowers per m^2	0.114	0.154	0.740	0.459	-0.188	0.416

*Table 13. Results of GLMM show the effects of landscape factors at a 2 km spatial scale on the number of visits to faba bean by bumblebees. Significant p-values are shown in bold ($\alpha = 0.05$). Level of significance: $p < 0.001$ = "***", $p < 0.01$ = "**", $p < 0.05$ = "*", $p < 0.1$= ".".*

Variable	Estimate	Std. Error	χ^2	P-value	Conf. Low	Conf. high
(Intercept)	0.632	0.562	NA	0.261	-0.470	1.734
Pasture	0.072	0.326	0.302	0.825	-0.566	0.710
Faba Bean 2024	-0.759	0.391	0.057	0.052	-1.525	0.008
Faba Bean 2025	-1.125	1.171	0.287	0.337	-3.421	1.171
Transect	-0.313	0.136	0.018	**0.021***	-0.578	-0.047
Avg. Flowers per m^2	0.380	0.188	0.011	**0.044***	0.011	0.749

*Table 1.5. Results of GLMM show the effects of landscape factors at a 3 km spatial scale on the number of visits to faba bean by bumblebees. Significant p-values are shown in bold (α = 0.05). Level of significance: p < 0.001 = "***", p < 0.01 = "**" , p < 0.05 = "*" , p < 0.1 = ".".*

Variable	Estimate	Std. Error	χ^2	P-value	Conf. Low	Conf. high
(Intercept)	0.075	1.077	NA	0.944	-2.036	2.186
Pasture	-0.313	0.518	0.366	0.545	-1.328	0.701
Faba Bean 2024	-1.231	0.718	2.940	0.086 .	-2.638	0.176
Faba Bean 2025	-0.944	1.433	0.434	0.510	-3.751	1.864
Transect	-0.312	0.141	4.919	**0.027***	-0.588	-0.036
Avg. Flowers per m^2	0.075	1.077	2.513	0.944	-2.036	2.186

*Table 14. Results of GLMM show the effects of landscape factors at a 1 km spatial scale on the number of eggs laid by Bruchus rufimanus on faba bean pods. Significant p-values are shown in bold (α = 0.05). Level of significance: p < 0.001 = "***", p < 0.01 ="*", p < 0.1 = "." .*

Variable	Estimate	Std. Error	χ^2	P-value	Conf. Low	Conf. high
(Intercept)	2.185	0.381	NA	**<0.001*****	1.438	2.932
Pasture	0.352	0.164	0.545	**0.032***	0.031	0.674
Faba Bean 2024	0.204	0.143	0.086	0.154	-0.076	0.485
Faba Bean 2025	0.339	0.233	0.510	0.145	-0.118	0.797
Transect	-0.036	0.216	0.027	0.869	-0.458	0.387
Avg. Flowers per m^2	0.037	0.224	0.113	0.869	-0.403	0.476

*Table 1.7.. Results of GLMM show the effects of landscape factors at a 2 km spatial scale on the number of eggs laid by Bruchus rufimanus on faba bean pods. Significant p-values are shown in bold (α = 0.05). Level of significance: p < 0.001 = "***", p < 0.01, p < 0.1 = ".".*

Variable	Estimate	Std. Error	χ^2	P-value	Conf. Low	Conf. high
(Intercept)	3.718	0.375	NA	**<0.001*** **	2.982	4.454
Pasture	0.780	0.221	4.607	**<0.001*** **	0.347	1.213
Faba Bean 2024	0.316	0.216	2.036	0.143	-0.107	0.738
Faba Bean 2025	2.202	0.782	2.120	**0.005** **	0.670	3.734
Transect	0.020	0.181	0.027	0.910	-0.334	0.375
Avg. Flowers per m^2	-0.007	0.218	0.027	0.976	-0.434	0.420

*Table 1.8. Results of GLMM show the effects of landscape factors at a 3 km spatial scale on the number of eggs laid by Bruchus rufimanus on faba bean pods. Significant p-values are shown in bold (α = 0.05). Level of significance: p < 0.001 = "***", p < 0.01 = "*", p < 0.1 = ".".*

Variable	Estimate	Std. Error	χ^2	P-value	Conf. Low	Conf. high
(Intercept)	4.787	0.746	NA	**<0.001*** **	3.326	6.249
Pasture	1.156	0.369	12.450	**0.002** **	0.433	1.880
Faba Bean 2024	0.283	0.425	2.140	0.505	-0.550	1.116
Faba Bean 2025	2.276	0.972	7.935	**0.019***	0.371	4.181
Transect	0.073	0.178	0.013	0.682	-0.276	0.423
Avg. Flowers per m^2	0.010	0.212	0.001	0.962	-0.406	0.426

*Table 1.9. Results of GLMM show the effects of landscape factors at a 2 km spatial scale on the proportion of damaged faba bean seeds. Significant p-values are shown in bold (α = 0.05). Level of significance: p < 0.001 = "***", p < 0.01 = "**" , p < 0.05 = "*", p < 0.1 = ".".*

Variable	Estimate	Std. Error	χ^2	P-value	Conf. Low	Conf. high
(Intercept)	-1.092	0.220	NA	**<0.001****	-1.524	-0.661
Pasture	0.598	0.113	27.943	**<0.001****	0.376	0.819
Faba Bean 2024	0.185	0.121	2.310	0.129	-0.053	0.423
Faba Bean 2025	1.655	0.475	12.155	**<0.001****	0.725	2.586
Transect	0.011	0.107	0.010	0.921	-0.198	0.219
Avg. Flowers per m^2	0.034	0.162	0.044	0.833	-0.284	0.352

*Table 1.10. Results of GLMM show the effects of landscape factors at a 3 km spatial scale on the proportion of damaged faba bean seeds. Significant p-values are shown in bold (α = 0.05). Level of significance: p < 0.001 = "***", p < 0.01 = "**" , p < 0.05 = "*", p < 0.1 = "." .*

Variable	Estimate	Std. Error	χ^2	P-value	Conf. Low	Conf. high
(Intercept)	-0.958	0.546	NA	0.080 .	-2.029	0.113
Pasture	0.704	0.266	7.021	**0.008****	0.183	1.225
Faba Bean 2024	0.302	0.321	0.888	0.346	-0.326	0.931
Faba Bean 2025	0.819	0.705	1.349	0.246	-0.563	2.201
Transect	-0.007	0.139	0.002	0.961	-0.279	0.265
Avg. Flowers per m^2	0.037	0.171	0.046	0.830	-0.298	0.372

Appendix 2 – Fact Sheet

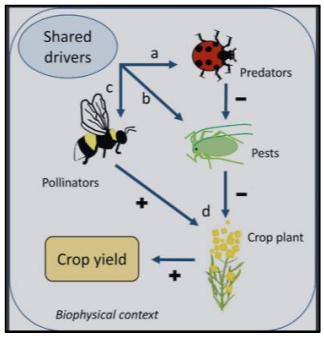
Bees, Beans and Beetles

Interannual landscape planning for pest and pollinator management in faba beans

CONCLUSION

Landscape factors in both the current and previous years were shown to alter the pest pressure and pollination services experienced by faba bean. Effects varied with pollinator taxa and spatial scale.

My work adds to a body of research which illuminates the complex web of interactions which affect crop production and protection from the crop to the landscape scale. Effective landscape management of pests and pollinators will require further study to better understand these landscape effects. To implement landscape management strategies, new social, political and economic structures at the regional and local levels will have to be created.



Lundin et al

INTRODUCTION

Global populations have skyrocketed, increasing the demand for food. This demand has been met through agricultural intensification. A series of methods, such as expanding crop land, reducing crop variety and increasing the use of inorganic fertilizers and synthetic pesticides. Although these methods have successfully increased the available food supply, they are not environmentally, socially, or economically sustainable, and so new ways of food production are necessary.

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Agroecology.

Agroecology is a scientific practice, a method of farming, and a social movement. All three of these aspects are focused on utilizing biodiversity and ecosystem services to help produce a more sustainable global food production system.

IPPM

Integrated pest and pollinator management (IPPM) is a decision-making framework for farmers. It encourages the use of multiple strategies at once to simultaneously decrease pest pressure and increase pollination services in cropland. This can be challenging as many insect pests and pollinators share common drivers. But there is also potential syngergies between drivers of insect pollinators and pest natural enemies.

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SCIENCE AND EDUCATION FOR SUSTAINABLE LIFE

Bees, Beans and Beetles

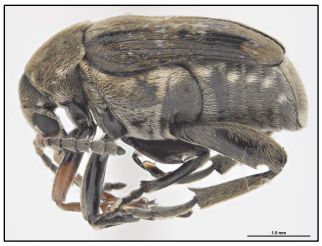
Interannual landscape planning for pest and pollinator management in faba beans

Faba Bean

Faba bean is a leguminous, mass flowering crop (MFC) grown around the world. It produces beans which are rich in protein and fibre, and that can reduce the need for Europe to import soy for use in animal feed. Although faba bean is not pollinator dependent, yield is greatly improved with the presence of pollinators.

Broad Bean Beetle

Scientific name *Bruchis rufimanus*, the broad bean beetle, is a major pest of faba bean. Adults consume pollen and lay eggs on the bean pods. When the larvae hatch, they burrow into the beans, where they pupate. New adults then cut their way out of the beans. This causes aesthetic damage to the beans, which can prevent their sale. It also reduces the germination rate and shoot vigour of the beans.



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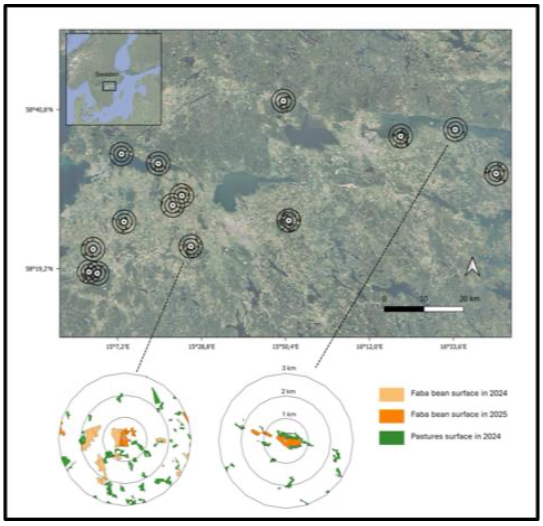

METHODS

Fourteen fields across Östergötland, Sweden, were selected. We measured several landscape factors in the surrounding area at a 1, 2 and 3km spatial scale. These landscape factors were:

- Proportion of faba bean in the landscape in the previous year
- Proportion of faba bean in the landscape in the current year
- Proportion of pasture in the landscape
- Average number of flowers per m^2 in each field
- Distance from the field edge (10 m or 50 m)

Using transect surveys, I collected data on the number of honeybees and bumblebee flower visitations and pest pressure from *Bruchus rufimanus*. This data was then put into general linear mixed models (GLMM) to determine the effect of each landscape factor.

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SCIENCE AND EDUCATION FOR SUSTAINABLE LIFE

Bees, Beans and Beetles

Interannual landscape planning for pest and pollinator management in faba beans

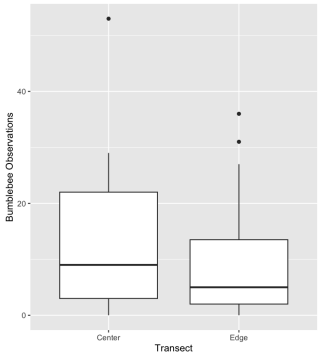
RESULTS

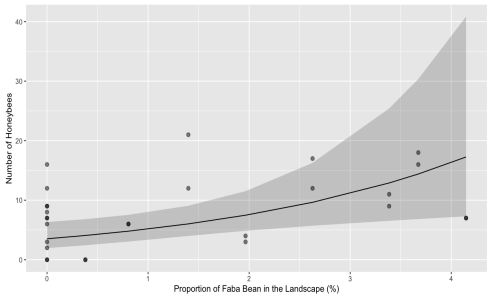
Pollinators

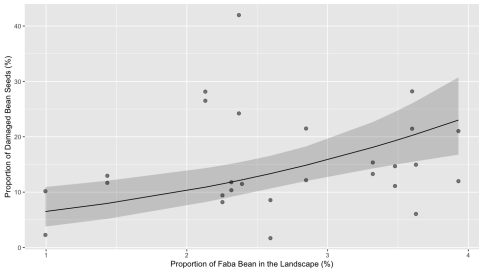
- The number of honeybee observations increased with the proportion of faba bean in the landscape in the previous year at the 2 and 3 km spatial scales
- The number of bumblebee observations increased with the average number of flowers per m^2 at the 1 and 2 km spatial scales
- Significantly more bumblebees were observed 50m from the field edge when compared to 10m from the field edge

Pests

- The number of beetle eggs and the proportion of damaged beans increased with the proportion of pasture in the landscape at the 2 and 3 km spatial scales; only the number of eggs was positively correlated at the 1 km spatial scale.
- The number of beetle eggs and the proportion of damaged beans increased with the proportion of faba beans in the landscape in the current year at the 2 and 3km landscape scales and the 3 km landscape scale respectively







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SCIENCE AND EDUCATION FOR SUSTAINABLE LIFE

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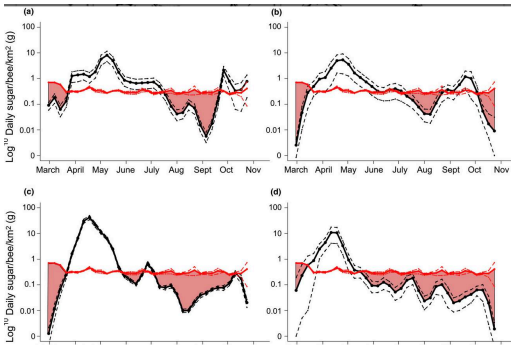
Interannual landscape planning for pest and pollinator management in faba beans

DISCUSSION

Pollinators

- I expected to find that both honeybees and bumblebees would be positively correlated with the proportion of faba bean in the landscape in the previous year. However, only honeybees were shown to benefit. I hypothesize that this is because, although a large proportion of MFCs in the landscape provide a significant amount of floral resources, these resources may not be consistent enough to increase bumblebee colony reproductive fitness. Honeybees may be able to use their large nectar storage capabilities to better utilize the spikes in floral resources and persist when there are fewer floral resources available. More semi-natural habitat (SNH) in the landscape can provide a more consistent supply of floral resources to wild pollinators and may be necessary to increase their populations.
- Bumblebees may bee found further from the field edge because of increased competition with honeybees which are known to prefer foraging near the field edge, forcing the bumblebees deeper into the fields.



Timberlake et al. 2019

Pests

- Pest pressure was shown to increase with the proportion of the pasture in the landscape. This contradicts what some studies have found but aligns with others. Pollinators are also known to benefit from increased pasture and other forms of SNH. This highlights the complexity of landscape-scale IPPM and the need for further research.
- I hypothesize that the positive correlation of pest pressure with the proportion of faba bean in the landscape in the current year could be due to a greater amount of volatile organic compounds in the atmosphere that could attract broad bean beetles.

Implementation of IPPM at a landscape scale

Landscape-scale management of pests and pollinators is challenging. Not only because of the complexity of the interactions taking place at multiple spatial scales requires a vast amount of information, but also because landscape-scale coordination of crop production is not currently viable. Greater coordination at the landscape scale will require new forms of governance and new social and economic structures. These new structures will have better disseminate information to local farmers and empower them in decision making processes in order to be socially just and equitable.

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