Understanding the impact of landscape composition on agrobiodiversity in a peri-urban context: learnings from a citizen-science approach

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“Die Limburger met z’n tuintjes”

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Frederik, 2 maart 2023

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Summary

The composition and configuration of agricultural landscapes and the associated functional agrobiodiversity (FAB) have changed significantly in recent decades. As the landscape composition is expected to influence the interrelated microclimate and arthropod community at different scales, these changes might have led to a decline in multiple agroecosystem services, with potential impacts for the growth of crops with different demands from the environment. FAB as natural resource could offer solutions to increase the sustainability of agricultural production and the resilience of our landscapes, for instance by creating a climate adaptive environment. Reinforcement has not been successful this far because too often a one actor-one parcel approach is used. To effectively reinforce agrobiodiversity, we need a landscape lens that should be used to look at two dimensions. First, considering ecological questions, we need to know what land uses and associated agrobiodiversity are needed at what scales to support a resilient agroecosystem. Second, considering the social issues, in densely populated areas, urban land use mixes with rural land use, so that agricultural landscapes do not belong only to farmers and peri-urban landscapes with multiple actors emerge. We need to know who those actors are, what their role is and how to mobilise them to ensure an integrated approach to strengthening agrobiodiversity. In this thesis we present a social-ecological framework and a unique citizen science tool which we used in two typical peri-urban landscapes we often find in Flanders.

Our first objective was to develop a framework and tools to collect ecological data related to different land uses, reach key actors and facilitate experimentation with agrobiodiversity. Therefore, in **chapter 2,** we discuss functional agrobiodiversity as a central resource in the social-ecological agroecosystem considering both the landscape and the local scale. In addition, we designed an innovative toolbox to experiment with agrobiodiversity in collaboration with local land users using a citizen science approach. The toolbox takes the form of a landscape observatory with small, 1m²-gardens distributed as monitoring points in agricultural landscapes. The 1m²-gardens were fully standardised with a fixed set of ten crops, microclimate sensors and invertebrate traps to fulfil a dual purpose. A first purpose was to collect data on pollinators, predators (natural enemies), temperature, soil moisture, leaf herbivory and performance of the crop species and relate these indicators for agroecosystem processes to FAB in the surrounding landscape. A second purpose of the 1m²-gardens was to involve local land users such as rural residents and farmers to build the ecological dataset, and learn about agrobiodiversity and possible advantages thereof. The learning

process during the immersive citizen science approach could facilitate transformative learning towards pro-environmental behaviour for functional agrobiodiversity.

Our second objective was to implement the 1m²-garden toolbox in Flanders and gain more insights in the relationships between land use composition and agroecosystem processes through the data collected in the 1m²-gardens, together with local land users. In **chapter 3** we describe the BEL-Landscape case where we sampled with 41 1m²-gardens in Melle, Merelbeke, Oosterzele (East Flanders, Belgium) in 2018 and 2019. During both field work seasons there was extreme drought and several heat waves. We found no clear relationship between the crops in the 1m²-gardens and the landscape composition in the 500-metre radius surroundings. We found that high green vegetation in the landscape (trees, hedges) buffered both temperature and soil moisture variation while microclimate variation was increased in arable conditions. Both pollinators and ground dwelling predators were most active in agricultural landscapes with arable land. Furthermore, non-agricultural land uses defined by domestic gardens, public green and built-up areas were negatively related to both pollinators and predators. These landscape-induced abiotic and biotic pathways did, however, not explain variation in crop performance. So, we found evidence that high green vegetation in the landscape buffers the microclimate and that beneficial arthropods are most active in arable areas, but no benefits of the multi-crop performance from neither a stable microclimate or higher activity of functional invertebrates.

Our third objective was to check whether the results and relationships found in the first case can be extrapolated to similar peri-urban contexts. In **chapter 4** we present a replication of the previously described experiment with 25 1m²-gardens in a spatially independent peri-urban landscape in the Campine region in Laakdal, Geel (province of Antwerp) in 2021. This second landscape observatory is named Merode and weather conditions during this season were opposite with average temperatures and the most summer precipitation since registration began. We found that relationships between landscape composition and ground dwelling predators were more consistent than for pollinators. The latter might be more dependent on weather conditions or differences between ecoregions such as soil or forest types. More specific, we found that positive relationships between ground dwelling predators and both valuable low green vegetation (e.g. road verges) and arable areas were consistent in both cases. Built-up areas were consistently negatively related to the activity of both functional invertebrate groups in both cases. The capacity of high green vegetation to buffer the microclimate was also consistent, yet more pronounced in seasons with heat and drought waves. In BEL-Landscape, arable land use aggravated microclimate extremes while in Merode these were caused by built-up areas. This inconsistency could be a result of differences in the sampled landscape compositional gradients. We, again, found no direct relationships between landscape composition and crop performance and the studied abiotic and biotic variables did not help to explain variation of multi-crop performance to the surrounding land use composition. In independent peri-urban contexts which are alike in terms of multi-actor pressure on agricultural land, some trends considering invertebrates and microclimate persist, despite opposite weather conditions and different ecoregions.

Our fourth objective was to investigate whether different actors in peri-urban areas learned or changed their behaviour in favour of agrobiodiversity during the citizen science projects. Although the goal was not to facilitate learning, the approach aiming for motivated and engaged citizen scientists resulted in transformative learning. In **chapter 5** we did a qualitative analysis of a post-project questionnaire distributed among 84 and 28 citizen scientists in BEL-Landscape and Merode, respectively. Using the Transformative Learning Theory as analytical framework we related learning outcomes to participants' prior knowledge and learning opportunities provided during the citizen science project. We found that all participants learned something. Most learning was about instrumental aspects such as insects and crops and to a lesser extent about participants' own or others' influences on functional agrobiodiversity in their environment. About half changed their opinion about agrobiodiversity or their attention for the environment while 31% and 12% in BEL-Landscape and Merode, respectively, changed their behaviour in favour of agrobiodiversity. For example, participants began mowing their lawns less frequently from an increased understanding of the importance of this action for functional agrobiodiversity. Prior knowledge of participants did not prevent learning but reduced the likelihood of transformative change. Repeated reading of information in newsletters, experimentation in the 1m²-garden and informal discussion with the researcher promoted learning and transformative change towards functional agrobiodiversity.

As a fifth objective, in **chapter 6**, we combined ecological insights from chapter 3 and 4 with social insights from chapter 5 to make an integrated analysis by zooming in on a specific example location of the BEL-Landscape case. After zooming in, we also zoomed out and made a comparison of both cases from this thesis to three other agricultural landscapes in Flanders to study the representativeness of our work. Finally, in **Chapter 7** we discussed potential roles of individual actors, governments and landscape organisations for functional agrobiodiversity. Finally, we discussed how the 1m²-garden toolbox can be improved and adapted to specific research needs considering both ecological and social requirements.

Nederlandstalige samenvatting

De samenstelling en configuratie van agrarische landschappen met de bijbehorende functionele agrobiodiversiteit (FAB) is de afgelopen decennia sterk veranderd. Aangezien de samenstelling van het landschap naar verwachting het onderling samenhangende microklimaat en de geleedpotigengemeenschap op verschillende schalen beïnvloedt, kan deze verandering hebben geleid tot een afname van meerdere agro-ecosysteemdiensten, met mogelijke gevolgen voor de groei van gewassen die verschillende eisen stellen aan de omgeving. FAB als natuurlijke hulpbron zou oplossingen kunnen bieden om de duurzaamheid van de landbouwproductie en de veerkracht van onze agrarische landschappen te vergroten, bijvoorbeeld door een klimaat-adaptieve omgeving te creëren. Versterking is tot dusver niet succesvol geweest omdat te vaak een één-actor-één-perceel aanpak wordt gehanteerd. Om de agrobiodiversiteit effectief te versterken, hebben we een landschapsbril nodig waarbij naar twee dimensies wordt gekeken. Ten eerste, gezien de ecologische kwesties, moeten we weten welke vormen van landgebruik en bijbehorende agrobiodiversiteit op welke schaal nodig zijn om een veerkrachtig agro-ecosysteem te ondersteunen. Ten tweede, wat sociale kwesties betreft, in dichtbevolkte gebieden vermengt stedelijk landgebruik zich met landelijk landgebruik, zodat landbouwlandschappen niet alleen aan landbouwers toebehoren en er peri-urbane landschappen ontstaan met meerdere actoren. We moeten weten wie deze actoren zijn, wat hun rol is en hoe we ze kunnen mobiliseren voor een geïntegreerde aanpak om de agrobiodiversiteit te versterken. In deze thesis presenteren we een sociaal-ecologisch kader en een unieke *citizen science* tool die we gebruikten in twee typische peri-urbane landschappen die vaak voorkomen in Vlaanderen

Onze eerste doelstelling was het ontwikkelen van een kader en *toolbox* om ecologische gegevens over verschillende vormen van landgebruik te verzamelen, actoren te bereiken en experimenten met agrobiodiversiteit te vergemakkelijken. Daarom bespreken we in **hoofdstuk 2** functionele agrobiodiversiteit als een centrale hulpbron in het sociaal-ecologische agro-ecosysteem, rekening houdend met zowel het landschap als de lokale schaal. Daarnaast hebben we een innovatieve *toolbox* ontworpen om te experimenteren met agrobiodiversiteit in samenwerking met lokale landgebruikers via een *citizen science* benadering. De *toolbox* heeft de vorm van een landschapsobservatorium met kleine 1m²-tuintjes die als meetpunten in agrarische landschappen zijn verspreid. De 1m²-tuintjes werden volledig gestandaardiseerd met een vaste set van tien gewassen, microklimaatsensoren en vallen voor ongewervelden om een dubbel doel te vervullen. Een eerste doel was het verzamelen van gegevens over bestuivers, predators (natuurlijke vijanden),

temperatuur, bodemvocht, blad-herbivorie en prestaties van de gewassoorten en het relateren van deze indicatoren voor agro-ecosysteemprocessen aan FAB in het omliggende landschap. Een tweede doel van de 1m²-tuintjes was het betrekken van lokale grondgebruikers zoals plattelandsbewoners en landbouwers bij het opbouwen van de ecologische dataset, en het leren over agrobiodiversiteit en mogelijke voordelen daarvan. Het leerproces tijdens de meeslepende *citizen science* aanpak zou transformatief leren kunnen vergemakkelijken richting aanpassing van gedrag ten voordele van functionele agrobiodiversiteit.

Onze tweede doelstelling was om de 1m²-tuintjes in Vlaanderen te implementeren en meer inzichten te krijgen in de relaties tussen de samenstelling van het landgebruik en agro-ecosysteemprocessen via de gegevens die in de 1m²-tuintjes worden verzameld, samen met lokale landgebruikers. In **hoofdstuk 3** beschrijven we de BEL-Landschap studie waarbij we in 2018 en 2019, 41 1m²-tuintjes bemonsterd hebben in Melle, Merelbeke, Oosterzele (Oost-Vlaanderen, België). Beide veldwerkseizoenen kenden extreme droogte en verschillende hittegolven. We vonden geen duidelijke relaties tussen de gewassen in de 1m²-tuintjes en de omgeving in een straal van 500 meter. We vonden dat houtachtige vegetatie in het landschap (bomen en hagen) zowel temperatuur- als bodemvochtvariatie bufferde, terwijl microklimaatvariatie hoger was met meer akkerbouw in de omgeving. Zowel bestuivers als predators waren het meest actief in akkerbouwlandschappen. Bovendien was er een negatief verband tussen niet-agrarisch landgebruik, gedefinieerd als tuinen, openbaar groen en bebouwde gebieden, en zowel bestuivers als natuurlijke vijanden. Deze landschap-specifieke abiotische en biotische mechanismen verklaarden geen variatie in de groei van de gewassen. Wij vonden dus aanwijzingen dat houtige vegetatie in het landschap het microklimaat buffert en dat nuttige geleedpotigen het meest actief zijn in gebieden met akkerland, maar geen voordelen hiervan voor meervoudige gewasprestaties door een stabiel microklimaat of een hogere activiteit van functionele ongewervelden.

Onze derde doelstelling was om na te gaan of de resultaten en relaties die in BEL-Landschap gevonden werden, geëxtrapoleerd kunnen worden naar gelijkaardige peri-urbane gebieden. In **hoofdstuk 4** presenteren we een replicatie van het eerder beschreven experiment met 25 1m²-tuintjes in een ruimtelijk onafhankelijk landschap in de Kempen in Laakdal, Geel (provincie Antwerpen) in 2021. Dit tweede landschapsobservatorium heet Merode en de weersomstandigheden tijdens dit seizoen waren tegengesteld met gemiddelde temperaturen en de meeste zomerse neerslag sinds het begin van de metingen. We vonden dat relaties tussen landschapssamenstelling en predators consistenter waren dan voor bestuivers. Deze laatste zijn wellicht meer afhankelijk van weersomstandigheden of verschillen tussen ecoregio's zoals bodem- of bostypes. In beide gevallen vonden we positieve relaties tussen natuurlijke plaagbestrijders en zowel waardevolle kruidachtige vegetaties (bv. wegbermen, extensief beheerde graslanden) als akkerbouwgebieden. Bebouwde gebieden waren consistent negatief gerelateerd aan de activiteit van beide functionele ongewervelde groepen in beide landschappen. Het vermogen van houtige vegetatie om het microklimaat te bufferen was ook consistent, maar meer uitgesproken in seizoenen met hitte- en droogtegolven. In BEL Landschap verergerde het gebruik van akkerland de microklimaatextremen, terwijl ze in Merode werden veroorzaakt door bebouwde gebieden. Deze inconsistentie zou te wijten kunnen zijn aan verschillen in de bemonsterde gradiënten van de landschapssamenstelling. We vonden, opnieuw, geen directe relaties tussen landschapssamenstelling en gewasprestaties, en de bestudeerde abiotische en biotische variabelen droegen niet bij tot de verklaring van de variatie in gewasprestaties ten opzichte van de omringende samenstelling van het landgebruik. In onafhankelijke peri-urbane contexten die sterk op elkaar lijken wat betreft de druk op landbouwgrond door meerdere actoren, blijven bepaalde trends met betrekking tot ongewervelden en microklimaat bestaan ondanks volledig tegengestelde weersomstandigheden en verschillende ecoregio's.

Onze vierde doelstelling was om te onderzoeken of verschillende actoren in peri-urbane gebieden tijdens de *citizen science* projecten leerden of hun gedrag veranderden ten gunste van agrobiodiversiteit. Hoewel het doel niet was om het leren te vergemakkelijken, resulteerde de aanpak gericht op gemotiveerde en betrokken burgerwetenschappers in transformatief leren. In **hoofdstuk 5** hebben we een kwalitatieve analyse uitgevoerd van een vragenlijst na afloop van het project, die werd verspreid onder respectievelijk 84 en 28 burgerwetenschappers in BEL Landschap en Merode. Met de transformatieve leertheorie als analytisch kader hebben we de leerresultaten gerelateerd aan de voorkennis van de deelnemers en de leermogelijkheden die tijdens het burgerwetenschapsproject werden geboden. We stelden vast dat alle deelnemers iets leerden. De meesten leerden over instrumentele aspecten zoals insecten en gewassen en, in mindere mate, over de invloed van de deelnemers zelf of anderen op de functionele agrobiodiversiteit in hun omgeving. Ongeveer de helft veranderde hun visie op agrobiodiversiteit of hun aandacht voor de omgeving, terwijl 31% en 12% in respectievelijk BEL Landscape en Merode hun gedrag ten gunste van agrobiodiversiteit veranderden. Deelnemers gingen bijvoorbeeld minder vaak hun gazon maaien omdat ze meer beseften hoe belangrijk deze handeling is voor functionele agrobiodiversiteit. De voorkennis van de deelnemers verhinderde het leren niet, maar verminderde de kans op een transformatieve verandering. Herhaaldelijk opeenvolgend lezen van informatie in nieuwsbrieven, experimenteren in de 1m²-tuintjes en informele discussie met de onderzoeker bevorderden het leren en transformatieve verandering ten aanzien van functionele agrobiodiversiteit.

Als vijfde doelstelling keerden we in **hoofdstuk 6** terug naar het sociaal-ecologisch systeem en combineerden we ecologische inzichten uit de hoofdstukken 3 en 4 met sociale inzichten uit hoofdstuk 5 om een geïntegreerde analyse te maken door in te zoomen op een specifieke voorbeeldlocatie van de casus BEL-landschap. Na het inzoomen hebben we ook uitgezoomd en beide cases uit dit proefschrift vergeleken met drie andere agrarische landschappen in Vlaanderen om de representativiteit van ons werk te begrijpen. In **hoofdstuk 7** bespraken we de mogelijke rol van individuele actoren, overheden op verschillende niveaus en de rol van landschapsorganisaties bij het coördineren van individuele inspanningen voor functionele agrobiodiversiteit. Ten slotte bespraken we hoe de *toolbox* van 1m²-tuinen kan worden verbeterd en aangepast aan specifieke onderzoeksbehoeften, rekening houdend met zowel ecologische als sociale vereisten.

Abbreviations

General terms

FAB	Functional agrobiodiversity
CAP	Common agricultural policy
AES	Agri-environmental schemes
ES	Ecosystem services
SES	Social-ecological system
CS	Citizen science
EU	European Union
LTSER	Long term socio-ecological research
TLT	Transformative learning theory
SNH	Semi-natural habitat
RO	Research objective
RQ	Research question

Statistical terms

pSEM	Piecewise structural equation model
IQR	Interquartile Range
Tmax	Mean of daily maximum temperatures
Tmin	Mean of daily minimum temperatures
Tmean	Mean of daily average temperatures
SMmax	Mean of daily maximum volumetric soil moisture

SMmin	Mean of daily minimum volumetric soil moisture
SMmean	Mean of daily average volumetric soil moisture
PCA	Principal component analysis
ANOVA	Analysis of variation

Chemical terms

pH	Indicator for acidity
CEC	Cation-exchange capacity
N	Nitrogen
P	Phosphorous

Chapter 1

General introduction

Agrobiodiversity loss

Biodiversity refers to the diversity of all living organisms, ranging from genetic diversity within species to landscape-scale variability in ecosystems (Feest et al. 2010). Agricultural biodiversity or agrobiodiversity refers to all biodiversity that associates with agriculture including crops and livestock planned by the farmer as well as associated biota such as weeds, herbivores or pollinators (Jackson et al. 2007). In this broad definition of agrobiodiversity, we refer to species that require agricultural environments for their survival (plant species that need disturbance, such as poppies) but also to species that survive on farmland despite agricultural practices (lapwings, bumblebees). Agrobiodiversity becomes functional (FAB – functional agrobiodiversity) when it is useful directly to humans by regulating or supporting agriculture (Jackson et al. 2012; Bianchi et al. 2013). Examples of FAB are both flora and fauna found on agricultural fields such as diverse crops, weeds, earthworms and soil microbiota. Another important part of functional agrobiodiversity is found in the landscape matrix in which agricultural field are embedded. Semi-natural habitats such as road verges, hedges and trees in between fields are important to host pollinators and predators and shape a favourable microclimate for crops (Bianchi et al. 2013; Van Vooren et al. 2017; Pardon 2018; Proesmans et al. 2019).

Since the last decades, agrobiodiversity and its functionality have declined dramatically (Kleijn et al. 2009) in many of the worlds biomes (Tscharntke et al. 2005; Jackson et al. 2012). Lower crop diversity combined with larger fields, the replacement of semi-natural habitats and increased application of synthetic fertilisers and pesticides caused losses in wild flora and fauna (Kleijn et al. 2009; Landis 2017; Le Provost et al. 2022) (Fig. 1.1).

Figure 1.1: *Evolution from a landscape in the upper left with an irregular interweaving of a grain field with grassland embedded in a variable matrix of trees and hedges, water features and unpaved roads to an intensively agricultural landscape in the lower right where fields and grasslands are larger, more uniform and rectilinear. Water features are drained and roads are straightened (Figure adopted from German National Academy of Sciences Leopoldina et al. 2020).*

While this has resulted in high productivity with unseen yields, it has come at the expense of regulating and supporting agroecosystem services based on FAB (Felipe-Lucia et al. 2022; Le Provost et al. 2022). Recent disruptive events have proven that the current farming system is neither resilient nor sustainable. Crop losses due to the increasing prevalence of drought, heat or excessive rainfall show that agricultural landscapes are susceptible to projected climate change (Altieri et al. 2015; Naumann et al. 2021). The large-scale application of fertilisers and pesticides causes excessive pressure on the rural environment (OECD 2021). Moreover, the current energy crisis is causing high prices for these agrochemicals (Eardley 2022), on which current cropping systems are highly dependent, partly because of disrupted regulatory and support agroecosystem services based on FAB (Jackson et al. 2012).

Reinforcement of agrobiodiversity in agricultural systems is urgently needed (Mupepele et al. 2021), not only for the functional purposes, but also because it is our ethical duty to do so (Minteer and Collins 2005). FAB should be considered a natural resource to cope with climate change, reduce pressure on the environment and reduce dependence on external agrochemicals such as fertilisers and crop protection (Jackson et al. 2012). Although the exchange of FAB with agrochemicals was quick and seemed right, changing back does not seem straightforward and more research is needed on how to improve the effectiveness of FAB reinforcements (Pe’er et al. 2014; Batáry et al. 2015).

Multi-actor trends in peri-urban areas

In addition to the loss of FAB due to the simplification of landscape structure and intensification of agricultural land use, diversification of land use actors occurred with respect to non-agricultural land use in rural areas under pressure from urban expansion (urbanization). The land usages introduced by these non-agricultural actors somehow diversified the landscape structure, but not by the reintroduction of original agrobiodiversity found in hedgerows or field margins or by increasing crop rotation. In densely populated areas, agricultural land was transferred to domestic gardens, recreational land uses (e.g. horse keeping), nature conservation (e.g. species-rich grassland restauration) and associated infrastructure such as roads, railways and industry zones (Bomans et al. 2010; Bomans et al. 2011; Zasada 2011; Kerselaers et al. 2013; Primdahl et al. 2013; Verhoeve et al. 2015). This is a typical feature of peri-urban areas with disorganised urban sprawl into the rural matrix (Opitz et al. 2016). Although there is no commonly agreed spatial definition for peri-urban areas (Opitz et al. 2016), these areas are defined as locations where farming competes with, and suffers from non-agricultural land uses related to nearby urban regions (Zasada 2011; Opitz et al. 2016). In Flanders, which is an example of a very densely populated region (488 inhabitants/km², Statbel 2021; Verbeek and Tempels 2016), there is a very high pressure of multiple land uses on the open space. Between 2013 and 2019, Flanders lost 5.1 ha remaining open space per day and in 2021, already 15% of Flanders was built-up with sealed surfaces (Fig. 1.2, Pisman et al. 2021).

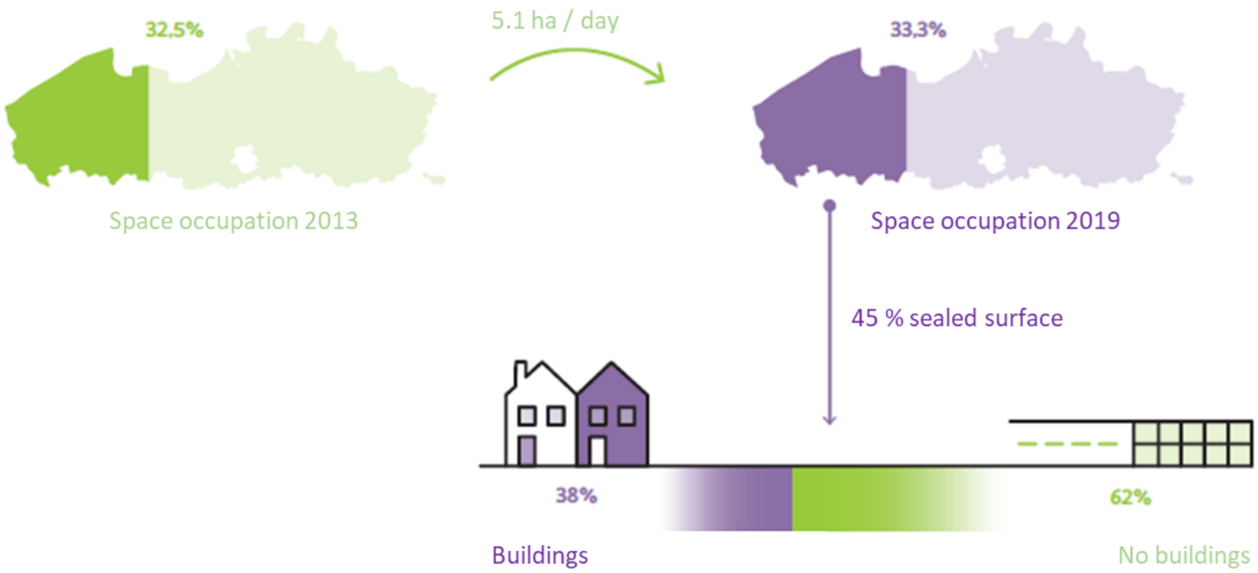

Figure 1.2: *Space occupation in 2013 compared to 2019 in Flanders. Space occupation is the space occupied through settlements: housing, commercial purposes etc. Between 2013 and 2019, 5.1ha of the open space (agriculture, nature outside settlements) was occupied per day up to 33.3% of Flanders in 2019. 45% of this occupied space is sealed surface of which 38% are buildings and 62% are other forms of sealing* (Figure adopted from Pisman et al. 2021).

A large part of non-agricultural land use in Flanders consists of houses and domestic gardens. There are 167.000 hectares of houses with domestic gardens (12.3% of Flanders) of which 56% is located outside the settlement cores along ribbon development or scattered in the rural landscape (Fig. 1.3) (Pisman et al. 2021).

Figure 1.3: *Surface occupation by houses and domestic gardens in Flanders' settlement cores, ribbons or scattered buildings* (Figure adopted from Pisman et al. 2021).

The large presence of domestic gardens and associated infrastructure such as roads and other land uses illustrates the potential relevance for FAB in peri-urban areas (Dewaelheyns et al. 2016). In addition to the effects of the predominant land use of intensively managed croplands and productive grasslands on FAB, the effects of domestic land use at the edge of rural and urban areas are increasingly recognised, but largely underexplored (Samnegård et al. 2011; Pereira-Peixoto et al. 2014). Besides the societal demand from rural residents for housing, various other actors in peri-urban landscapes have demands from the open space (Zasada 2011; Zasada et al. 2013) and could therefore also strengthen semi-natural habitats such as field margins, road verges, hedgerows, forest fragments and permanent grasslands that contain FAB. For instance, municipalities, professional or recreational horse keepers, hobbyist or semi-professional farmers (e.g. vineyards), recreational infrastructure (walking trails), health care institutions or industry zones can have opportunities to invest in FAB (Bomans et al. 2011).

While one would expect that a simplified and intensive rural area results in a simplified set of land users, this does not seem to be true in contemporary peri-urban areas. Despite the undeniable influence of these different actors on FAB, the current focus is still on reinforcement measures on farmers' fields. Rural residents, horse owners, municipalities, nature managers and many other actors in peri-urban areas can also make their contribution for FAB. Different rural actors have diverse backgrounds, interests, influences and goals and therefore may not be reached or activated in the same way to engage in FAB. It is not clear what understanding these actors have of the role they could play for FAB in their environment (Dewaelheyns et al. 2016). Clearly, communication and outreach efforts need to go beyond farmers as rural land uses in peri-urban areas. Yet, today these efforts were mainly pointed to farmers for enhancement efforts on their fields, without recognising the possible role of other land users in the environment.

The necessity of a landscape scale approach

Before we illustrated the increasing social complexity when zooming out to the landscape level in peri-urban areas. The variety of land uses that come with the increasing social complexity has ecological impacts on FAB at the landscape level and therefore the resilience of the agroecosystem. There is now ample evidence that the effectivity of local efforts to reinforce FAB depends on surrounding land uses (Tscharntke et al. 2012b; Haan et al. 2021; Meier et al. 2022). However, most of the research on relationships between biodiversity and agroecosystem services is currently done at field level (Le Provost et al. 2022). It is expected that if, for example, a flower-rich field margin is sown locally in an otherwise very monotonous and intensively farmed landscape with few other flowers, this may lead to few gains for functional invertebrates. The landscape as a whole then provides insufficient food resources and refuges for a viable population in the wider environment, and the distances between those sources of food or refuges may be too great. In contrast, if these measures are taken in locations where there are already a lot of flowers for insects, the gains for biodiversity may also be limited because the relative contribution of the flower border is dwarfed by what is already present (Tscharntke et al. 2012b; Gerits et al. 2023). This is an example of the 'intermediate landscape hypothesis', which is one of the eight hypotheses proposed in the review of Tscharntke et al (2012b, p. 662). This hypothesis points to the possibility that "the effectiveness of local conservation management is highest in structurally simple, rather than in cleared (i.e. extremely simplified) or in complex landscapes. Examples of other hypotheses are "the landscape-moderated concentration and dilution hypothesis: spatial and temporal changes in landscape composition can cause transient concentration or dilution of populations with functional consequences". Or "the landscape-moderated insurance hypothesis: landscape complexity provides spatial and temporal insurance, i.e. high resilience and stability of ecological processes in changing environments". Additional to this review on possible effects of landscape structure on plant- and arthropod mediated effects on agroecosystem functioning, there are also indications of local microclimate being impacted by the surrounding landscapes structure, yet this topic is currently largely under-explored (but see Tougeron et al. 2016; Alford et al. 2018).

The importance of the landscape level is therefore clear for both the social and ecological side of agroecosystems. Considering the ecological side, research on FAB at the landscape scale is usually done by calculating indices for landscape structure. Landscape structure encompasses both compositional and configurational heterogeneity of land uses or habitats in the landscape (Turner et al. 2006; Leitão et al. 2009; Fahrig et al. 2011). Landscape structure (often referred to as landscape complexity) is most often characterized by the relative proportion of arable land use in a given radius as proxy for agricultural land-use intensity or conversely by the share of non-agricultural habitats in the surrounding landscape as a proxy of semi-natural habitats (Chaplin-Kramer et al. 2011; Winqvist et al. 2011; Tuck et al. 2014; Schirmel et al. 2018).

However, recognising the complex social side, this might be insufficient for peri-urban areas, where zooming out to the scale of the landscape includes many non-agricultural land uses types in addition to semi-natural habitats. Domestic gardens, sealed surfaces, road verges, public parks, nature areas, forests fragments are examples of other land use types relevant for FAB in peri-urban landscapes. All these land uses involve different actors with their own interests in and influence on FAB. Working towards optimal landscape-scale land use composition for FAB-related agroecosystem services will therefore require involvement of multiple land users and some form of coordination between them (Herzon et al. 2021). To study the impact of landscape structure on FAB and related agroecosystem services such as natural pest control, pollination and microclimate regulation, a more diverse set of land uses needs to be considered than what is currently done in research. Therefore, below we illustrate how deepening and refining the concept of landscape structure can lead to better understanding of its impact on FAB-mediated agroecosystem services such as microclimate regulation, natural pest control, pollination and crop performance. We first discuss agricultural land use followed by semi-natural habitats and non-agricultural land uses. These forms of land use will be used throughout this thesis to explain variation in FAB mediated agroecosystem services and linked to local actors in peri-urban areas.

Agricultural land use

Arable land and productive grasslands remain the dominant land use in many peri-urban landscapes, despite the infiltration of many non-agricultural land uses between productive fields (Gerits et al. 2021). Together they create the agricultural land use component of peri-urban areas (Fig. 1.4). The agricultural land is furthermore divided into individual fields belonging to different farmers. These farmers often rotate different crops (potato, wheat, grassland, maize, barley, cover crops etc.) on their own fields, but do often not coordinate with neighbouring farmers who collectively define the crop diversity in the rural landscape. Existing research suggests mainly negative effects of landscapes with high shares of intensively managed arable lands on functional invertebrates because they shape an unfriendly environment due to high inputs of crop protection and fertilisers, leaving less space for non-crop habitats (Le Provost et al. 2022). In contrast to arable land, productive, temporary grasslands are not often considered separately from other types of grasslands to explain variation in local agroecosystem functioning.

Figure 1.4: *Images of both categories of agricultural land: productive temporary grassland with intensively managed and fertilised grasses for fodder production (left) and arable crops (here potato and maize) (right). Drone images provided by ILVO.*

Semi-natural habitats

Landscape-scale semi-natural habitats between agricultural fields often involve a combination of high green vegetation such as hedgerows, wood rows, lane trees, forest fragments and low green vegetation with ecological value such as permanent grasslands, field margins or road verges rich in wild flora. The way these habitats are included as explanatory variables for local agroecosystem processes or service provision varies widely. In their study, Duflot et al. (2015) stress the need to consider different semi-natural habitats separately and to separate high green habitats from low green ones. Within these low green habitats, a separation is also needed between temporary, species-poor and intensive grasslands and other permanent and species rich grasslands (Herzon et al. 2021; Le Provost et al. 2022). The former could, in terms of ecological value, resemble arable crops more than biologically valuable low green vegetation (Fig. 1.4). Yet, today the characterisation of landscape structure related to semi-natural habitats is often too general and misses important distinctions between these ecologically different habitats (Duflot et al. 2015).

The design and management of semi-natural habitats is often not the same when a functional objective is given to it or when species conservation is sought (Bianchi et al. 2013). For example, wildlife organisations may consider hedgerows for the conservation of sensitive or protected species (Vanneste et al. 2020), while other actors like farmers might want to optimise natural pest control, pollination (Dainese et al. 2017) or microclimate buffering (Alford et al. 2018) as functions in agricultural landscapes. In general, researchers agree that flower rich and extensive managed habitats provide food (nectar and pollen) and shelter for functional invertebrates (Bianchi et al. 2013). Therefore, it is relevant to separate habitats with or without ecological value when considering agroecosystem services involving arthropods, such as natural pest control, pollination, nutrient cycling, etc. On the other hand, if microclimate buffering is considered as regulatory agroecosystem service, the separation of high green vegetation from other low green semi-natural habitats seems crucial, while the ecological value considering floral resource, alternative food or shelter provisioning is less relevant.

Figure 1.5: *Images of different semi-natural habitats in the peri-urban matrix. On the left, permanent species-rich grassland managed for biodiversity conservation. Forest fragment on the right. Drone images provided by ILVO.*

Non-agricultural land uses

As we mentioned before, non-agricultural land uses such as domestic gardens, recreational land use and associated built-up areas are infiltrating the rural areas in peri-urban landscapes (Zasada 2011; Kerselaers et al. 2013; Primdahl et al. 2013). Domestic gardens or public green areas (parks) are a well-represented non-agricultural land use and can contain high green vegetation and ecologically valuable or less valuable low green vegetation (Dewaelheyns et al. 2016). Intensively managed domestic gardens often contain a shortly mown and heavily fertilised lawn with very few species and borders of alien plants, of which some are invasive (Dewaelheyns et al. 2016). Other, more naturally managed gardens contain vegetation that resembles semi-natural habitats which were once abundant in the rural landscape and with recognised value for several agroecosystem services.

Relevance of domestic gardens for agroecosystem services is shown, especially for pollination mediated by pollinating insects (Samnegård et al. 2011; Langellotto et al. 2018; Levé et al. 2019). In peri-urban areas, rural residents with domestic gardens are probably the largest group of actors, but with relatively little land and thus limited influence. Yet, Fig. 1.3 shows that 12.4% of Flanders' area is used by houses and domestic gardens of which 56% (94.752 ha or 7% of Flanders' area) lies outside settlement cores along ribbon developments or as scattered buildings (Pisman et al. 2021). This suggests that many domestic gardens are intertwined with agricultural fields and therefore Levé et al. (2019) acknowledge the cumulative importance of these land use for agroecosystem services. Additionally, in 2010 it was calculated that nearly 70.000 ha (or 5% of Flanders' area) is used for horse pastures, pointing towards a significant occupation of the open space (Bomans et al. 2011). So, there might be a largely underexplored potential for contributions of these rural actors to agroecosystem services mediated by FAB on neighbouring agricultural fields.

Figure 1.6: *Images of residential land use (domestic gardens) with associated built-up areas in between agricultural fields. Drone images provided by ILVO.*

It is clear that peri-urban landscapes contain many different land use types relevant to FAB and related agroecosystem services. The various actors who own and manage these landscapes might not be aware of their impact on FAB in the surrounding landscape. Where it is already difficult to engage farmers in FAB because of a lack of financial space or the current productive paradigm, it becomes even more complex when other actors are involved (Gerits et al. 2023). However, forms of pooling efforts for FAB is crucial for sustainable production. Research on FAB in peri-urban areas is challenging and requires an innovative approach.

A social-ecological lexicon for landscape ecology

In the foregoing we described both the social end ecological side of agroecosystem services using landscape ecological concepts such as landscape structure, complexification, simplification, diversification and so on. Because these terms are not often combined in a social-ecological framework, this can be ambiguous. For instance, diversification can on the one hand point towards the increase of crop species used in a certain area or throughout time (crop rotation). Diversification, on the other hand, could also mean the expansion of various non-agricultural land use actors in peri-urban areas. Therefore, in this section, we bring clarity on terminology used throughout this thesis.

Considering metrics for ecological landscape patterns, we refer to landscape structure which is composed of (1) landscape composition and (2) landscape configuration (Turner et al. 2006; Leitão et al. 2009; Fahrig et al. 2011). More specific, in this thesis, we focus on landscape composition which is defined as "what land use types are present and in their relative amounts, or proportions, without reference to where on the landscape they may be located" (Turner et al. 2006, p.8). With scale (or radius), in this thesis, we refer to the buffer in which the relative proportion of different land uses is defined as % area used. The landscape composition is thus defined by the relative proportions of different land uses in a certain scale (or radius). Although both landscape composition and configuration are highly relevant in peri-urban areas, we focus on composition in this thesis. We do so because the involvement of many small-scale, non-agricultural land uses (e.g. private gardens, road verges) makes the calculation of, for instance, proximity and connectivity metrics very complex compared to studies involving only agricultural land uses. Furthermore, we deliberately deviate from landscape complexity as metric for landscape patterns, which is used in many other studies, because this term can point to several very distinct processes (functions, composition, configuration, fractality in landscapes).

Considering the landscape composition, we include the relative proportion of the land use types described above:

- semi-natural habitats which we divide into high green habitats (e.g. trees) and biologically valuable low green habitats (ecologically managed road verges, extensive grasslands etc.),
- agricultural land use which we divide into arable land and productive grassland and
- residential land usage which we divide in low green vegetation that is not classified as biologically valuable and built-up areas.

The term "simplified agricultural landscape composition" points to agricultural landscapes with decreased crop types and a lower proportion of semi-natural habitats due to agricultural intensification. Landscape compositional heterogeneity is defined as the prevalence of proportions of various land uses (both agricultural and non-agricultural). As described above, with agricultural diversification we point to spatial and/or temporal crop diversification. With actor diversification we point to expansion of urban land uses into rural areas, leading to peri-urban areas.

New ways of research on functional agrobiodiversity in peri-urban landscapes

The above shows that the single-actor, single-field approach needs to be transformed into a multi-actor landscape approach to strengthen FAB (Westerink et al. 2017a). However, current policies aimed at strengthening agrobiodiversity and supporting agroecosystem services still focus on promoting actions taken by individual actors (mainly farmers) on individual plots (Tscharntke et al. 2012a; Landis 2017). The regional translation of the Common Agricultural Policy (CAP) to Flanders provides a wide range of voluntary actions that farmers can take on their fields to promote agrobiodiversity (Gerits et al. 2023). In addition, conditionalities for farming practices attempt to reclaim a place for agrobiodiversity in agricultural landscapes. The shortcomings of these policies are discussed further in the second chapter of this thesis and in the recently published book chapter by Gerits et al (2023). Although highly necessary, taking the scale of the landscape into account has implications. Peri-urban actors demand many different services from their environment and may not be aware of their role in the landscape to support their land-use choices. Food production has an important role in peri-urban areas (Opitz et al. 2016) so the landscape composition with associated FAB should support multiple crops. A landscape approach is thus complex and the issue of strengthening FAB for multiple agroecosystem services becomes challenging.

A recent example of progressive landscape scale research is provided by Le Provost et al. (2022), who assessed the impact of biodiversity at both local and landscape scales on no less than 16 ecosystem services in grassland agroecosystems. Moreover, they identified several local grassland actors: local residents, conservation organisations, agriculture and tourism. Yet, they only assessed the demand side of the social system and not what these actors themselves could contribute to the landscape as a whole by adjusting their land use. Including the supply side of the social system in an interdisciplinary approach could open up opportunities for FAB. More specifically, a holistic systems approach can link the ecological to the social subsystems in peri-urban areas. This is also advocated by Wanger et al. (2020) and Herzon et al. (2021) who state that recognising the social-ecological complexity inherent to multi-stakeholder, multiscale processes could support biodiversity conservation and agroecosystem services. A social-ecological lens has been proposed to improve

FAB management in rural landscapes (Jackson et al. 2012; Lescourret et al. 2015). Additionally, Lescourret et al (2015, p. 73) mention the need for participatory approaches that “make it possible to share, visualise and use for diagnostic and prospective studies, both the perceptions of the various stakeholders and the available scientific ecological knowledge, to foster synergy between ecosystem functioning and social dynamics”.

It is recognised that participatory strategies are important to understand and take into account the values, perspectives, knowledge and culture of different groups of actors, which is key to joint management of landscapes as socio-ecological networks (Villamor et al. 2014; Westerink et al. 2017b; Westerink et al. 2017a). Citizen science could be a promising method to serve as such a participatory approach. Citizen science makes it possible to work with local actors to collect data on local land use and FAB-mediated agroecosystem services, thus uniting the social and ecological components of the agroecosystem. Furthermore, experience of participants could induce transformative change towards pro-environmental behaviour (Bela et al. 2016). Through an immersive and collaborative citizen science approach, participants could gain instrumental, practical knowledge and learn about agroecosystem services or gain communicative insights in their role in FAB enhancement of that of other land users in their surroundings (Bela et al. 2016; Veeckman et al. 2019). Yet transformative learning outcomes of citizen science projects stays under evaluated and it is not known how to adjust the design of participatory and citizen science approaches for facilitating pro-environmental behaviour (Bela et al. 2016; Phillips et al. 2018; Peter et al. 2021).

Above, we highlighted the importance of enhancing FAB for multiple agroecosystem services to make agroecosystems more sustainable. Yet this is a challenge, especially in densely populated areas where multiple groups of actors benefit from agroecosystem services and may decide whether or not to invest in FAB. First, we need to know how different peri-urban land uses at different scales affected agroecosystem services demanded by multiple crops. Second, we need to know which actors are involved and how they see agroecosystems and can be motivated to enhance FAB on their property. This requires an interdisciplinary approach to unite social and ecological disciplines. We conclude this general introduction by stating the lack of both ecological data and social data, coupled to the possibility to create a learning network which might be addressed by a citizen science approach. For this complex issue we conducted four year of research using an innovative approach with the following research objectives.

Research objectives and outline of this thesis

The **overall objective** of this thesis is to understand how FAB at the landscape scale supports multiple agroecosystem services for multiple crops, with multiple actors. The **overarching assumption** is that zooming out to the landscape scale provides new insights on how FAB associated with peri-urban land use relates to agroecosystem functioning and service provision. Moreover, when we look at the landscape scale in peri-urban areas, multiple actors with different interests and motives appear to be involved in FAB. We divide the general objective into **five specific research objectives** that will be addressed in the next five chapters of this thesis (Fig. 1.7).

As a first specific objective, we want to describe FAB as a natural resource within multi-actor peri-urban areas in an understandable way using an interdisciplinary method. Therefore, in **Chapter 2**, we develop a social-ecological framework linking the agroecosystem and its actors with FAB as a central resource. Furthermore, we develop an interdisciplinary measurement tool that we apply in this framework in the other chapters of this thesis. Specifically, 1m²-gardens fulfil a dual role as a measurement point to investigate the effects of FAB at the landscape scale and engage local actors by experimenting with their garden. We apply the 1m²-garden toolbox for three years in two regions in Flanders (Belgium) using an immersive citizen science approach.

As a second specific objective, we want to investigate how land use composition at different scales affects a range of agroecosystem services relevant to multiple crops. Therefore, in **Chapter 3**, in 2018 and 2019, a first experiment with 41 m² gardens was carried out along a gradient of landscape composition in a typical peri-urban area in the province of East Flanders, Belgium. The hypothesis was that in an environment with merely cropland and productive grasslands, a less suitable microclimate and less functional arthropods would lead to reduced agroecosystem processes related to microclimate buffering, pollination, natural pest control and services related to crop performance. A greater proportion of semi-natural habitats such as high green vegetation and roadside verges in the landscape could improve microclimate regulation, natural pest control, pollination and related crop performance services. Infiltration of non-agricultural land uses (such as residential gardens) and its associated buildings in the rural matrix could also improve or worsen the functioning of the agroecosystem.

As a third specific objective, we want to investigate the generality of the relationships between land use composition and agroecosystem services when comparing peri-urban areas in different ecoregions and weather conditions. To verify whether the relationships from Chapter 3 hold in an independent peri-urban area in Flanders, we repeat the 1m²-garden experiment in the province of

Antwerp in **Chapter 4.** The growing seasons in 2018 and 2019 (Chapter 3) were extremely dry and hot, while the summer conditions for replication in 2021 were the wettest since measurements began. This allowed the hypotheses to be tested whether the found relationships between landscape composition and agroecosystem indicators hold in peri-urban areas experiencing similar pressures from multiple actors on the agroecosystem, despite differences in weather conditions and ecoregions.

As a fourth specific objective, we want to explore the suitability of our immersive citizen science approach to reach different rural land users and encourage engagement in FAB as a possible first step towards collaborative governance. Therefore, in **Chapter 5**, we use qualitative data from a post-project questionnaire from both cases to assess whether our immersive citizen science project contributes to learning and pro-environmental behaviour. In addition, we want to examine which peri-urban actors we reach with the 1m²-garden project and whether profiles and backgrounds of participants determine their learning trajectories. For this, we will use transformative learning theory as an analytical framework and investigate whether individual learning can act as a stepping stone to pro-environmental behaviour for FAB as a natural resource. The hypotheses are that 1m²-gardens as a tactile learning tool in an immersive setting lead to individual learning. We further hypothesise that prior knowledge, frequent (informal) interactions and experimentation of participants influence their individual learning trajectories.

As a fifth specific objective, we want to combine the findings related to the previous objectives into practical social-ecological guidelines relevant to peri-urban areas. Therefore, in chapter 6 of this thesis, we combine the findings from all previous research chapters and discuss their relevance by analysing a spatially explicit example case. Using our social-ecological framework (Chapter 2), we project both our ecological (Chapters 3, 4) and social findings (Chapter 5) to the most agricultural measurement site in this thesis. We then zoom out from our two case studies and compare them to other agricultural areas in Flanders. In the last chapter of our thesis **(Chapter 7)** we reflect on our approach, look beyond the set of agroecosystem services in this thesis and explore pathways to combine individual learning trajectories into collaborative FAB management. Finally, we draw on our socio-ecological framework (Chapter 2) to highlight new knowledge gaps and outline avenues for future research.

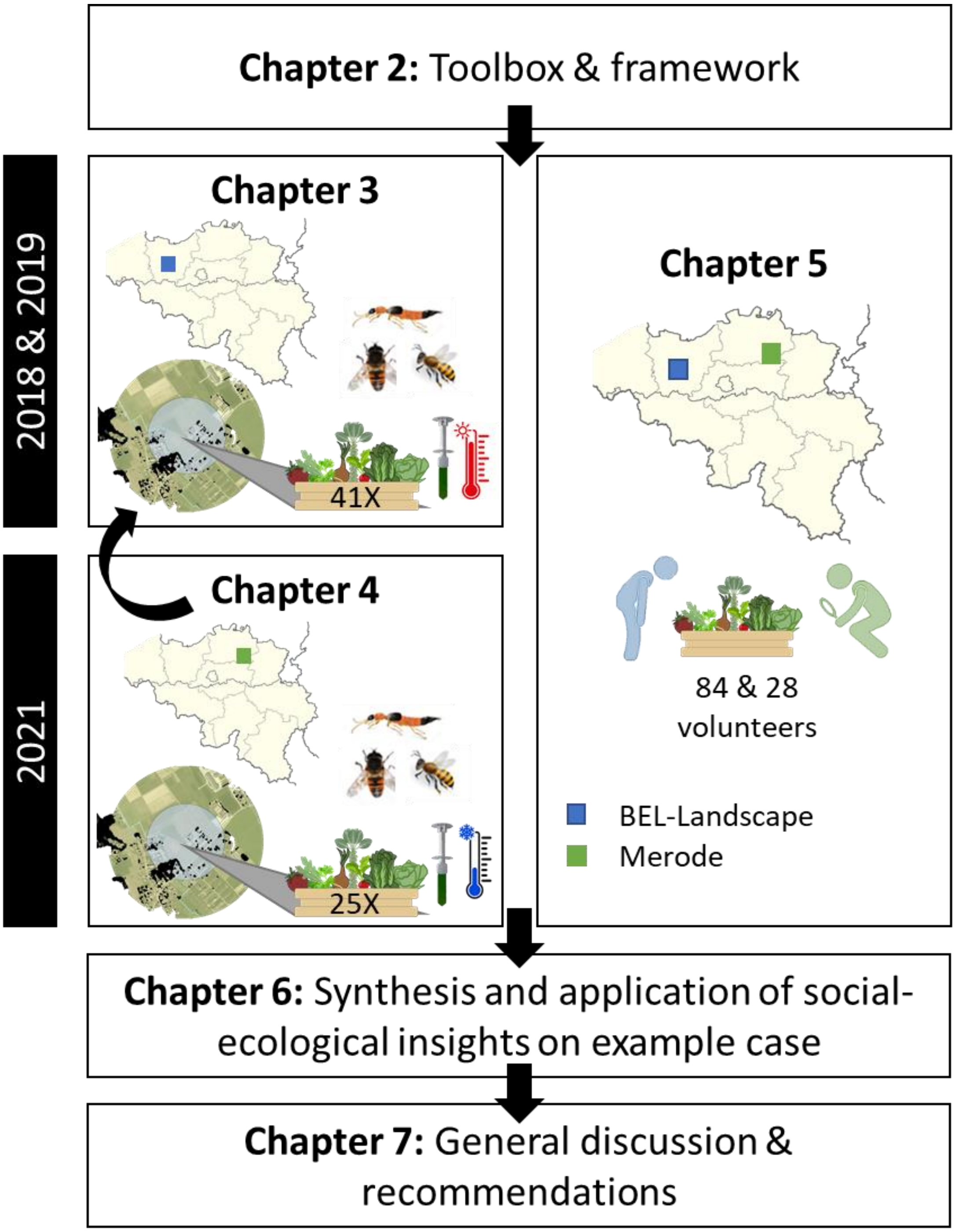

Figure 1.7*: Schematic overview of this thesis.* ***Chapter 2:*** *social-ecological framework and toolbox with 1m²-gardens.* ***Chapter 3:*** *ecological data from 2018 and 2019 of first case study BEL-Landscape.* ***Chapter 4:*** *ecological data from 2021 of replication experiment in second case study Merode.* ***Chapter 5:*** *presenting qualitative data on learning process and outcomes towards pro-environmental behaviour during citizen science projects in both cases.* ***Chapter 6:*** *synthesis of social-ecological insights and application to a specific example case.* ***Chapter 7:*** *general discussion on future pathways for peri-urban landscapes and the 1m²-garden citizen science toolbox.*

Chapter 2

A social–ecological framework and toolbox to help strengthening functional agrobiodiversity-supported ecosystem services at the landscape scale

Adapted from: Gerits, F., L. Messely, B. Reubens, and K. Verheyen. 2021. A social–ecological framework and toolbox to help strengthening functional agrobiodiversity-supported ecosystem services at the landscape scale. Ambio 50: 360–374.

Frederik Gerits designed the social-ecological framework and methodology of the 1m²-gardens together with Lies Messely, Bert Reubens and Kris Verheyen. The BEL-Landscape experiment was initiated by Frederik Gerits with the help of the co-authors. Frederik Gerits drafted and submitted the manuscript after several revisions by the co-authors.

Abstract

Functional agrobiodiversity (FAB) has severely declined during the last decades. Current efforts to reinforce FAB are mainly focused on single-actor, parcel-based measures, whereas multi-actor landscape approaches are supposed to be more effective. In this chapter, we propose a social-ecological framework that structures how different land users at both the parcel and landscape level interact with FAB as a natural resource. Furthermore, we introduce 1m²-gardens as an interactive multipurpose measurement tool to gather data on agroecosystem services in collaboration with land users. The presented citizen science approach can provide new insights in how different land users learn about FAB and how experimenting can result in a higher motivation to invest in FAB. Using a case study in Flanders, we illustrate the 1m²-garden concept and highlight its strengths and necessary considerations to properly complement other research approaches in this social-ecological system.

Introduction

Since the second half of the 20th century, biodiversity loss has been particularly high in rural areas (Kleijn and Sutherland 2003; Kleijn et al. 2009), where intensification of agricultural practices has led to environmental degradation, habitat loss and habitat fragmentation (Tscharntke et al. 2005; Concepción et al. 2012; Jonsson et al. 2015; Schulte et al. 2017).

More and more it is recognized that the loss of biodiversity has important consequences, as it is known to play a key-role in the functioning of ecosystems (Cardinale et al., 2012; Duffy et al., 2017). All biodiversity influences ecosystem functioning, but here we specifically focus on the so-called functional agrobiodiversity (FAB), i.e. the biodiversity that directly supports agroecosystem services (ES), such as pollination, pest control, and nutrient cycling (Wäckers et al. 2019). To meet their needs for feeding and shelter, FAB organisms such as bees, hoverflies, carabid beetles, depend on favourable conditions in FAB habitats such as cover crops and semi-natural habitats. The latter are defined as extensively managed, permanent features of the agricultural landscape such as hedgerows, field margins or small forest patches. Due to intensification at the landscape scale (e.g. landscape simplification) and locally at the parcel level (e.g. increased use of agro-chemicals), semi-natural habitats including FAB habitats and organisms have disappeared with consequences for the provision of ES (Tscharntke et al. 2005; Emmerson et al. 2016).

Different European policy instruments aim at halting further farmland biodiversity loss and at restoring FAB, including the EU Biodiversity Strategy and the Common Agricultural Policy (CAP), through which agri-environment schemes (AES) have been implemented since 1985 (Kleijn and Sutherland 2003; Batáry et al. 2015). However, the effectivity and efficiency of AES for biodiversity conservation is highly variable (e.g. Kleijn and Sutherland 2003; Tscharntke et al. 2005; Marshall et al. 2006; Batáry et al. 2015). In terms of biodiversity impact, conclusions from these studies are that in general, AES have a rather modest positive effect on species richness or abundance (Kleijn and Sutherland 2003; Batáry et al. 2015). An important remark is that these studies often concern local, plot-based agri-environmental measures (e.g. flower strips as field borders). Yet, it has been confirmed that the effect size of parcel-based biodiversity reinforcement depends on the biodiversity level already in place in the surrounding landscape (Batáry et al. 2011; Scheper et al. 2013; Batáry et al. 2015). Also, many studies are limited to AES' effects on biodiversity for conservation rather than FAB as a basis for provisioning of different ES (Batáry et al. 2015).

Today, research focus has shifted more towards the effects of agrobiodiversity reinforcement (whether or not via AES) on both biodiversity conservation and the delivery of ES via FAB (Scheper et al. 2013; Batáry et al. 2015). Many experts further criticize the implementation of parcel-focused measures to enhance FAB-supported ES without considering the broader ecological landscape context (Tscharntke et al. 2005; Batáry et al. 2011; Concepción et al. 2012; Gonthier et al. 2014). Indeed, several important FAB-supported ES (e.g. pollination, pest control etc.) depend on the FAB condition already present in the surrounding landscape, such as semi-natural habitats that shape beneficial microclimates and provide suitable habitat and food source for FAB-organisms (Chaplin-Kramer et al. 2011; Winqvist et al. 2012; Kleijn 2013; Jonsson et al. 2015; Schirmel et al. 2018). Nevertheless, current measures to restore FAB are still implemented at the parcel scale, despite several authors stating that these parcel-based policies are likely to be ineffective and cost-inefficient (Tscharntke et al. 2005; Lefebvre et al. 2015; Landis 2017).

When FAB-reinforcement is to be lifted up to the landscape level, we automatically come across a broad diversity of land users with various interests and roles in rural areas. This is particularly the case in densely populated and heavily urbanized regions (peri-urban regions) where more claims of diverse land uses on the open space also result in a higher pressure on and a higher fragmentation of agricultural plots (Kerselaers et al. 2013). In Flanders (northern Belgium), for example, the average productive parcel size is small (1.40 ha)(ALV 2018) and land properties are fragmented resulting in a mosaic in land use and land users. Common examples of other land uses besides agricultural production functions, are residential functions, recreational or horse keeping, business parks and nature conservation (Verhoeve et al. 2015). Within each of these actor groups, the interests and priorities for land use are also divergent. Other regions both inside and outside Europe encounter a similar evolution where substantial parts of rural areas are used by a range of different land users not always directly related to farming activities. All these actors can have an impact on FAB and, hence, need to be considered when aiming at FAB reinforcement at the landscape scale (Primdahl et al. 2013; Zasada et al. 2013; Lefebvre et al. 2015; Lescourret et al. 2015; Landis 2017; Westerink et al. 2017a; Barnaud et al. 2018).

Considering the diverse social situation on the countryside (Kerselaers et al. 2013; Primdahl et al. 2013; Verhoeve et al. 2015), it seems inefficient to optimize FAB at the landscape scale for only a single function and one actor group (Zasada et al. 2013). Both the delivery and the utilisation of ES are related to different rural actors. This advocates for coordinated, multi-actor FAB-efforts at the landscape scale. It was only since the previous CAP reform that AES compensation payments were allowed to groups of farmers, or groups of farmers and other land-managers (Westerink et al., 2017; Regulation (EU) No 1305/2013, article 28, sub-clause 2). Up to date however, efforts for FAB are rarely coordinated among different land users to support ES at the landscape scale (Lefebvre et al. 2015; Lescourret et al. 2015; Prager 2015; Emmerson et al. 2016; Barnaud et al. 2018).

The meta-analysis of Newig & Fritsch (2009) points out that environmental preferences of involved land users determine the environmental results of decision making. Therefore, coordinated multi-actor FAB-efforts need investigation of barriers and levers of individual land users to start collaborations. It is consequently important to start from an analysis on land users' positions, interests and needs concerning FAB since these will influence their decision making (Renn 2006; Jackson et al. 2012). Current studies mainly focus on farmers' financial and social incentives to participate voluntarily in AES (Lastra-Bravo et al. 2015; van Dijk et al. 2016), without an evaluation of farmers' environmental concerns. As an answer to the narrow focus of FAB-reinforcement on parcel or farm level, opportunities are recently being investigated for cooperation for FAB-reinforcement between land users at the landscape level (Prager 2015; Westerink et al. 2017a). However, these studies generally only consider farmer-farmer collaborations and do not include other land users. Considering the complex multi-actor trend in peri-urban areas, inclusion of non-farmer actors into the discussion could facilitate landscape level governance of FAB resources (Newig and Fritsch 2009).

In this chapter we aim to deliver a first step in developing new perspectives on how FAB can be reinforced more effectively to support multiple ES. We involve various land users to explore opportunities for coordination of efforts at the landscape scale, using both ecological and social knowledge. We first propose a social-ecological framework with FAB as central resource. Next, a landscape observatory toolbox is presented with a citizen science measurement tool to perform transdisciplinary research within the social-ecological system, illustrated by a case study in Flanders. We conclude with a reflection on strengths and considerations of the approach.

FAB in a social-ecological system

For effective reinforcement of FAB as natural resource, a more general adoption and understanding of its resource value is needed by different land users at different scales (Bianchi et al. 2013; Lescourret et al. 2015; Landis 2017). This requires knowledge on ecosystem functioning being translated towards multiple actors on the countryside. Such processes can be facilitated by a framework that combines parcel and landscape scales in an integrated social-ecological system (Lescourret et al. 2015; Barnaud et al. 2018).

Inspired by Ostrom's (2009) framework for social-ecological systems, we define our focal resource (FAB) on the interface between the ecological and social subsystem (Fig. 2.1). FAB bridges both subsystems because the functional, ecological component of agrobiodiversity serves human needs and consequently relates closely to the social subsystem. Land users who influence FAB and (or) draw from it via ES can decide to invest in FAB individually or collectively at the parcel or landscape scale. Similar feedback loops from beneficiaries of ES are described in comparable conceptual frameworks (Lescourret et al. 2015; Opdam et al. 2015; Maes et al. 2016). While many studies confirm that FAB reinforcement for multiple ES requires a multilevel approach (Lefebvre et al. 2015; Emmerson et al. 2016), existing social-ecological systems concerning biodiversity do not clearly distinguish between landscape or local levels (Lescourret et al. 2015; Opdam et al. 2015; Maes et al. 2016). Our proposed framework considers both levels equally in both subsystems. Later in this chapter, the framework will become more concrete after application of the citizen science toolbox (Fig. 2.6). In the following three chapters of this PhD, both subsystems will be analysed in depth.

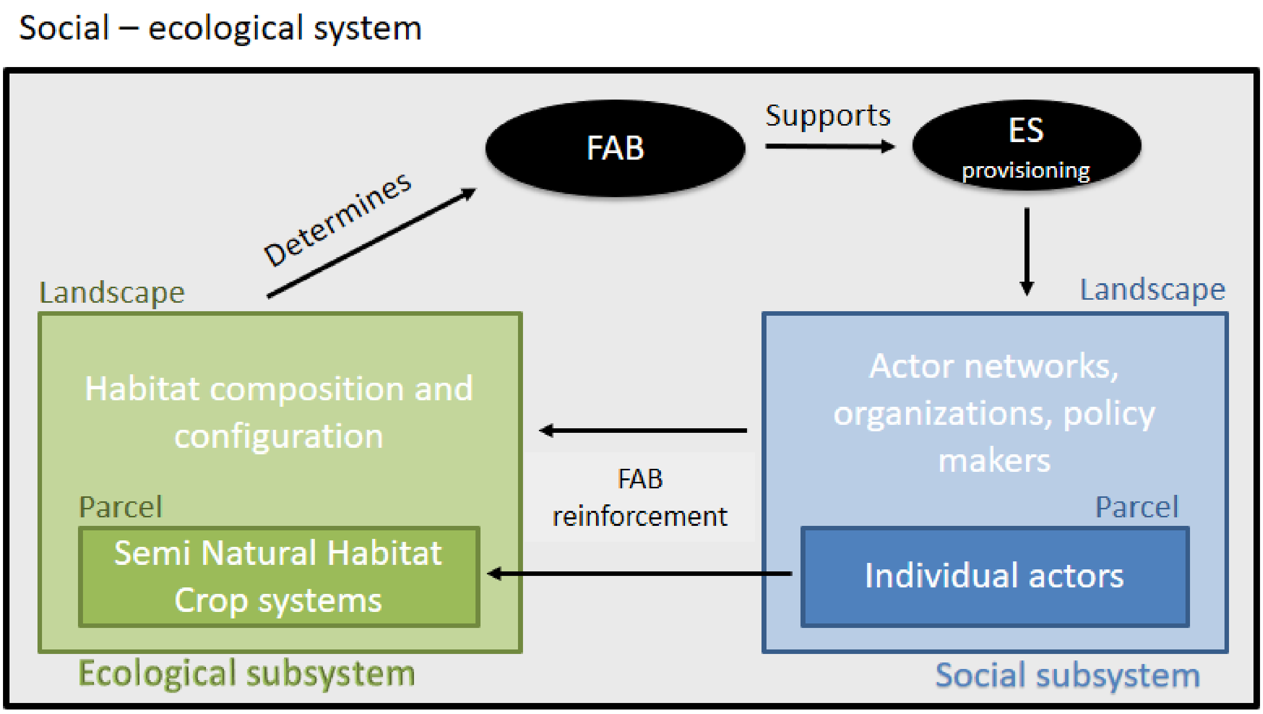

Figure 2.1: *Functional agrobiodiversity (FAB) situated on the ecological – social interface. FAB habitat and organisms present in semi natural habitats and crop systems at the parcel and landscape scale determine the functional agrobiodiversity (FAB) as a natural resource. FAB in its turn supports multiple ecosystem services (ES) to rural actors both at the landscape and parcel scale. Actors close the feedback loop when they decide to invest (or not to invest) in FAB-reinforcement via measures they take individually at the parcel scale or collectively at the landscape scale.*

After proposing their social-ecological framework, Lescourret et al. (2015) conclude that the research community "must design new stakeholder organisations for coordinated management planning and build practical instruments for use in participatory approaches by these groups" (p. 73). Barnaud et al. (2018) also mention the necessity of actionable social-ecological frameworks and propose companion modeling as practical tool in an action research context.

With our framework we provide a structure to link land users at two relevant levels to concrete landscape elements that shape FAB. Furthermore, in the next section, we present a toolbox to perform transdisciplinary research in this social-ecological framework illustrated with a case study in Flanders.

A landscape observatory with 1m²-gardens as social-ecological measurement tool

To empirically gather data on FAB as natural resource in a social-ecological framework, we present a landscape observatory approach. Although there is no strict definition (van Herwaarden et al. 2017), the European Landscape Convention defines a landscape observatory as an approach to study and monitor the dynamics of landscapes, and to facilitate the collection, production and exchange of information and study protocols between states and local communities (Recommendation CM/Rec(2008)3). A landscape observatory is suitable to study social-ecological systems because it is able to produce data on both the social and ecological subsystem and their interactions. Landscape observatories furthermore facilitate citizen participation, which is crucial according to van Herwaarden et al. (2017, p. 6): "if the landscape that we have inherited is to be adequately managed and protected for the future, it is essential that all citizens have a clear understanding of what has made the landscape". They can serve as Long-Term Socio-Ecologic Research (LTSER) infrastructure which brings in time as important factor to grasp the long term dynamics of landscapes (Angelstam et al. 2019).

To suit the transdisciplinary purpose, the proposed landscape observatory consists of a network of locations within a study landscape where systematic measurements and observations are conducted in collaboration with local land users. Science-based positioning of the network of locations allows to test the landscape dynamics of interest. In the case of FAB-supported ES, observation points need to (1) detect, in a standardised way, the provisioning of multiple ES supported by FAB present in the surrounding landscape and (2) trigger interests and engagement of land users to be involved in measurements. For that purpose we designed '1m²-gardens', which are standardised measurement tools for multiple FAB-supported ES. The gardens are each one square metre in size and are planted with a fixed set of crops of different plant families. Crop species' selection can be based on several criteria, including sensitivity to different groups of pests, diseases and dependency on pollination (Fig. 2.2). The exact set-up of the crops in the 1m²-gardens allows a focus on specific ecosystem processes of interest and measure, for instance, arthropod activity signs (plant herbivory, prevalence in traps, observations), observed services (natural pest control, pollination etc.) and the overall ecosystem performance (yield). An overview of possible indicators for ES assessment is given in Table 2.1. As described by Potschin and Haines-Young (2011) the distinction is made between "final services that contribute to people's well-being and the intermediate ecosystem structures and functions that give rise to them" (p. 578). Although the crop composition can be adjusted to answer specific research questions, it is essential that the 1m²-gardens are completely identical to allow relative differences between ES indicators in the gardens to be attributed to differences in the surrounding landscape. The growing medium and crops need to be as identical as possible, the orientation and planting methods standardised. Standardisation of plant material, growing media etc. enables a reliable relative comparison between different observation points. This implies that the only varying factor is the surrounding landscape structure in which the 1m²-gardens are embedded, so that the latter can be used as the principal explanatory variable for the FAB-supported ES measured in the 1m²-gardens. An important remark is that, due to their small size, the 1m²-gardens are not meant to provide an absolute figure of ES provision at specific locations, but enable a relative comparison of ES processes between different locations.

To provide sufficient statistical power, the number of 1m²-gardens needs to be in line with the selected landscape parameters to be tested as explanatory variables (Pasher et al. 2013). 1m²-gardens can, for instance, be installed in contrasting landscape compositions (open arable fields, adjacent to forest edges, hedgerows etc.) with sufficient replications per composition (Pasher et al. 2013). Another possibility is to install the 1m²-gardens along a landscape gradient, where a defined set of landscape structure variables is gradually changing between measurement locations (Dainese et al. 2017; Herbst et al. 2017; Hass et al. 2019).

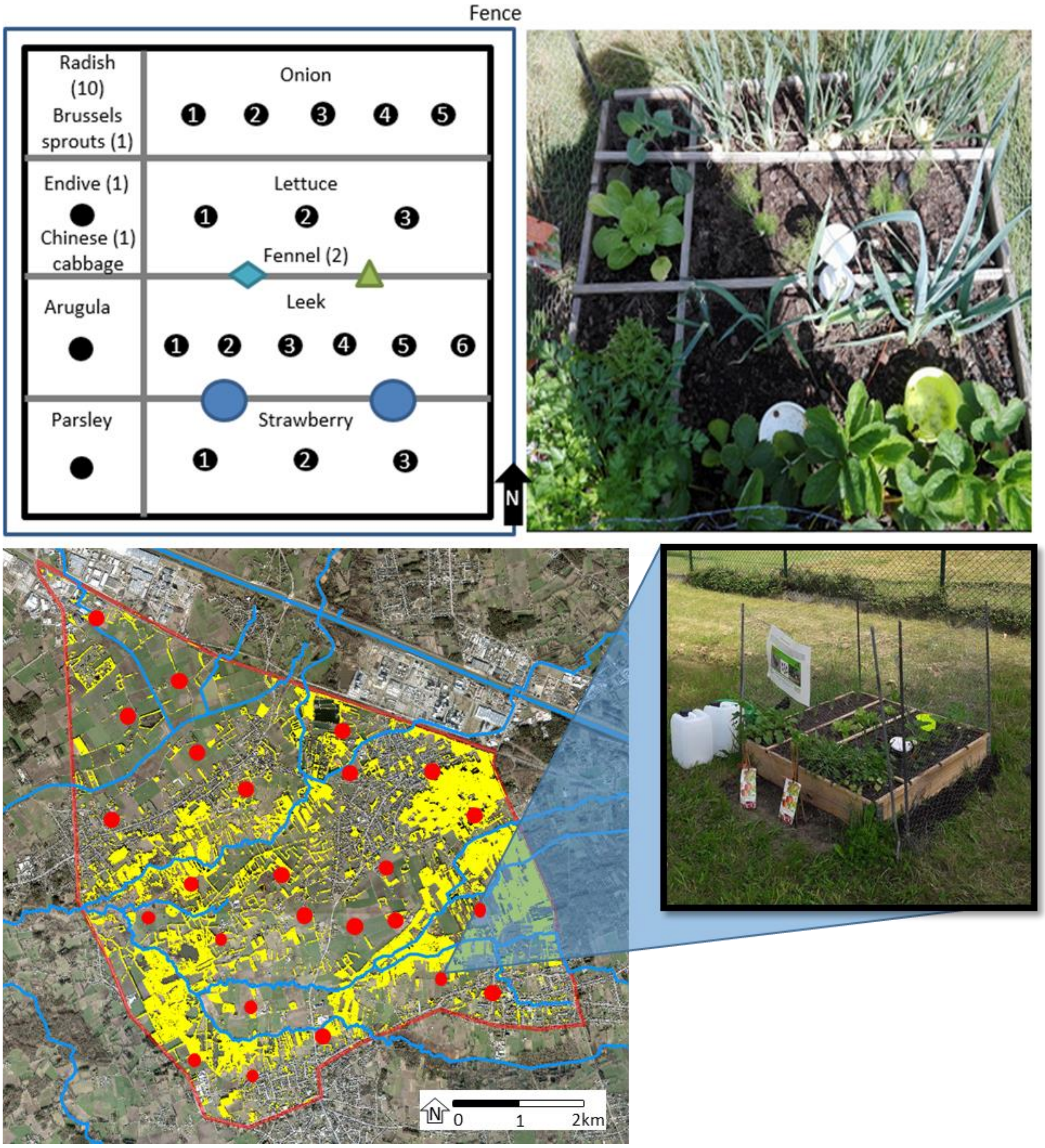

Figure 2.2: *Above:* *1m²-garden design. Blue diamond: sensor for soil moisture and temperature. Green triangle: soil temperature sensor. Blue circles: (1) fluorescent yellow pan trap for flying arthropods (2) pitfall trap to catch soil dwelling arthropods. Brussels sprouts, Chinese cabbage and fennel are planted after early harvest of radishes, endive and lettuce.* *Below:* *hypothetical distribution of 1m²-gardens (red dots) in different landscape compositions within a study landscape (red line). The yellow pixels represent forests, tree rows and other high green vegetation higher than 3 metre. The blue lines represent water streams. The red dots in this example are 1m²-gardens located in conditions with a different relative proportion of high green vegetation in the surroundings.*

Table 2.1: *Overview of possible indicators for supporting agroecosystem services, disservices and final agroecosystem service provisioning. More details and relevant literature on the methodologies and protocols is given in the appendices (Table A1).*

		Microclimate regulation	Nutrient cycling	Natural pest control		Pollination	Primary production
Supporting services	Indicators	Temperature, soil moisture	Activity-density of ground dwelling or soil detritivores	Activity-density of ground or plant dwelling carnivores	Pest species prevalence and diversity	Activity-density of pollinators	Plant growth
	Method	Climate data loggers	Pitfall traps, soil sampling, litter sampling	Pitfall traps, plant tilling	Pest species detection, plant tilling	Pan traps, netting, flower visits, hives	Field estimation biomass
Final service provisioning	Indicator	Microclimate buffering	Plant available nutrients, comminution rates	Pest suppression	Plant herbivory (disservice)	Fruit success	Harvest
	Method	Tmax, Tmin, Tmean, Growing Degree Hours	Mineral nitrogen, phosphorus, litter bags	Parasitized / predated pest individuals	Estimation plant herbivory	Fruit quality, seed set	Edible biomass weight

Besides the requirements for monitoring ES, the 1m²-gardens also have to trigger interests and engagement of land users to be involved. Therefore, 1m²-gardens are designed to closely involve non-researchers (citizens) in the monitoring, which is a specific target in landscape observatories (van Herwaarden et al. 2017) and long term social-ecological research (Angelstam et al. 2019). In that way, the landscape observatory approach is an example of action research, because it “seeks to bring together actions and reflections, theory and practice, academic and local knowledge via active participation” (p. 478) (Reason and Bradbury 2001). In the landscape observatory, involved land users can demonstrate their knowledge and learn from other volunteers and researchers. FAB, ES and landscape contexts can be visualised in the field, making these difficult concepts more tangible. This facilitates the confrontation of the social and the ecological subsystem, because social entities act and react on elements of the ecological subsystem they encounter. The close involvement of land users (residents, farmers, nature conservationists etc.) in gathering and interpreting data will allow to explore and map FAB-stakeholders bottom-up and stimulate reflection on the roles they (can or wish to) play in reinforcing FAB at the landscape level (Fig. 2.1). This social interaction makes the action research approach a robust qualitative research process with opportunities for improving the current situation of FAB in the landscape (Reason and Bradbury 2001). Via participation of land users, opportunities can be explored for direct individual or collaborative implementation of FAB measures. For instance, if involved land users experience the positive effects of hedgerows on the microclimate or arthropod prevalence in their 1m²-garden, they might want to invest in local FAB measures themselves, whether or not in collaboration with others. It is therefore key that land users can compare results from their own observations to other locations with other landscape compositions. This can be organised by the research team via guided tours, sharing the location of all 1m²-gardens and frequent visual communication of results from sites in contrasting locations.

Data collection in the 1m²-gardens builds upon a citizen science approach**,** which has become a prominent method in environmental research topics (Dickinson et al. 2012). A citizen science approach particularly suits our purposes because: (1) It enables monitoring in a substantial number of 1m²-gardens (multi-site) across the whole study landscape (Pocock et al. 2014); (2) It opens up possibilities to study private lands (Dickinson et al. 2012); (3) It allows personal contact with citizens on their motivation, interest and needs; (4) It allows to make difficult concepts such as FAB and ES tangible for citizens. Local land users volunteer to grow the crops and maintain the 1m²-gardens. While some tasks are performed by the participants (watering, weeding, reporting pests, harvesting), other tasks, i.e. those that require more standardisation, are performed by the research team (identifying pests, estimating the degree of damage, etc.). To assure standardised data and minimize the chance of drop-out, a variety of contingency measures are taken for the participant selection, communication, distribution of information and the follow-up of the data (Dickinson et al. 2012; Pocock et al. 2014). A table on contingency measures for the citizen science approach can be consulted in the appendices (Table A2).

In addition to the pool of directly involved participants, other land users can be involved to map the stakeholders with an influence on, or who are influenced by FAB in the rural landscape. Semi-structured interviews with the participants but also with local authorities, different government parties, regional NGOs, nature organizations, farmers, horse keepers etc. are conducted in this perspective (Creswell 2009). After a clear image is shaped of these FAB-stakeholders, social theories can be constructed on how knowledge, opinions, positions and needs of these different land users influence their decision making on actions for FAB (Fig. 2.1). Data sources are interviews together with emails and spontaneous conversations with participants and other land users. The latter are inherent to action research and often unfairly ignored because these informal interactions give important knowledge on true perspectives (Moon et al. 2019).

The participatory process of the 1m²-garden approach consists of a start and training phase, followed by monitoring seasons and post-project phases (Fig. 2.3). In the start phase, a broad group of land users including policy makers and press is involved to create support and interest in the project and select engaged volunteers. The latter are prepared in a training phase. During the field season, the research team weekly communicates news and guidelines for monitoring to the volunteers. Individual observations in the 1m²-gardens are frequently discussed personally in the field or via email with the principal researcher. In the weekly newsletter a compilation of results is distributed among volunteers to facilitate discussions and comparison between individual 1m²-gardens (Fig. 2.3). Focus groups and information shared on social media facilitate peer-to-peer learning between participants. In the end, frequent contacts with local FAB-stakeholders allow to guide land users with ambitions towards real actions for FAB. Researchers, or local organisations with experience in coordinating landscape processes can observe this process and identify levers and barriers that FAB-stakeholders encounter. In the short term after each growing season a collective interpretation is organised to translate the first results in conclusions and practical implications for the participants. In the long term we tend to stimulate the volunteering community and other involved land users to keep observing effects of FAB in their environment. The research team can assemble data on perspectives and motivations of stakeholders in all research phases.

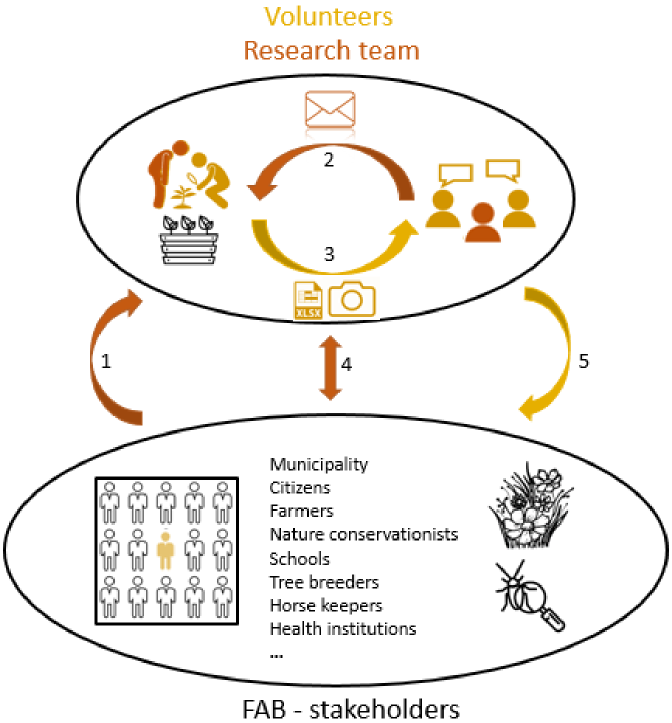

Figure 2.3: *Yellow = volunteer, brown = research team. 1: Volunteer selection from different types of land users and training phase. 2: Weekly newsletter with guidelines and information to volunteers. 3: Weekly monitoring in the individual 1m²-gardens. Observations and experiences are discussed with the research team and among volunteers after which a new newsletter is compiled. 4: information from the 1m²-gardens and participatory trajectory is used in conversations with other land users and policy makers in the landscape observatory to explore and stimulate individual or collective actions that benefit FAB. 5: Ambassadorship of volunteers towards the wider group land use actors to perform monitoring and reinforce FAB.*

The ‘BEL-Landscape’- case in Flanders (northern Belgium)

In this section we aim to make the abovementioned social-ecological framework and toolbox with 1m²-gardens more tangible, by presenting a concrete application of this approach that has been tested and operationalised in Flanders since 2018. The case study demonstrates how the proposed approach can be used in practice, and is further referred to as ‘BEL-Landscape’ (see www.bel-landschap.be). In what follows we give a first description of the BEL-Landscape case, which is needed to facilitate discussion about the 1m²-garden toolbox in the final part of this chapter. A more in-depth description of the applied methodology and statistical analysis, together with results, will be presented in the third chapter of this thesis.

The study area covers 29 km² and 51% of the area is used for agriculture with grassland (41%), maize (29%), cereals (12%) and potatoes (8%) as major cultivation types (ALV 2018). Other land use types are (1) forests and other tree-based elements (19%, ‘high green’ or vegetation higher than 3 m), (2) road verges, natural grasslands, gardens (16%, ‘low green’ or vegetation lower than 3 m) and (3) built up surfaces (14%).

Two other criteria for the landscape selection were considered to assure the representativeness for peri-urban Flanders as a whole (Fig. 2.4), i.e. (1) presence of fragments of high value nature (forest patches, semi-natural grasslands, small streams; partly incorporated in the European Natura 2000 network) of which the relative proportion is variable across the research landscape, providing different landscape compositions and a gradient in FAB. (2) Presence of a wide range of different land users (horse keepers, residents, farmers, nature conservationists, companies etc.).

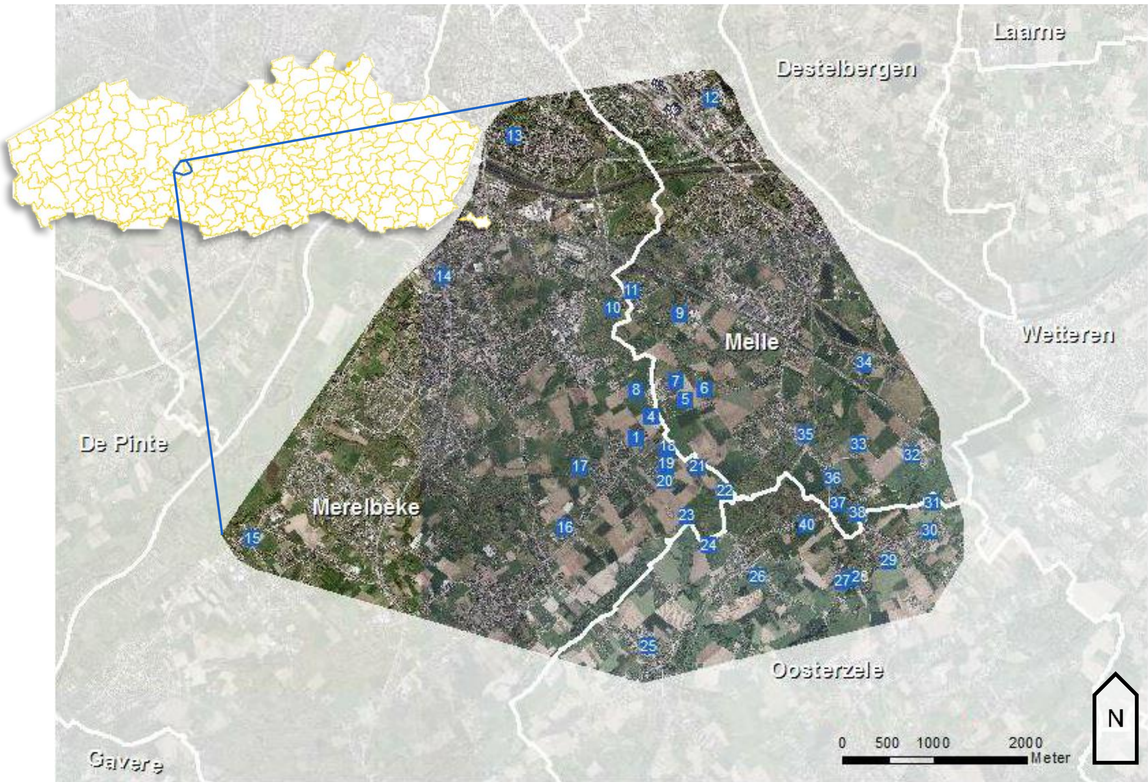

Figure 2.4: *The landscape observatory 'BEL-Landscape' in Flanders, Belgium. 41 1m²-gardens are spread in a study area representative for peri-urban Flanders with 51% agricultural land use, several small municipalities, fragments of high value nature and a considerable pressure on the open space from different land users.*

The landscape observatory BEL-Landscape consists of 41 1m²-gardens (Fig. 2.4) that give insight into the ecological reality by distribution along a gradient of landscape composition. To examine the impact of FAB habitat (related to landscape composition) at different scales in the landscape on local ES provisioning, the 1m²-gardens were installed along a gradient of relative proportion of semi-natural habitat presence (SNHs) in a 500-metre radius (scale) (Fig. 2.5). In this case study, the relative proportion of high green vegetation and biologically valuable low green vegetation (as components of SNH) around the 1m²-gardens hence serves as explanatory variable for relative differences in ecosystem processes measured in the different 1m²-gardens.

To select the locations for the 41 1m²-gardens we adopted the approach described by Pasher et al. (2013) for the optimisation of sample selection along a landscape gradient. Doing so, three statistical pitfalls were avoided when the effects of landscape variables on ecological responses are studied, i.e. by (1) covering the widest possible range of SNHs, (2) avoiding spatial autocorrelation between measurement points, and (3) avoiding dependency between SNHs. We divided the SNHs in vegetation higher than 3 m ('high green') and biologically valuable vegetation lower than 3 m ('valuable low green'). The first is composed of all vegetation higher than three metre (trees, hedges). The second is composed of low green vegetation lower than three metre height that is furthermore classified as biologically valuable by a habitat assessment (Vriens et al. 2011). The SNH overall is used as proxy for FAB habitat. The division of high and low green is useful because it mainly involves respectively woody and herbaceous vegetation, and thus quite distinct habitat types (as discussed in chapter 1). For potential locations, the percentage high and valuable low green is defined in a radius of 500 metre around each location. The locations of the 1m²-gardens were chosen in such a way that the meaningful range of semi-natural habitat (sum valuable low and high green vegetation) is covered (cf. pitfall 1) while the orthogonality between high and valuable low green (cf. pitfall 3) is guaranteed and spatial autocorrelation is avoided (cf. pitfall 2) (Fig. 2.5). The orthogonality assures the possibility to disentangle effects of high and low green vegetation as different FAB-habitats on local agroecosystem service delivery. After selection of the 1m²-garden locations along the landscape compositional gradient we coupled the interested citizen scientists that reacted to an open call for participants to these locations.

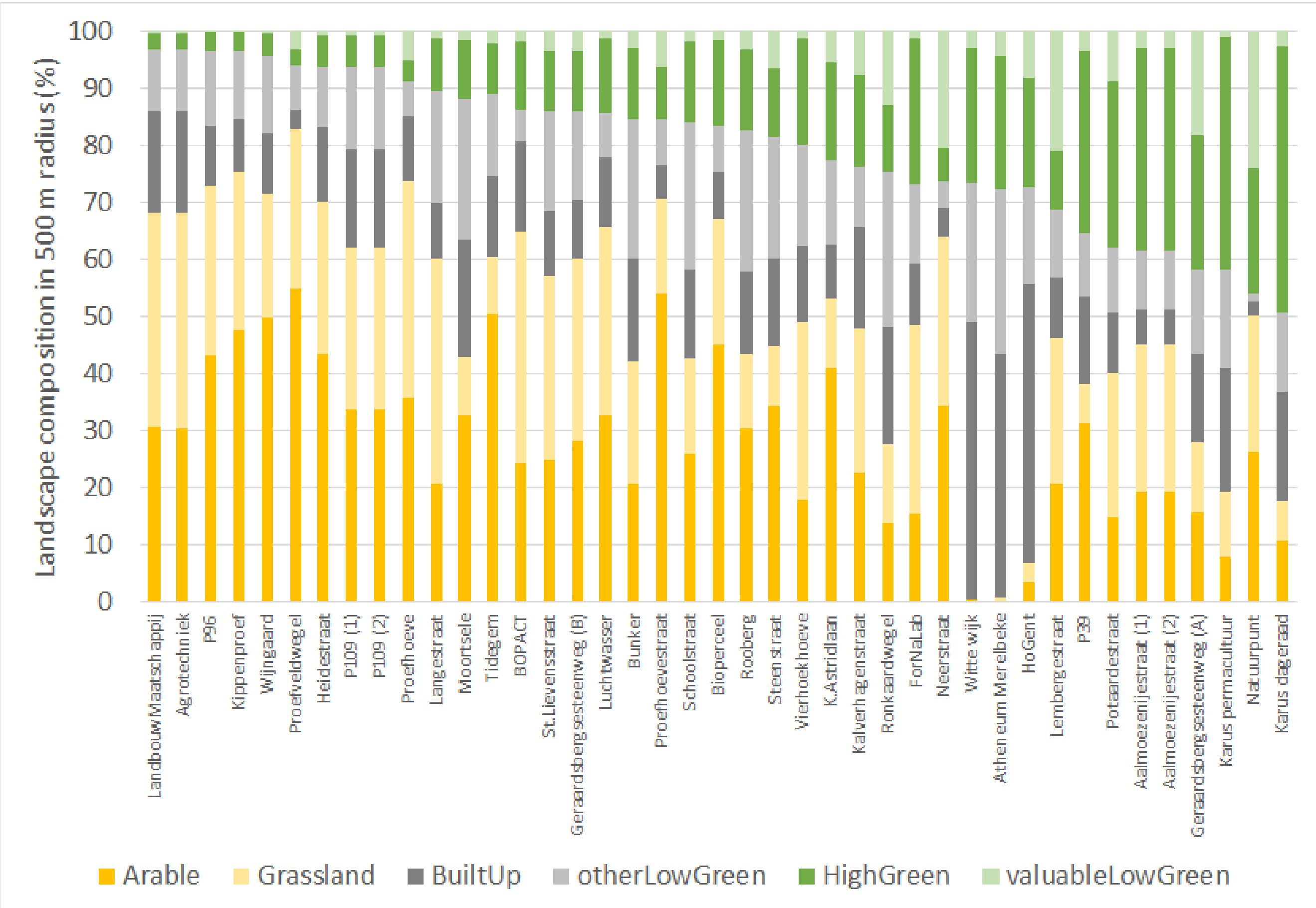

Figure 2.5: *The landscape compositional gradient of relative proportion in semi-natural habitat (green), agriculture (yellow) and other land use (grey) (Y-axis) within a 500 metre radius (scale) around the location of the 41 1m²-gardens (X-axis). Semi-natural habitat is the sum of high green (dark green) and valuable low green (light green) in a radius of 500 metre. The amount of semi-natural habitat correlates negatively with the proportion cultivated land in the radius. The locations of 1m²-gardens Witte Wijk, Atheneum Merelbeke and HoGent are located in urbanised environments, explaining why there is more built-up and no agricultural land use there.*

In BEL-Landscape, the distribution of 1m²-gardens along a landscape compositional gradient of SNH allows to test the effect of landscape composition on the multifunctional agroecosystem performance in the 1m²-gardens (Fig. 2.6, left thick arrow). More specifically, relative proportions of 'high green' SNH, 'valuable low green' SNH, or total SNH at different scales (i.e. in buffers with different radii) are used as explanatory variables.

In the BEL-Landscape observatory pitfall and pan traps are used to estimate the activity density of respectively ground dwelling detritivores, predators (natural enemies) and pollinators. Together with the continuous logging of the temperature, soil moisture content and the monitoring of plant herbivory and plant growth, these are indicators that measured supporting ES in the 1m²-gardens. The monitoring of plant herbivory, the harvest of edible biomass, temperature buffering and the fruit set and quality of strawberries are used as indicators for ES (Table 2.1). The simultaneous measurement of supporting services and ES provisioning allows to hypothesise mechanisms in pre-assumed causal relationships, with abiotic conditions and activity of functional arthropods as intermediate variables (Fig. 2.6, left dashed arrows) using, for instance, Structural Equation Modelling (Emmerson et al. 2016). A compilation of weekly overview pictures from a participant is given to illustrate the development of one 1m²-garden throughout the growing season (Fig. 2.7).

The citizen science approach facilitates the mapping of diverse land users related to FAB and also to involve them in the research process. The citizen scientists in BEL-Landscape represent a first group of land users and are monitored via interviews and personal contacts. The citizen scientists involved in the BEL-landscape observatory are residents, nature organisations, farmers, researchers, health institutions, semi-professional vineyard farmers and schools and are thus a representative sample of the multifunctional countryside. For a robust stakeholder analysis, a group of FAB-stakeholders outside the volunteers are interviewed as well (policy makers, residents, nature conservationists, farmers etc.). For both the citizen scientists and the wider actor-group, the 1m²-gardens in BEL-Landscape prove valuable to make concepts such as FAB and ES tangible and enable true identification of opinions and intentions.

A thorough stakeholder analysis is important to have FAB-initiatives supported by different land users (Fig. 2.6, right panel). As described by Reed et al. (2009), a first step is a stakeholder identification, where all actors with a relation to FAB are listed (FAB-stakeholders). A second step is to categorise these stakeholders according to their interest, demand and impact in relation to FAB. This will deliver information on why stakeholders do or do not act in relation to FAB and thus how they could be stimulated. In a classic stakeholder analysis, a third step is to investigate the relationships between different stakeholders (Reed et al. 2009). Insights on the relations between the actors are necessary in order to be able to stimulate (multi-) stakeholder engagement for FAB. For instance, knowledge on intentions, motivations and influence of FAB-stakeholders together with knowledge of local policies and initiatives will be used to explore where existing collaborations or platforms can shape opportunities to coordinate FAB reinforcement. Enqvist et al. (2020) show, for instance, that bottom-up initiatives can improve the fit between social systems and lake systems as central natural resource in their social-ecological system. They found this fit to be stronger especially when municipal or non-governmental partners are linked with citizen groups. A detailed overview of the participatory process in the BEL-Landscape observatory is provided in the appendices (Table A3).

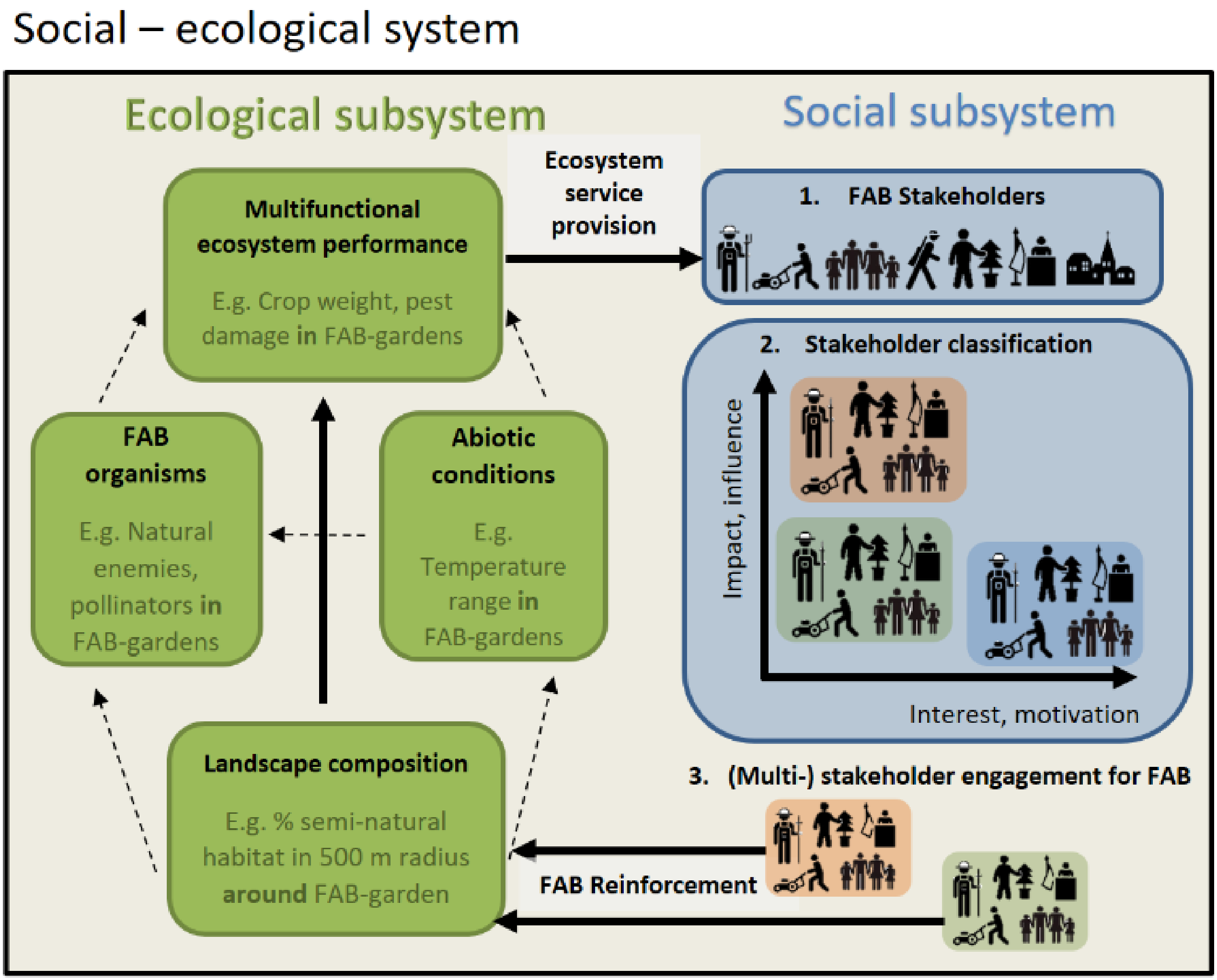

Figure 2.6*: Research focus in the BEL-Landscape observatory situated in the proposed social-ecological system (Fig. 2.1). The* <u>*left panel*</u> *represents the ecological hypotheses with central effects (full arrow) and the underlying mechanisms (dashed arrows). The* <u>*right panel*</u> *represents the social subsystem where FAB-actors are identified (1), categorised (2) and related to each other (3).*

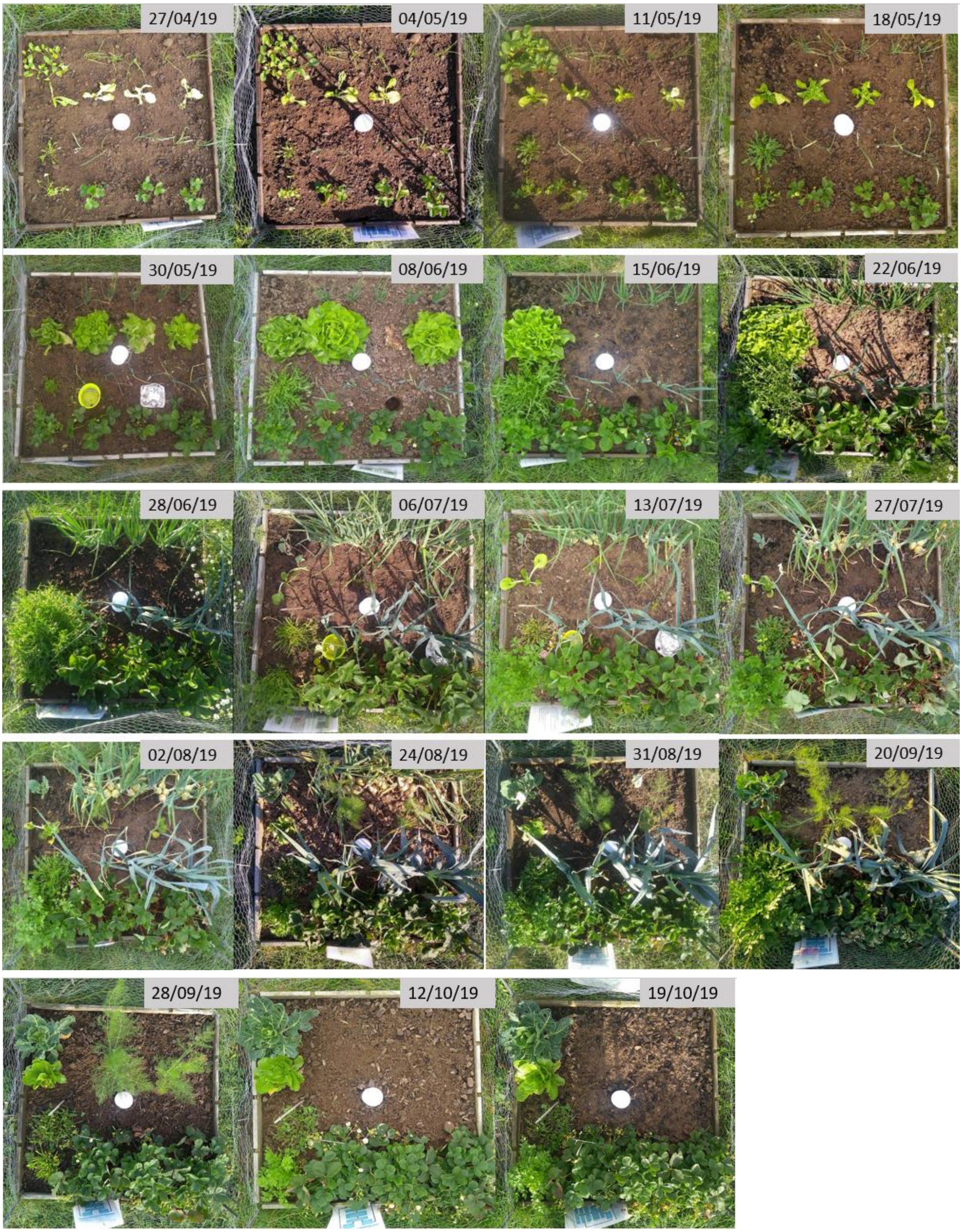

Figure 2.7: *A time lapse of overview pictures taken from one 1m²-garden throughout the growing season in 2019. Pictures are taken weekly by a participating volunteer. At defined moments during the growing season, crops are harvested and registered by the participant which explains why biomass seems to disappear from the 1m²-garden.*

Discussion and conclusions

In this chapter of the thesis we conceptualised FAB in a social-ecological framework and proposed a toolbox to study this framework using transdisciplinary research, illustrated by a first introduction of the BEL-Landscape observatory as case study. In the final section of this chapter, we reflect on the similarities and differences between the suggested toolbox and other studies. We formulate trade-offs and important considerations for other researchers with interests in the 1m²-garden approach.

Innovative aspects of our approach

Social-ecological frameworks are useful to put hypotheses, methods and results in perspective. In the BEL-Landscape case, we structured our research questions in the social-ecological framework assisting dialogue with volunteers and keeping balance between different research disciplines (Fig. 2.6). Barnaud et al. (2018) also structure cases of social interdependencies of beneficiaries and providers of ES in their proposed social-ecological framework. This renders clear images and consequent comparisons between different case studies. Lescourret et al. (2015) conclude that participatory instruments used on social-ecological systems need to capture "perceptions of various stakeholders and available scientific knowledge, to foster synergy between ecosystem functioning and social dynamics" (p. 73). Likewise, Barnaud et al. (2018) confirm the urgency of social-ecological frameworks to be actionable and use companion modelling as instrument. Nonetheless these methods are useful, they allow no actual experience of local stakeholders with the ecological subsystem. Our proposed landscape observatory with 1m²-gardens suits as toolbox to let stakeholders experience and discuss the ecological subsystem while researchers can observe both subsystems simultaneously and is therefore especially suitable to measure in social-ecological frameworks (Lescourret et al. 2015).

The approach of 1m²-gardens is complementary to other research on the relation between landscape management and ES in several ways. Frequently, research on the effects of landscape structure on ecosystem functioning focusses on one (Holzschuh et al. 2007; Winqvist et al. 2012; Karp et al. 2018), or multiple ES (Dainese et al. 2017; Dainese et al. 2019a; Martin et al. 2019) in classical crop systems. For instance, Dainese et al. (2017) focus on natural control of cereal aphids and measure the activity density of pollinators to estimate the potential for pollination. Indicators for pollination success as ES provisioning are not assessed, because cereals as crop type under study do not provide the means for this at the same time and study site (Dainese et al. 2017). The installation of standardised ‘phytometers’ to measure ecosystem functions and consequent services at locations of interest is a different approach which enables relative comparisons of ES of interest between locations of interest at the same time, but is less present in the existing literature (for examples see Albrecht el al. 2012). Phytometers are defined as (Dietrich et al. 2013, p.370): “standardised plant species experimentally transplanted to indicate between-site differences in environmental conditions through, for example, growth variation (Antonovics and Primack 1982)”. Next to better standardisation compared to field conditions, another advantage is that the combination of crops in the phytometer can be selected in such a way so as to study multiple ES at the same time, at the same place. 1m²-gardens take the phytometer design towards a multipurpose-sensor for a broad spectrum of ecosystem functioning and services at locations of interest. The individual indicators and methods as described in Table 2.1 are common practice in studies that compare ecosystem functioning between different landscape compositions. Researchers can adopt and combine these and other existing methodologies for application in 1m²-gardens or similar multifunctional phytometers, adjusted to the need for ES of local stakeholders. The key innovation of the 1m²-gardens is the ability to connect land users directly to relevant, tangible ES and introduce them to scientific reasoning. Researchers can study the learning process of different profiles and identify barriers and opportunities for FAB-reinforcement with different land users.

Trade-offs and considerations for application

The 1m²-garden toolbox is a holistic, process-oriented methodology and complements existing studies with a new, transdisciplinary point of view. To be meaningful, several considerations are to be made when adopting the approach in experiments. The time investment for action research and citizen science should not be underestimated. Inadequate communication about citizen science aspects or research findings will cause mistakes in data gathering and participants losing their motivation. Research teams should carefully consider the aims of the citizen science approach and consequently which monitoring tasks are assigned to volunteers. Lakeman-Fraser et al. (2016) highlight the common trade-off between outreach goals and rigorous scientific data in citizen science projects. Whereas some projects focus on large, solid datasets (crowd sourcing), other projects are more process oriented (social learning). The 1m²-garden toolbox, takes on the win-win approach for both rigorous data and social learning (Lakeman-Fraser et al. 2016). All tasks that ask expert knowledge are performed by the principal researcher (arthropod trapping, sensor installation, pest identification, herbivory estimation). Tasks that require no specific knowledge and can be clearly explained in guidelines, are assigned to the volunteers (watering, weeding, harvest protocols). The principal researcher frequently visits the individual 1m²-gardens for the expert-based monitoring and is therefore able to verify the practices of the volunteers and provide feedback and explanations. In the BEL-Landscape observatory, volunteers are nevertheless asked to observe and share their findings on prevalence and identification of pest species to stimulate learning and enthusiasm. These participant observations are helpful for the principal researcher who can consequently observe this through a standardised method. In any scientific approach that is process-oriented, and especially when balancing social learning and crowd-sourcing, the principal researcher takes a non-traditional scientific role. Facilitation skills are needed to perform a role as knowledge broker between all different land users to manage the participation process. It is required to involve partners with expertise in this field of action research.

The number of 1m²-gardens needs consideration because it reflects a trade-off in research objectives. More gardens render more data, at a spatially larger extent. This will, however, decrease the level of volunteer involvement per measurement point. In that case, only basic monitoring can be requested from volunteers because this does not require intense follow up by the researchers (towards crowd sourcing). The latter, however, diminishes the possibility to construct social theories on peoples' opinions on FAB, because no frequent interactions are maintained with participants. Even more, close involvement of a limited number of volunteers ensures a trust-based relationship between the researcher and citizens. In our experience, this engages volunteers to assemble at least the minimal asked dataset and alert the researchers if problems occur. Besides the intensity of the monitoring, the number of 1m²-gardens should be in line with the number and type of landscape variables that will be used as explanatory variables (Pasher et al. 2013). In the BEL-Landscape case we sampled 41 1m²-gardens along uncorrelated gradients of high and low green SNH. Similar sampling densities along a landscape gradient are also used in other studies. Hass et al. (2019) sampled with exposed bumblebee colonies in two fields (maize and oil seed rape) in 20 landscapes of 1 X 1 km² along uncorrelated gradients of landscape compositional and configuration heterogeneity. Dainese et al. (2017) sampled 26 field margins (three margin types) along uncorrelated gradients of arable land cover and hedgerow cover in a 1 km buffer. The advantage of sampling along a landscape gradient (Holzschuh et al. 2007; Dainese et al. 2017; Hass et al. 2019) compared to replicated sampling in contrasting landscapes is that nuances between different landscape compositions can be better described.

Given the small size of the 1m²-gardens, no absolute values for ES but only relative differences in ecosystem indicators between 1m²-gardens are observed, so as to optimise landscape scale management for multifunctional ecosystem performance. This will deliver insights in the effectiveness of landscape management for multifunctional ecosystem performance, but not on the efficiency or absolute values at field scales. The small size allows the tool to easily fit in between fields and is therefore more acceptable for land users to coexist with their current practices. The time necessary to manage the 1m²-garden is rather low and allows volunteers to focus on the individual plants to recognise plant specific pest species and flowering processes. The small scale proves to be effective to get land users in touch with ES.

Thoughtful use of our social-ecological framework will deliver valuable new insights on improving the effectiveness of FAB strengthening efforts in many rural or peri-urban areas. We therefore invite other research groups, society organisations and policy makers to test our toolbox with 1m²-gardens, or derivatives thereof, in many distinct contexts. Through their social function of triggering interest, the 1m²-gardens make knowledge accessible for stakeholders who are to implement research findings and thereby increase the impact of scientific work. In the following chapters of this thesis we describe detailed applications of the approach in two independent case studies and the social-ecological results and implications thereof.

Chapter 3

Disentangling the interrelated abiotic and biotic pathways linking landscape composition and crop production

Adapted from: Gerits, F., B. Reubens, L. Messely, P. De Smedt, D. Landuyt, A. Loos, and K. Verheyen. 2022. Disentangling the interrelated abiotic and biotic pathways linking landscape composition and crop production. Journal of Applied Ecology 59 (11): 2742 – 2755

Frederik Gerits designed the experimental design with 41 1m²-gardens together with Lies Messely, Bert Reubens and Kris Verheyen. The sampling during both seasons was performed by Frederik Gerits, in the second year supported by Annelies Loos. The processing of the arthropod, microclimate, leaf herbivory and yield was done by Frederik Gerits with support of Pallieter De Smedt and Annelies Loos. Statistical analysis was done by Frederik Gerits with support of Dries Landuyt, Pallieter De Smedt, Kris Verheyen, Annelies Loos and Bert Reubens. Frederik Gerits drafted and submitted the manuscript after several revisions by all co-authors.

Abstract

Landscape composition and its related functional agrobiodiversity (FAB) was severely changed during the last decades. As landscape composition is expected to influence the interrelated microclimate and arthropod community at different scales, these changes might have led to a decline in multiple agroecosystem services, with potential impacts for the growth of crops with different demands from the environment. To study landscape-scale effects on multi-crop yield and herbivory in combination with its potential drivers, including functional arthropod community and microclimate, we applied the standardised 1m²-garden toolbox presented in the previous chapter in the BEL-Landscape case in 2018 and 2019. We found no relationship between landscape composition in a 500-metre radius and crop yield. Considering possible mechanisms, we found that a higher relative proportion of woody vegetation (> 3 m high) at different scales in the surrounding landscape is important to buffer the temperature and soil moisture variation in the 1m²-gardens.

The relative proportion of arable land use and residential green (< 3 m high) is, respectively, positively and negatively related with the activity-density of predators and pollinators. The growth of different crops responded differently to higher temperature ranges and we found no relation between predators and leaf herbivory. In conclusion, these abiotic and biotic pathways did not relate to an overall relationship between landscape composition and yield. These outcomes indicate that high green vegetation can be implemented both at the local and the landscape scale to buffer soil moisture and temperature variation. Furthermore, optimisation of the landscape composition helps to stimulate local activity of arthropods. Yet high arthropod activity is no assurance for arthropod mediated ecosystem service delivery nor is microclimate buffering an assurance for higher crop yields.

Introduction

Landscape structure encompasses both compositional and configurational heterogeneity in land use types (Fahrig et al. 2011; Haan et al. 2021) and influences ecosystem services such as pollination, natural pest control and yield (Tscharntke et al. 2012b; Dainese et al. 2019b; Martin et al. 2019; Haan et al. 2021). Loss of compositional structure of landscapes is reported worldwide due to the decreased variation in crop types, larger plots and lower relative proportions of semi-natural habitats (Landis 2017). The resulting larger scale landscapes with reduced crop variety often cope with persistent pests, diseases and require intensive input of chemical pest control and fertilisation (Tscharntke et al. 2012a). The use of these external inputs can be reduced by increasing the landscape structure and its related floral and arthropod Functional Agrobiodiversity (FAB) (Bianchi et al. 2013). Increasing the relative proportion of semi-natural habitats such as spontaneous wild flower patches, hedgerows and forest fragments can support microclimate regulation (Alford et al. 2018), natural pest control (Karp et al. 2018) and pollination (Dainese et al. 2017).

There is an increasing body of literature on the effect of crop and non-crop compositional landscape structure on agroecosystem services, most often pollination, natural pest control and yield, sometimes supplemented with nutrient cycling, carbon storage, water quality regulation and microclimate regulation (Tougeron et al. 2016; Dainese et al. 2017; Landis 2017; Birkhofer et al. 2018; Dainese et al. 2019b; Martin et al. 2019). Dainese et al. (2017), for instance, show that a higher relative proportion of hedgerows in the landscape increase aphid parasitism and potential pollination in cereal fields. Sutter et al. (2017) also show that landscape scale greening improves both pollination and pest control in oilseed rape fields. Birkhofer et al. (2018), on the other hand, found no relation between landscape structure and multiple ecosystem services for spring barley as focal crop and suggest that there are trade-offs between services. Karp et al. (2018) synthesised data on multiple crops and reported inconsistent responses of natural pest control to the relative proportion of semi-natural habitat in the surroundings. Although research including microclimate variables is less common, intensively farmed, structurally homogeneous landscapes are known to have higher average temperatures and temperature variations (Suggitt et al. 2011; Tougeron et al. 2016; Alford et al. 2018). Furthermore, these microclimatic conditions influence the local arthropod community, especially for flying arthropods which require minimum temperatures to forage (Sgolastra et al. 2016; Tougeron et al. 2016; Alford et al. 2018; Caselles et al. 2019).

However, it is not clear how the landscape mediated microclimate regulation relates to other ecosystem services such as pollination, natural pest control or crop growth, since it has not yet been looked at together in landscape scale experiments. Another research gap is related to the fact that crop species have different needs from the environment. More specific, crops have different requirements from the environment considering temperature and soil moisture (Jackson et al. 2011)**.** Also, the crop species influences the response of pest species to non-crop habitats in the landscape (Tamburini et al. 2020). Furthermore, for some crops, non-crop habitats in the surroundings could provide more resources for pests than for their predators (Tscharntke et al. 2016). The current focus on crop specific knowledge has to be extended with multi-crop experiments to study which land use compositions support microclimatic conditions and arthropod communities for a sustainable production of a wide range of crops, less dependent on external agrochemicals.

Multi-crop data has not yet been assembled together with a microclimate and arthropod pathway in an experiment along a landscape composition gradient. Therefore, in this chapter, we apply the presented 1m²-garden approach in the BEL-Landscape case. As a general objective of this chapter we aim to simultaneously assess the impact of landscape composition on the microclimate, on the abundance of specific functional arthropod groups, on pollination and pest control, and ultimately on crop performance through this set of interrelated abiotic and biotic pathways. We hypothesise that (Figure 3.1), in landscapes with a higher relative proportion of non-crop land use types

(H1) the multi-crop yield increases,

(H1a) through increased buffering of temperature and soil moisture content;

(H1b) and increased activity-density of predators and pollinators and decreased crop herbivory;

(H1c) while the importance of these pathways and net effects on yield depend on the crop being studied.

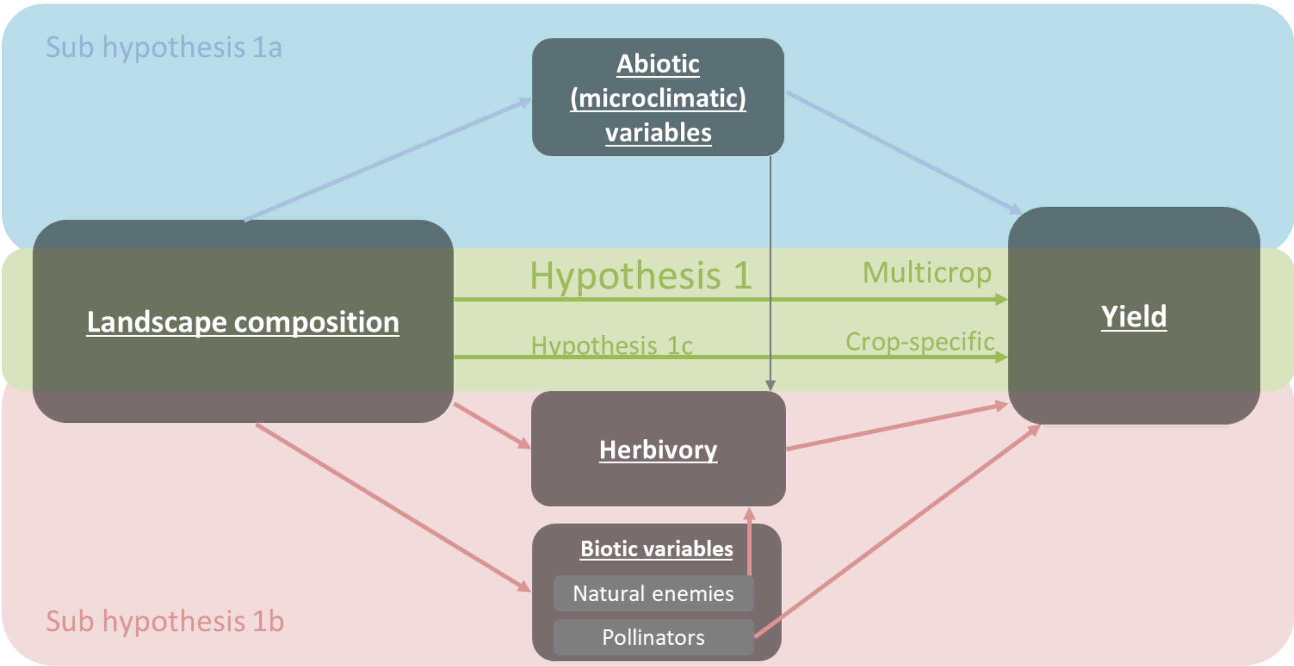

Figure 3.1: *Data blocks and hypothesised relationships. Black boxes represent the groups of variables. Arrows indicate the hypothesised relationships with their colours being in line with the hypotheses.*

Material and methods

In this section, we build on the introduction of the BEL Landscape case in the previous chapter and deepen the methodological principles needed to understand and interpret the results of this first 1m²-garden experiment.

Study design

We use the landscape observatory 'BEL-Landscape' to study the relationship between landscape composition and abiotic and biotic variables related to agroecosystem services. To study the influence of landscape composition on local microclimate, natural pest regulation, pollination and yield, the described 1m²-gardens are installed along a gradient of landscape composition considering high, woody and low, herbaceous non-crop habitats (Fig. 3.2). The average share of agricultural land use (sum arable and productive grassland) in a 500 m radius around the 1m²-gardens was 50.2% (max = 84.0%, min = 0.5%) and coincides with the average for Flanders. For high green vegetation the average was 15.3% (max = 46.8%, min = 2.9%). The distribution of land use types can be found in the appendix (Fig. B2). 1m²-gardens were installed at locations that are free of nearby high green vegetation (10 m radius) to avoid shade and litterfall. Presence of concrete surfaces was also avoided. The vegetation around the 1m²-garden was kept short to avoid interference. This nearby vegetation was highly associated with the land-use in the wider environment. For instance, 1m²-gardens in arable conditions were situated between agricultural fields and had often crops in the 10 m radius. 1m²-gardens in domestic gardens had often lawns in the 10 m radius.

All 1m²-gardens hosted ten crop species, planted following a standard planting scheme (Figure 3.2, appendix Table B1 for crop details). To have landscape composition as sole varying factor, a growing medium was used in the gardens consisting of 70% loamy sand and 30% ripe compost. In 2018 and 2019 there were, respectively, 40 and 38 1m²-gardens[1] where yield and leaf herbivory of all crops were monitored together with the hourly temperature and soil moisture content and the arthropod community (Figure 3.2). The field campaigns in 2018 and 2019 were conducted from the last week of April until the end of September. The summer months of 2018 and 2019 were considered respectively the warmest and third warmest since 1981 (KMI, 2020). The 2018 summer was the fourth driest since 1981 and the 2019 summer was averagely dry, despite three heat waves. The extreme summer temperatures in 2018 compared to 2019 were confirmed by the temperature logger data in the 1m²-gardens (appendix Fig. B1). To avoid drying out, we irrigated all 1m²-gardens twenty-one times with ten litres water in the 2018 season and respectively thirteen and four times with ten and five litres water in the 2019 season. Five or ten litres irrigation (mm) per square metre

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[1]In 2018, 40 1m²-gardens were installed. In 2019, three out of 40 1m²-gardens were excluded and one was added, resulting in 38 1m²-gardens in 2019 and a total of 41 sampling locations. One 1m²-garden sampled in both years was eventually excluded from the statistical analysis.

in a few minutes is a high amount compared to natural precipitation. By this irrigation, differences due to spatial variation in local showers is minimalised, yet not completely avoided. Possibly, variability in local showers added limited noise to the registered yields. Weeds were regularly removed. To support the standardised management of the 1m²-gardens a collaboration was set up with volunteers. Considering irrigation, we announced to the involved volunteers how much water must be applied to the 1m²-gardens every Wednesday evening in a weekly newsletter. The volunteers had the chance to do this on Thursday, Friday or Saturday but were asked not to do this in direct sunlight. Below we describe the methodological principles applied for monitoring.

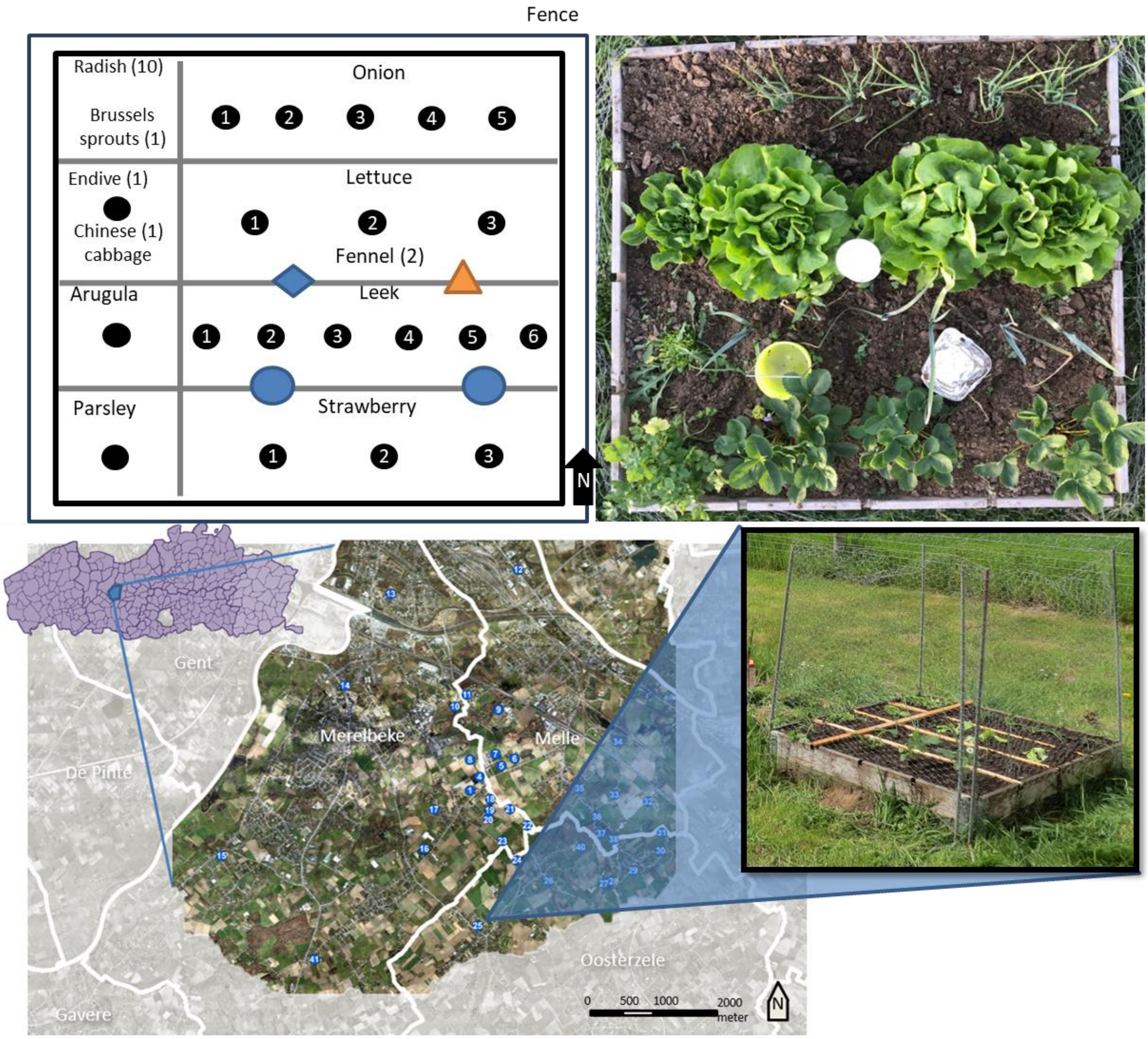


***Figure 3.2**: **Below:** The 'BEL-Landscape' observatory in Flanders. 41 1m²-gardens are spread in a study area representative for peri-urban Flanders. **Above**: 1m²-garden design. Blue diamond: sensor for soil moisture and temperature. Orange triangle: soil temperature sensor. Blue circles: (1) fluorescent yellow pan trap for flying arthropods (2) pitfall trap for soil dwelling arthropods. Brussels sprouts, Chinese cabbage and fennel are planted after early harvest of radishes, endive and lettuce.*

Landscape composition

We determined the relative proportion of six land use categories around each 1m²-garden at 10, 50, 125, 250 and 500 metre radius (scale), using 1 m resolution thematic maps (Informatie Vlaanderen 2015; INBO 2020), the agricultural parcel identification system (Department of Agriculture and Fisheries 2020) and the Spatial Analyst toolbox in ArcGIS Desktop (ESRI 2011) (Table 3.1). In a first phase, landscape data was used to sample 41 locations for 1m²-gardens along a gradient of relative proportion of non-crop habitats in a buffer of 500 metre. Non-crop habitats include all vegetation that is no productive grassland or arable land, being high green vegetation and both biologically valuable and non-valuable, residential low green vegetation. We used the 500 m scale because of its relevance for the wide variety of response variables included in the study. Also, in Flanders, 500 m is the largest radius that allows selection of sites that are surrounded merely by agricultural land use. If radii are larger, forest fragments or built-up areas are included. A remark is that several invertebrate species forage at radii wider than 500 m. The land use composition at 500 m radius can be found in the appendices (Fig. B6). Land use types are typically correlated (Grab et al. 2018; Billaud et al. 2020), therefore, for the analysis, we reduced the land uses in two orthogonal principal components (Table 3.1 and appendices Fig. B7, Fig. B8). There was overlap between the landscape buffers surrounding the 1m²-gardens, with increasing overlapping areas from 10 to 500 metre radii (appendix Table B2, Table B3). At three locations there were two 1m²-gardens at close spatial proximity to have a replication of those three locations. Yet, overlapping buffers are shown to not be causing statistical dependency or spatial autocorrelation if a robust spatial design is used, avoiding the influence of exogeneous environmental factors (Zuckerberg et al. 2012; Zuckerberg et al. 2020). The robust design (see previous chapter for more details) was validated by an analysis of spatial autocorrelation in the model residuals for all response variables (Dormann et al. 2007; Kühn and Dormann 2012; Zuckerberg et al. 2020) (appendix Table B4). We found no significant autocorrelation except for the model of multi-crop herbivory in 2019 (not in 2018), which could potentially be attributed to exogeneous factors (e.g. pesticide usage) causing unexplained spatial correlation.

***Table 3.1**: Six land use categories measured around each 1m²-garden and interpretation of the two principal components (PCA 1 and 2) explaining respectively 46% and 22% of the variation at 500 m radius.*

Land use	Description of the habitat
High green vegetation	Woody vegetation higher than 3 m (forests, solitary trees, hedges)
Valuable low green vegetation	Vegetation lower than 3 m that is classified as biologically valuable or managed for nature conservation and is flower rich (extensive grassland, road ditches etc.)
Arable land	Productive cropping systems (maize, wheat, potato etc.)
Productive grassland	Productive grassland managed as meadow or grazing areas. Not managed for nature and typically species poor.
Non-valuable low green vegetation	Residential vegetation lower than 3 m that is not classified as biologically valuable (private gardens, public park areas etc.)
Built-up area	Surfaces that contain no vegetation (buildings, roads, concrete surfaces etc.)
PCA 1	Productive grassland and arable land (+) versus built-up and non-valuable low green and high green vegetation (-)
PCA 2	High green vegetation and valuable low green (+) versus built-up and non-valuable low green (-)

Abiotic factors: soil temperature and soil moisture

We used hourly measurements of HOBO Pendant 8T sensors (-10 cm in centre of 1m²-garden) from May 25th until September 29th in 2018 and 2019. Temperatures were integrated in daily maxima, minima and means and further aggregated to average daily maxima, minima and means (Zellweger et al. 2019). Furthermore, the difference between the third and first quartile of the hourly temperatures is determined as proxy for temperature range (temperature interquartile range, TIQR). Because of high correlation between daily max, daily mean and inter quartile range we only use the latter in further analysis. Additionally, in 2019, TOMST data loggers (Wild et al. 2019) continuously measured soil moisture content. At the end of the second season, fresh soil samples were taken to determine the gravimetric soil moisture content and chemical parameters (pH, CEC, N, P etc.) to check for unwanted local influences (e.g. nutrient inflow).

Biotic factors: invertebrate community

Arthropods were sampled using pitfall traps and yellow pan traps and grouped into functional groups based on the dietary needs of the majority of the species in these taxonomic groups (Table 3.2) (Billaud et al. 2020):

***Table 3.2**: Arthropods caught with two trapping systems, the taxonomic name and the functional group.*

Common name	Taxonomic classification	Trap type	Functional group
Carabid beetles	*Carabidae*	Pitfall	Natural enemies
Rove beetles	*Staphylinidae*	Pitfall	Natural enemies
Spiders	*Araneae*	Pitfall	Natural enemies
Hoverflies	*Syrphidae*	Pan	Pollinators
Bees	*Apidae*	Pan	Pollinators
Millipedes	*Diplopoda*	Pitfall	Detritivores
Woodlice	*Isopoda*	Pitfall	Detritivores
Ants	*Formicidae*	Pitfall	Multifunctional

The fluorescent yellow pan traps were 10 cm in diameter filled with 400 ml water and a drop of detergent. The pitfall traps were 10 cm in diameter filled with 450 ml ethanol-glycogen holding anti-freeze (approx. 50% ethylene glycol and 50% water) and a drop of detergent. The traps were covered by aluminium roofs to prevent precipitation to enter. A gap of at least 3 cm between the trap and the roof allowed arthropods to enter. The exact setup and fluid of pitfall traps influences the composition of specimens, so comparisons with other studies is difficult (Skvarla et al. 2014). Traps were installed in the middle of the 1m²-gardens both in 2018 and 2019 in May, July and August for 14 days. Arthropods were sorted to groups (Table 3.2) and counted. Carabids were further identified to the species level to determine their diets. At least 72% of the caught individuals were carnivorous (18% omnivorous). Thus, 90% have other insects at least as part of their diet and therefore the trapped carabid community can be considered as possible pest control group. We summed abundance data over different periods within each group. Models with arthropod count data were based on negative binomial distributions to account for overdispersion in count data

(O'Hara and Kotze 2010). We interpreted the number of individuals in the traps as activity-density of arthropods, since trap data is a result of both activity and abundance of animals rather than true abundance (De Smedt et al. 2019). A comparison of the abundance of the different taxonomic groups between both years can be found in the appendices (Fig. B3).

Leaf herbivory

For each individual plant, pest-specific leaf herbivory was estimated biweekly using a six-level categorical scale (see appendices Table B5, Fig. B9, Fig. B10). Per individual plant and pest species, the average leaf herbivory was calculated during the growing period. This was further aggregated in an overall multi-pest leaf herbivory index per plant species. We additionally combined species-specific information into a multi-crop herbivory index per 1m²-garden. Multi-crop herbivory was calculated as the number of crops in a 1m²-garden with herbivory exceeding a threshold (ti), which is calculated as 40% of the average of two highest herbivory levels for that crop (Byrnes et al., 2014)

$$MCH_{FAB-Garden} = \sum_{i=1}^{F} (\text{herbivory}_i > t_i).$$

With threshold per crop ti = 0.4* average (herbivory i, two highest) for crop i = 1 to F. Both crop-specific and multi-crop herbivory were square root transformed when used as response variable in models.

Fresh yield of edible biomass

Fresh edible biomass was registered for all individual crops in the 1m²-gardens (Figure 3.2, appendix Table B1) by weighing the fresh aboveground, edible biomass. Before weighing, roots and dirt were removed. Arugula and parsley were harvested three times. Ripe strawberries were harvested weekly. For crops with multiple plants per garden, onions and Brussels sprouts the average weight was calculated. Crop specific yield was combined in a multi-crop yield index using the same methodology as for multi-crop herbivory (Byrnes et al. 2014). Both crop-specific and multi-crop yield were square root transformed when used as response variable in models.

Statistical analysis

All statistical analyses were executed in R 4.0.4 for Windows (R Core Team 2020). The overall hypothesis (H1) and first two sub hypotheses (H1a, H1b) were tested by fitting general and generalised linear mixed effect models using the R-package *lme4* (Bates et al. 2015) with landscape variables and year as fixed factors and location as the random intercept term. We did not include year as random term in the model since it only has two levels (2018, 2019) and could cause severe issues with the model estimation. P-Values are derived with an ANOVA using the drop-one method of a full and reduced model. Estimates from the landscape variables in the full model are reported. For the third sub hypothesis (H1c), piecewise structural equation modelling (*piecewise SEM package*, Lefcheck 2016) was used. Arthropod count data was log-transformed for these SEMs, since the package does not return standardised estimates for negative binomial distributions. We tested one model structure in line with our third sub hypothesis for the multi-crop indices (appendices Fig. B16, Table B12) and separate crops (appendices Fig. B17, Table B12). Shipley's test of direct separation (Shipley 2009) was used to assess the overall consistency of the model with the data. A Fisher's C $\chi 2$-value below the significance level ($p<0.05$) indicates that there are important pathways missing in the proposed model and thus that it should be rejected. The Fisher's C $\chi 2$-value is interpreted together with the standardised path coefficients and the marginal R^2 of the model components to avoid overspecified models fitting data with little signal present (Hertzog 2018).

Considering the significance levels used in all chapters of this dissertation we use $p < 0.001$= ***, $p < 0.01$ = **, $p <0.05$= *, $p < 0.1$ = '.'. Although the latter is marked in the figures, these results ($p < 0.1$ = '.') should not be interpreted as significant.

Results

The relationship between landscape composition and multi-crop yield

PCA1 did not associate with multi-crop yield (2018: $F_{1,35} = 1.21$, $p > 0.05$, 2019: $F_{1,34} =2.76$, $p>0.05$). PCA2 did not associate with multi-crop yield (2018: $F_{1,35} = 1.04$, $p > 0.05$, 2019: $F_{1,34} = 1.28$, $p > 0.05$). The data are visualised per year in the appendices (Fig. B11).

Considering the first two sub hypotheses, we found positive relationship between the relative proportion of arable land at all scales (all radii) and the activity-density of both predators, pollinators (Fig. 3.3). This means that the relative proportion of arable land use in 10, 50, 125, 250 and 500-metre radius around the 1m²-gardens correlated positively with the activity-density of both pollinators and predators. For all scales there was no relationship between productive grassland, high green vegetation and both arthropod groups. Valuable low green vegetation at 10, 50 and 125 metres related with predators but not with pollinators. Non-valuable low green vegetation (urban low green, Table 3.1) related consistently negative with pollinators, while only at 10, 250 and 500 metres for predators. Built-up area related consistently negative with predators at all scales and only at 125 and 250 metre for pollinators. For the soil moisture interquartile range (SMIQR) we found a consistent positive relationship with arable land, which was only significant at 500 metres for the temperature interquartile range (TIQR) (Figure 3.). Productive grassland related only positively with TIQR at 50 metres. At 10, 50 and 500 metres, biologically valuable low green related with SMIQR. A consistent negative relationship was found between both TIQR and SMIQR and high green vegetation (not 10 m radius). At the 500 m radius, non-valuable low green related negatively to the TIQR. Built-up area did not relate to the TIQR or SMIQR for all scales. Plots with the different land uses grouped as PCA1 and PCA2 as explanatory variables for the activity-density of different taxonomic groups and the TIQR for multiple scales can be found in the appendices (Fig. B13, Fig. B15). We also provide visualisations of the data and models for PCA1 explaining the activity-density of the considered taxonomic groups and the TIQR separately for 2018 and 2019 to visually explore the consistency of the results over both years (Fig. B12, Fig. B14).

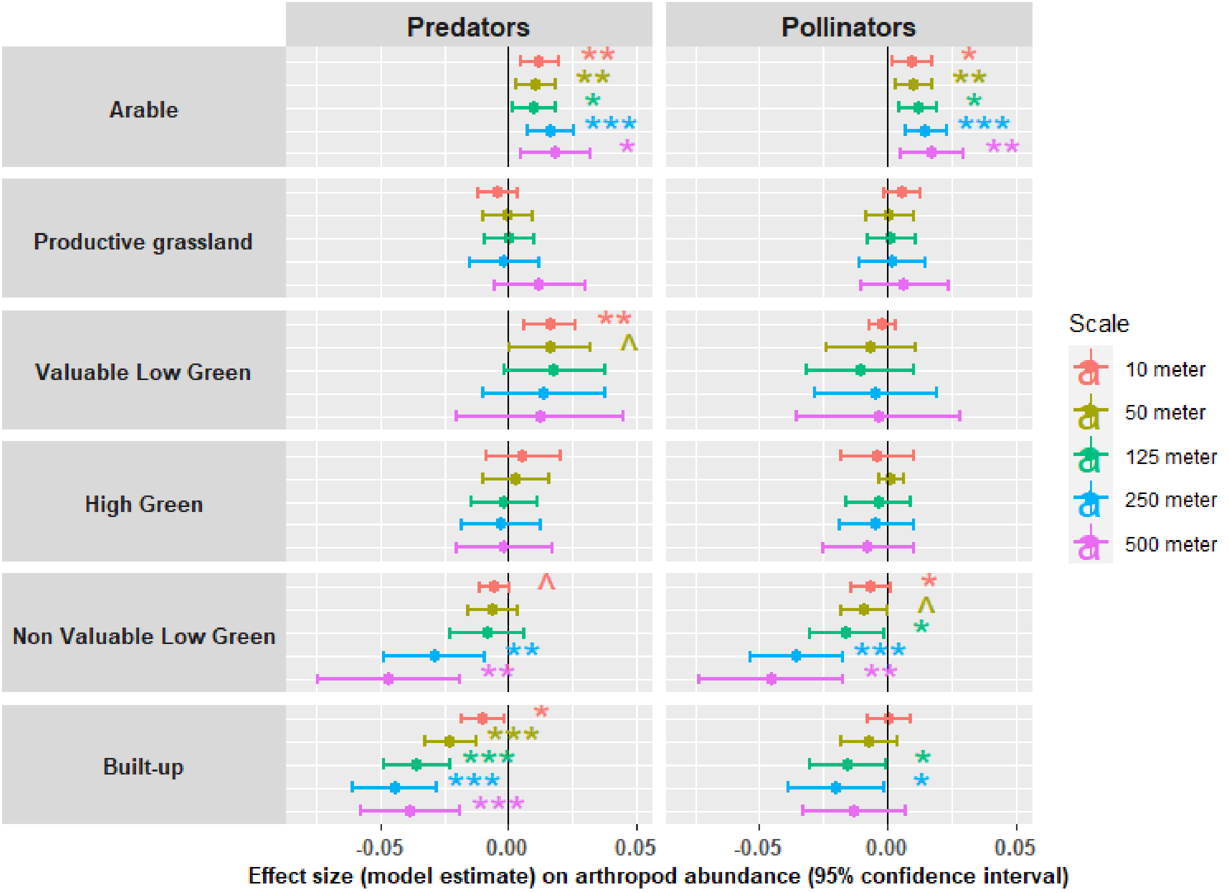


Figure 3.3: The effect size (model estimate) of landscape composition (relative proportion of arable, productive grassland, biologically valuable low green, high green, non-valuable low green, built-up) in five different scales on the abundance of predators (spiders, carabids and rove beetles), pollinators (hoverflies and bees). Model estimates and 95% confidence intervals are calculated with a generalised mixed effect model with, next to the landscape variable, year as fixed factor and location as the random term. Significance levels are given in the corresponding scale colour (p < 0.001= ***, p < 0.01 = **, p <0.05= *, p < 0.1 = ^). Predator-models have 4 estimates (k), based on 70 observations (n), in 39 plots (random term) resulting in 65 residual degrees of freedom (n-k-1). For pollinators there were 71 residual degrees of freedom (76-4-1). R^2m values for individual models can be found in the appendices (Table B6, B7).

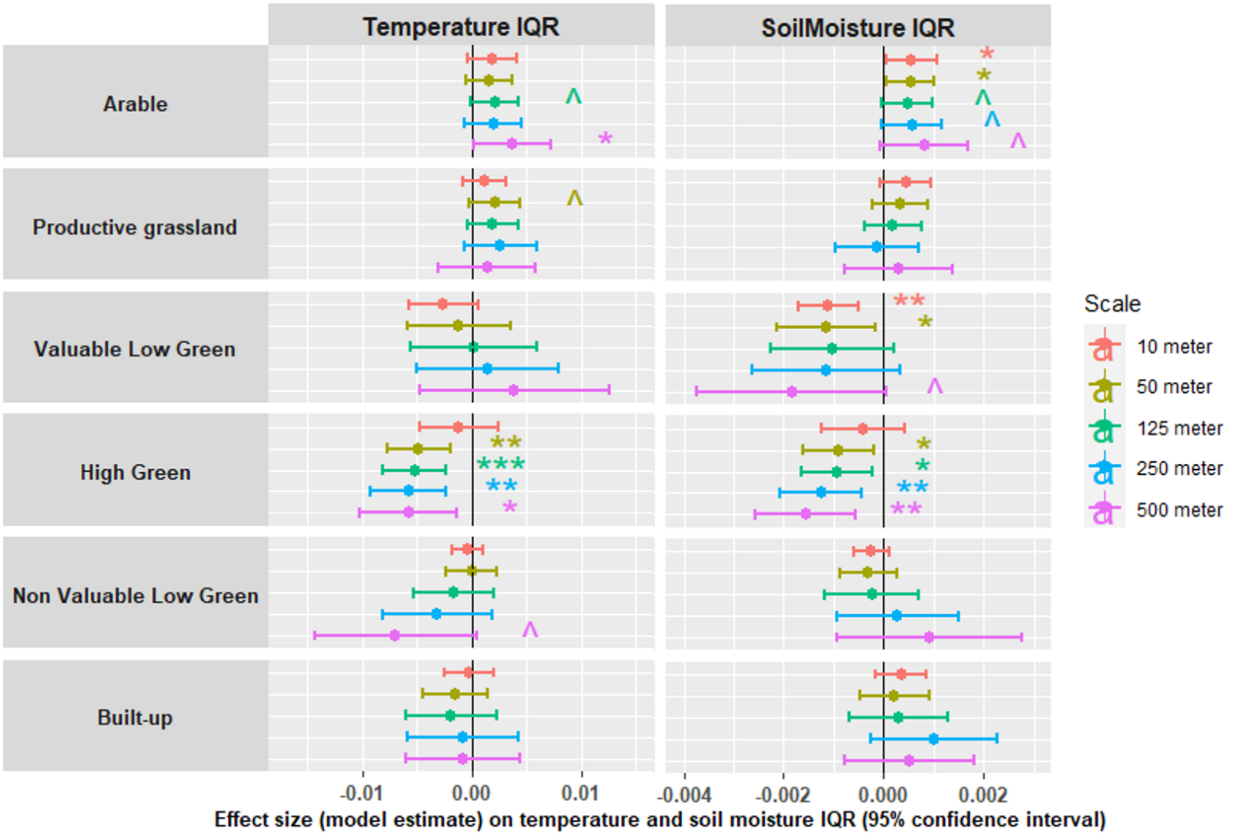


***Figure 3.4**: The effect size (model estimate) of landscape composition (*relative proportion of *arable, productive grassland, biologically valuable low green, high green, non-valuable low green, built-up) at five different scales on the square root transformed interquartile temperature range (TIQR) and the interquartile soil moisture range (SMIQR). For TIQR, model estimates and 95% confidence intervals are calculated with a linear mixed effect model with, next to the landscape variable, year as fixed factor and location as the random term. For SMIQR, estimates are made with linear models (only 2019 data available). Significance levels are given in the corresponding scale colour ($p < 0.001$= ***, $p < 0.01$ = **, $p <0.05$= *, $p < 0.1$ = ^). TIQR -models have 4 estimates (k), based on 75 observations (n), in 40 plots (random term) resulting in 70 residual degrees of freedom (n-k-1). SMIQR- models have 34 residual degrees of freedom (37-2-1). R^2m values for individual models can be found in the appendices (Table B9, B10).*

The independent sensors for soil moisture and soil temperature showed similar trends, although these variables were not correlated (appendix Fig. B18). The gravimetric soil moisture content, measured at the end of the 2019 season, correlated negative with Tmax, Tmean, TIQR and SMIQR and therefore further confirms this trend. Considering these correlations and since the SMIQR data is only available for 2019, we continue with the temperature interquartile range in the Structural Equation Models.

Piecewise Structural Equation Models (SEMs)

For simplicity, we only continue with the 500 m scale for further analysis. In this next step the landscape scale influences on local abiotic and biotic parameters are related to herbivory and yield of different crops. The comparison of average yield and herbivory of different crops between 2018 and 2019 can be found in the appendices (Fig. B4, Fig. B5).

The piecewise SEM with multi-crop yield explained by the interrelated multi-crop herbivory, arthropod activity-density and interquartile temperature range is in line with the abovementioned results at 500 m scale (Fig. 3.5). PCA1 had a positive relationship with the activity-density of pollinators, rove/carabid beetles and spiders. PCA2 had a strong positive relationship with the activity-density of spiders. PCA1 was positively related to the TIQR. The piecewise SEM indicates a positive relationship between the TIQR and the activity-density of pollinators. There was no relationship between the activity-density of both predatory groups and multi-crop herbivory. The multi-crop leaf herbivory had a negative effect on the multi-crop yield. The TIQR did not influence multi-crop yield, nor multi-crop herbivory. There was a slight positive relationship between PCA2 and multi-crop yield. Yet, when years are looked at separately, this effect seems not significant (see appendix Fig. B11 for data separated per year). The overall P value ($P = 0.62$) indicates that there were no missing paths of relevance, but did not necessarily imply that the model is a good fit for the data (Lefcheck 2016; Hertzog 2018). This is reflected by the insignificant paths towards the multi-crop herbivory and the rather low R^2 of this model components. An overview of the terms in the SEMs is given in the appendices (Fig. B16, Fig. B17).

The crop-specific models indicate that there was no relationship between the PCA's and yield of any crop (appendix Table B13). Only PCA2 reduced leaf herbivory for leek. Activity-density of predators did not associate with herbivory levels for any crop. There was a relationship between activity-density of hoverflies and the average strawberry weight. The temperature variation (TIQR) associated negatively with herbivory on parsley and yield of leek. Leaf herbivory associated negatively with yield for parsley, lettuce, endive, radish and Chinese cabbage.

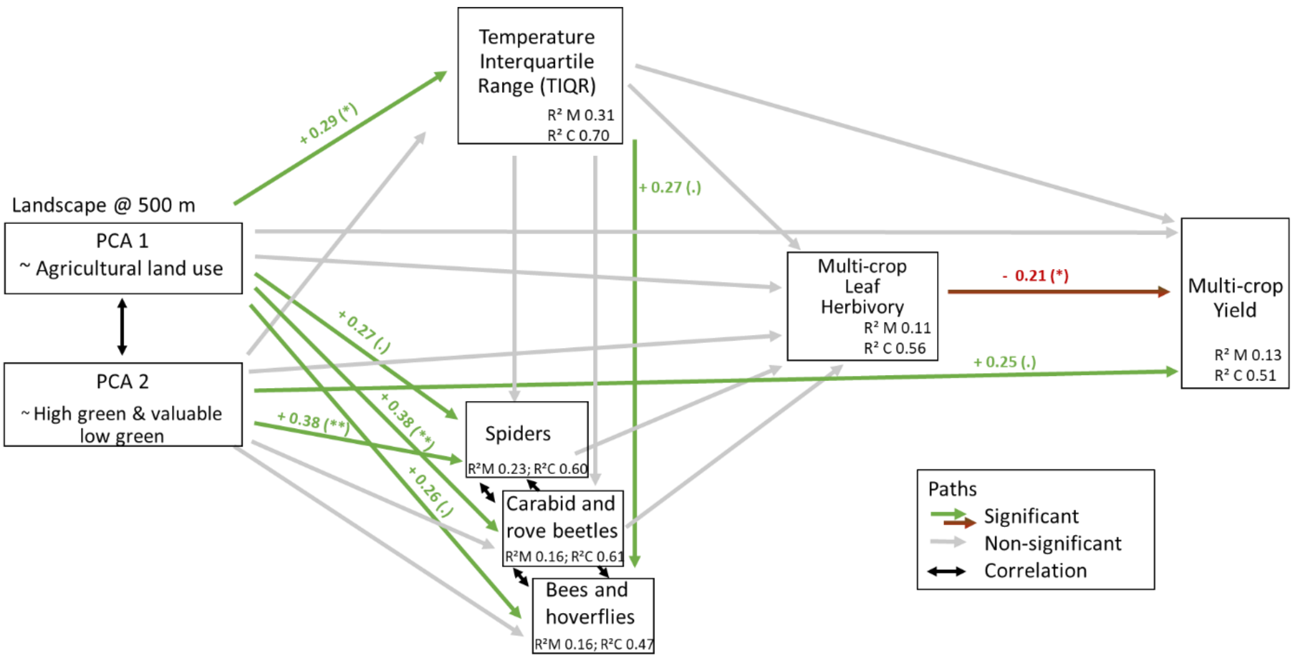


Figure 3.5: *Piecewise SEM of the determinants of multi-crop yield. PCA1 correlates positively with arable- and grassland and negatively with build-up area, non-valuable low green- and high green vegetation. PCA2 correlates positively with high green vegetation and biologically valuable low green vegetation and negatively with build-up area and non-valuable low green vegetation. There is no link hypothesised between pollinator activity-density and multi-crop yield as the latter is mainly not pollinator-dependent. Coloured standard estimates in the figure indicate significant pathways (negative = red, positive = green, p < 0.001= ***, p < 0.01 = **, p <0.05= *, p < 0.10 = .). All non-significant standard estimates are in grey. The marginal and conditional R^2 are given for all component models. The overall goodness of fit is P=0.62 with 8 degrees of freedom. The data is resulting from 33 and 35 1m²-gardens in respectively 2018 and 2019, which is a reduced dataset due to missing values in the compiled citizen science dataset. Year is included in the SEM as fixed term and location as the random term.*

Discussion

We found that the multi-crop yield is not related to landscape composition at a 500 m radius, thereby rejecting the first hypothesis. In line with the first two sub hypotheses, the results support that landscape composition influences both the microclimate and the activity-density of arthropods. The direction of the latter was partially to the expectations from other studies. More specifically, the higher activity-density of pollinators in open, agricultural areas is not supported by the literature (Shackelford et al. 2013; Dainese et al. 2017; Kleijn et al. 2018; Hass et al. 2019). Neither of the two mechanisms, however, explain the variation in yield of different crops along the landscape compositional gradient. Only the yield of leek was considerably lower in areas with a higher temperature range, yet no direct relationship of landscape variables with yield was observed for this crop. We structure the discussion according to the sub hypotheses after which management implications are formulated.

The buffering of temperature and soil moisture increases with a higher relative proportion of high green vegetation in the landscape

Landscapes with a higher relative proportion of high green vegetation provide increased buffering of soil temperature and soil moisture compared to landscapes with higher relative proportions of agricultural land use. The buffering effect related to the relative proportion of high green vegetation in buffers of 50, 125, 250 and 500 metre around the $1m^2$-gardens.

Several other studies confirm the buffering effects of high green vegetation (Suggitt et al. 2011; Tougeron et al. 2016) and complex landscapes (Alford et al. 2018). This relationship is addressed to (1) windbreaking, resulting in temperature buffering and higher relative humidity (Chen et al. 1999; Quénol and Beltrando 2006; Tougeron et al. 2016; Alford et al. 2018) and (2) reduced solar radiation (Chen et al. 1999). Since the $1m^2$-gardens were installed at locations that are free of high green vegetation in a radius of 10 metre, this scale offers no meaningful interpretation but is included for completeness. According to Martini et al. (2018), the buffering effects of urban forests reach in general up to 200 metre into the surroundings. At the first sight, our results would suggest that buffering effects of high green vegetation reach even further in the landscape. However, our results do not allow to fully separate the effect of local versus landscape scale high green on the local microclimate, since the share of high green vegetation is correlated along scales. For the temperature range, the size of the buffering effect does not vary among scales, suggesting that both the local and landscape scale high green vegetation are important for temperature buffering. For the soil moisture range, however, the buffering effect (negative estimate for effect of relative proportion of high green vegetation on the soil moisture variation) becomes slightly stronger negative at 250 and 500 metre radius compared to the 50 and 125 metre radius. This suggests that the wider landscape share of high green vegetation is important for the process of soil moisture buffering. It can be hypothesised that mainly local presence of high green vegetation determines solar radiation, impacting temperature buffering. Yet, cooling by evapotranspiration of high green vegetation (Zellweger et al. 2019) is supposed to reach further than the local surroundings of the vegetation. Also, for wind speed, the relative proportion of high green in the landscape (for instance 500 m) could be more important, impacting soil moisture buffering. However, this is only speculation and it could be valuable to study this in future experiments. Furthermore, the results suggest that local presence of biologically valuable low green vegetation is important for soil moisture buffering additionally to high green vegetation.

Summarised, in open agricultural landscapes, high green vegetation can be introduced to buffer soil moisture and temperature extremes. Biologically valuable low green vegetation such as road ditches or extensively managed grasslands can locally complement high green to buffer soil moisture. More research is needed to determine at what scale, and what proportion of the countryside should be devoted to high green vegetation.

The activity-density of predators and pollinators is higher in areas with higher relative proportions of arable land relative to areas with more residential land use

The most variation in activity-density of the studied taxa was explained by the landscape compositional gradient of residential versus agricultural land use, with pollinators and predators showing higher activity-density in areas with higher relative proportions of arable land. This result does not support our hypothesis that in areas with a higher relative proportion of non-crop vegetation pollinators and predators have a higher activity-density.

Higher activity-density of carabids in open, agricultural areas is confirmed in other studies (Tscharntke et al. 2012b; Martin et al. 2016; Dainese et al. 2017; Martin-Chave et al. 2019; Billaud et al. 2020) and can be attributed to higher prey availability within crop fields (Tscharntke et al. 2012b; Dainese et al. 2017; Billaud et al. 2020). For spiders and rove beetles this is reported less frequently. For spiders, the variation in activity-density is better explained by the landscape axis of high green and valuable low green vegetation versus residential, then by the axis residential versus agricultural land. This suggests that spiders' total activity in agricultural environments is higher than in residential areas, but they are most active in areas rich in non-crop habitat. Similar results are reported by Lemessa et al. (2015) and Schmidt et al. (2005), who respectively found the highest spider abundance and highest spider species richness in areas with high cover of open, non-crop habitats and high tree cover at either the local or landscape scales. We found a positive relationship between local biologically valuable low green vegetation with the activity of the studied predators. Up to 250 m radius the relative proportion extensively managed non-crop habitat was significantly positive. Shackelford et al. (2013) also report positive effects of local compositional landscape structure on both the abundance and diversity of spiders.

Against our expectations, we found no evidence for reduced herbivore damage on any of the crops at locations where the activity-density of predators was higher. Dainese et al. (2017) and Mitchell et al. (2014) found similar results, the latter concluding "that patterns of arthropod diversity and abundance across agricultural landscapes are not necessarily correlated with pest regulation or crop production". A possible explanation could be that the plant dwelling herbivores causing the observed damage were not predated by the ground dwelling predators in the pitfall traps. Another explanation can be that the higher activity-density of predators is counteracted by a higher density of diverse herbivores (Mitchell et al. 2014). Also, herbivores in the $1m^2$-gardens were flying (lepidoptera, diptera, hemiptera), except for slugs. While predators access the $1m^2$-gardens via the wooden board (large spiders) or at least have the capabilities to do so, next to their flying or ballooning capacities (carabids, rove beetles, small spiders). It is therefore possibly that predators had limited access to the $1m^2$-gardens compared to herbivores, resulting in an underestimation of the biocontrol potential.

In contrast to pitfall traps, fluorescent pan traps are designed to attract target organisms which possibly causes a concentration effect when situated in flower poor environments (Dainese et al. 2017; Portman et al. 2020). Since the pan traps at the agricultural side of the landscape compositional gradient stood out in maize or grass dominated environments, we argue that the pan traps in these conditions caught more pollinators because bees and hoverflies searching for flowers mainly find the pan traps (Portman et al. 2020). The contrast between the pan trap and the environment was only observationally noted by the researchers and was not confirmed by field data on flower availability in the surroundings at the time that traps were installed. Also, pan traps tend to catch more Halictid species because of their aggregated nesting behaviour compared to other occasionally visiting bees (Portman et al. 2020). A swift exploration of taxa represented in the pan traps confirms this bias although no full taxonomic study is done. Halictidae bees are mainly generalist foragers that are common in anthropogenically disturbed habitats (Eickworth 1988), probably explaining their high abundance in the areas with high relative proportions of agricultural land use. Following this interpretation, flower-rich residential gardens could be distracting pollinators from the traps, resulting in less caught individuals. Samnegård et al (2011) also used pan traps and phytometers and found higher abundance and species richness of bees and higher pollination services near residential gardens in intensive agricultural landscapes. Yet, an important remark is the difference in agricultural intensity between our Flemish case (50.2 ± 3.2% agricultural land use) and the case in southernmost Sweden (81.7% ± 5.9% agricultural land use) (Samnegård et al. 2011). Suggesting that residential gardens in the Swedish study are more important as refuge and source for bees than in our Belgian case. Similar to Pereira-Peixoto et al. (2014), who sampled bees in the garden-rural interface (43.1 ± 14.5% agricultural land use), we suggest that in our case mainly generalist bee and hoverfly species spill over from hospitable garden environments to neighbouring agricultural areas to forage.

According to our data, the activity-density of pollinators (bees, hoverflies) was not related to the average strawberry weight. However, when hoverflies and bees are included as separate factors, hoverflies positively associate with the average weight of strawberries. The importance of hoverflies (Syrphidae) for strawberry yield is also reported in other studies (Hodgkiss et al. 2018), yet Abrol et al. (2019) reported 93.4% of the flower visits to be by bee species and only 5.3% by syrphid flies.

The negative relationship of built-up area with predators and pollinators increases from the 10 m up to the 250 m radius and slightly falls back at 500 m radius. However, for the non-valuable low green vegetation (urban and residential green), the negative relationship becomes increasingly strong at larger radii. This suggests that the relationship between residential gardens and public green with the activity-density of predators and pollinators differs from the relationship with built-up areas. It is clear that the activity-density of arthropods in relation to landscape scale drivers is complex to understand. Further research is needed to look, for instance, into management practices within the studied land uses to fully understand its influence at the landscape level.

There are drawbacks related to the trapping methods and to working with broader taxonomic groups. We cannot include species richness, specific dietary needs and mobility of organisms or interactions between species (Bucher et al. 2014; Billaud et al. 2020). Pitfall traps are the most common trapping method for ground dwelling arthropods and could be combined with sampling of plant dwelling hunters (parasitoids, lacewings, ladybirds, hoverfly larvae etc.) to have a more complete overview of the predatory community. Also pan traps need critical interpretation because of taxonomic biases and unknown concentration effects due to floral resources on catch rates, although not confirmed in this study (Portman et al. 2020). To better understand possible concentration effects, a flower availability study at the moment of trapping should be done. Furthermore, we looked at abundance of arthropods from a functional point of view to provide natural pest control and pollination, while from the conservation perspective biodiversity metrics could show other trends.

Landscape-driven relationships of abiotic and biotic parameters with (multi) crop yield

From the ten crops in the 1m²-gardens, only the yield of leek decreased in areas with higher temperature ranges. This indirect relationship via temperature range does, however, not result in a direct negative or positive relationship of respectively agricultural land use or high green vegetation with leek yield. This suggests that probably other variables are at play. The effects of soil moisture buffering via high green vegetation in the landscape were probably overshadowed by weekly irrigation of the 1m²-gardens during the dry summer months in 2018 and 2019.

We found clear relationships between landscape composition and predators but for none of the ten crops this caused lower leaf herbivory where the activity of spiders and carabid/rove beetles was higher. Leaf herbivory had negative effects on the yield for parsley, lettuce, endive, radish and Chinese cabbage, probably because for these crops, the fresh weight of the leaves was registered as yield. For other crops, such as strawberry, onion and Brussels sprouts, other parts than the leaves were harvested and registered as yield. Considering the pollination-dependent crop in the $1m^2$-gardens, the total number of hoverflies was positively associated with the average strawberry weight. Agricultural land use had a positive indirect relationship with strawberry yield via increasing the activity-density of hoverflies.

When all crops' herbivory and yield are combined as the multi-crop indices, the results do not support the hypothesis that landscape composition relates to multi-crop yield. Although the abiotic and biotic mechanisms emerge as a pathway, we did not observe any ecosystem service delivery in the $1m^2$-gardens.

Management implications

Land users, land management organisations, local governments and policy makers involved in landscape development should work towards a landscape composition with a sufficient proportion of high green vegetation to buffer temperature extremes while still providing optimal forage situations for generalist pollinators and predators. Doing so could benefit a diverse cropping system with a complex demand from the environment. The exceptional drought and heat waves during the summers of 2018 and 2019 are in line with the expectations predicted by the ongoing climate change causing lower yields of vegetable crops. Apart from high green vegetation in agroforestry or permaculture systems, it can also be implemented at the landscape scale since the buffering effects are still effective in a 500 metre radius. Identification of optimal proportions considering high green vegetation in a 500 metre radius requires additional research.

The sampled functional arthropod community showed a higher activity-density in environments that have a higher share of arable land relative to residential areas with intensively managed low green vegetation. For predators**,** residential gardens could provide more food and shelter by using less herbicides and more extensive management. Also, locally, up to a radius of 125 m, biologically valuable low green vegetation such as extensively managed grasslands, buffer strips or road ditches is beneficial for predators. Spiders specifically benefit from high green and biologically valuable low green vegetation at the landscape scale. Despite these guidelines to promote the activity-density of different predators, it is important to state that these measures not necessarily lead to improved natural pest control as ecosystem service. Pollinators are assumed to forage and shelter in residential gardens and areas with non-crop habitats and spill over generalist pollinator species which go actively foraging on the agricultural matrix and could provide pollination. Therefore, it is advised to supply sufficient floral resources for bees and hoverflies and nesting possibilities.

Generalisation of our results is limited to regions with comparable landscape compositions and climatic conditions. This is the case for at least many peri-urban landscapes in Flanders. For further generalisation, spatially independent replications of our experiment are necessary. Therefore, in the next chapter of this thesis we present a replication of this experiment to further explore the generality of the results presented in this BEL-Landscape case study.

Data availability statement

Data available via the Dryad Digital Repository https: https://doi.org/10.5061/dryad.jq2bv q8cc.

Chapter 4

Consistency of landscape compositional effects on microclimate, invertebrates and plant performance across different years and regions

Adapted from: Gerits, F., L. Messely, B. Reubens, and K. Verheyen. 2023. Consistency of landscape compositional effects on microclimate, invertebrates and plant performance across different years and regions. Under review at Landscape Ecology.

Frederik Gerits designed the experimental design with 25 1m²-gardens together with Lies Messely, Bert Reubens and Kris Verheyen. The sampling during the measurement season was performed by Frederik Gerits. The processing of the data on arthropods, microclimate, leaf herbivory and yield was done by Frederik Gerits with support of Pallieter De Smedt. Statistical analysis was done by Frederik Gerits with support of Kris Verheyen and Bert Reubens. Frederik Gerits drafted and submitted the manuscript after in depth revisions by all co-authors.

Abstract

Reinforcement of agrobiodiversity in peri-urban areas requires a landscape lens. Relationships between land use composition and biotic and abiotic indicators of regulatory and provisioning ecosystem services can depend on weather conditions and differ between regions. In this study we check if relationships between landscape composition and indicators of regulating and provisioning ecosystem services are consistent between two different ecoregions and different years. We compare the results of replicated experiments in two different ecoregions in Flanders (Belgium). One in the province of East Flanders in 2018, 2019 (BEL-Landscape from previous chapter) and the other in the province of Antwerp in 2021. Some relationships are consistent while others are not. There is more consistency in the response of predatory invertebrates to the landscape composition than in the response of pollinators. The latter might be more dependent on weather or characteristics of the ecoregion. Although we cannot disentangle the effect of weather conditions and ecoregion, it is valuable to study the consistency of results in very similar peri-urban contexts but in

different conditions in terms of weather and region. The buffering effect of high green in the landscape magnifies when temperature and drought extremes occur. Arable land and built-up areas increase temperature and soil moisture variation. Using our methodology of 1m²-gardens as phytometers, we were able to link landscape composition to the local microclimate and activity-density of functional invertebrates but we did not succeed in explaining variation in crop performance via these mechanisms. The extent and maintenance of high green vegetation can be enhanced at landscape level to maximise their ability to buffer extreme weather conditions. In peri-urban areas we should avoid further urban sprawl into the rural matrix. Biologically valuable low green vegetation, which can be found in extensive grasslands, road verges or extensively managed domestic gardens, promotes ground dwelling arthropods, particularly when intertwined with arable land use.

Introduction

Functional agrobiodiversity refers to all living organisms that contribute to agriculture and includes both crops and livestock as associated biota such as weeds, hedgerows, predators or pollinators (Jackson et al. 2012). Intensification of agricultural practices caused a strong decline in crop diversity and semi-natural habitats such as hedgerows with crop production being highly dependent on fertilisers and crop protection (Tscharntke et al. 2005; Kleijn et al. 2009; Tscharntke et al. 2012a). High crop yields are achieved, but this system comes at the expense of other regulating ecosystem services and has little resilience to climate change (Felipe-Lucia et al. 2022).

In densely populated regions such as Flanders (492 inhabitants/km², Statbel 2021), simultaneous to agricultural intensification, there is a trend of actor diversification with intake of agricultural land by non-agricultural land-uses (Verhoeve et al. 2015). This results in a peri-urban space where multiple non-agricultural land uses coexist with arable land and productive grasslands. An example is urban sprawl where domestic gardens and built-up surfaces infiltrate rural areas via ribbon development, all with an impact on functional agrobiodiversity (as discussed in chapter 1).

Current actions for maintaining and reinforcing functional agrobiodiversity are mainly focused at parcel scale interventions (Estrada-Carmona et al. 2022), where flower strips are for instance used to boost invertebrates (Haaland et al. 2011). To increase the effectivity of functional agrobiodiversity reinforcement we need to zoom out to the landscape scale and make the rural landscapes more resilient and adaptive in collaboration with all land users (Landis 2017; Estrada-Carmona et al. 2022). We must consider functional agrobiodiversity as natural capital and consider it as a central resource in the peri-urban social-ecological system (Jackson et al. 2012). Agrobiodiversity is a crucial resource to create peri-urban landscapes that are less dependent on agrochemicals and resilient to the predicted climate change.

Results from the BEL-Landscape case study are presented in the previous chapter and show clear relationships between different land use types and abiotic and biotic ecosystem processes in the 1m²-gardens. We do not know whether the relationships observed in this first case study also apply in other peri-urban areas. To study the generality of the first case studies' results, we replicated the experiment in another ecoregion in Flanders in 2021. With ecoregions being areas "with a unified climate, geology, topography, soil, potential natural vegetation, and predominant land use" (Hughes and Omernik 1999). The first case in 2018 and 2019 took place during seasons with multiple heat and drought waves in a river valley ecoregion, the second case in 2021 during the season with the highest precipitation since the start of weather measurements and average temperatures in a Campine region.

Invertebrate communities differ between ecoregions (Steinke et al. 2022). Because of interactions between land use and ecoregions it is important to perform regional studies for different taxa (Kohler et al. 2020). Weather conditions could furthermore influence the invertebrate community (Diehl et al. 2011; Gontijo 2019). Microclimate buffering by forests is magnified when temperatures reach higher extremes (De Frenne et al. 2019). Because landscape compositional effects on invertebrate activity-density and microclimate could differ between years and ecoregions, an altered effect on ecosystem service delivery in terms of crop herbivory control, pollination and crop performance could be expected as well.

Hypotheses

Our overall hypothesis is that differences in weather conditions and between ecoregions influence how landscape composition relates to local agroecosystem processes and agroecosystem service delivery. More specifically we hypothesise that

1. effects of landscape composition on microclimate are similar but weaker when weather conditions are less extreme;
2. the effects of landscape composition on the density of invertebrate activity are robust, but weaker or stronger because of different ecoregions and weather conditions;
3. differences in the sampled landscape compositional gradient [2] cause differences in magnitudes of landscape compositional effects on microclimate or invertebrates;
4. landscape compositional effects on microclimate and invertebrate activity explain only to a limited extent observed variation in crop herbivory and crop yield.

Material and methods

Research landscape

The research landscape for this chapter was located in the province of Antwerp 2021 (Flanders, Belgium) and is called "Merode" (Fig. 4.1). Within the municipalities Geel and Laakdal (indicated on map in Fig. 4.1), we sampled a smaller study landscape (21 km²). We also provide parallel information on to the earlier BEL-Landscape case study in the Province of East Flanders to facilitate comparison in the discussion section of this chapter.

[2] With differences in sampled landscape compositional gradients we mean that in BEL-Landscape we had more 1m²-gardens in surroundings with agricultural land use while in Merode there were more 1m²-gardens in residential areas (see Fig.2.5 and Fig. 4.3).

	Variable	Merode (1)	BEL-Landscape (2)	
Project	Communities	Geel, Laakdal (Antwerp)	Merelbeke, Oosterzele, Melle (East Flanders)	
	Years	(May – October) 2021	(May – October) 2018 & 2019	
	Study area (convex hull)	21 km²	29 km²	
	# 1m² - gardens	25	41	
	Ecoregion	Campine region	Pleistocene river valleys	
	Dominant soil texture	Sand	Sandy loam	
Landscape composition	Forest	21 %	19 %	
	Built-up	15 %	14 %	
	Residential green	18 %	16 %	
	Agriculture	**47 %**	**51 %**	
	Grassland	*49 %*	*39 %*	
	Maize	*36 %*	*26 %*	
	Grains, seeds, legumes	*4 %*	*12 %*	
	Potato	*5 %*	*5 %*	
	Vegetables, spices, ornamental plants	*1 %*	*7 %*	
	Other	*5 %*	*11 %*	
		2021	**2018**	**2019**
		Season value (normal value)**	**Season value (normal value**)**	
Climate *	Average temperature	17.8 °C (17.9) N	19.8 °C (17.6) **E**	19.1 °C (17.6) **V**
	Average max temp	21.8 °C (22.5) N	24.7 °C (22.1) **E**	24.0 °C (22.1) **V**
	Average min temp	13.9 °C (13.4) N	14.8 °C (13.2) **E**	14.0 °C (13.2) N
	Precipitation total	411 mm (234) **E**	135 mm (225) **A**	199 mm (225) N
	Precipitation days	50 days (43) N	20 days (44) **E**	33 days (44) N
	Global sunshine	410 kWh/m² (443) N	498 kWh/m² (430) **E**	488 kWh/m² (430) **A**
	Relative humidity	75 % (72) **A**	62 % (73) **E**	70 % (73) N

Figure 4.1: *Location and details of landscape observatory Merode (1) and BEL-Landscape (2) in the northern region of Belgium (Flanders). The agricultural land use is further divided into different crop groups. *Climate data are defined for Ukkel* (KMI 2022). ***The normal values for the season are given between brackets (average value of period 1981 – 2010 for 2018, 2019 and average value of period 1991 – 2020 for 2021) together with a code referring to the exceptionality of the values with N: normal (repetition period < 5 years), A: abnormal (6 < repetition period < 10), V: very abnormal (10 < repetition period < 30), E: exceptional (repetition period > 30).*

Study design

For this study we again use the 1m²-garden toolbox described in chapter 2 and apply it in a second landscape observatory Merode to replicate the study on the relationship between landscape composition and abiotic and biotic variables related to agroecosystem services (chapter 3), but in an independent landscape. The Merode observatory is located within a 21 km² area and represents another peri-urban landscape in Flanders (Belgium) with a variety in land uses and land use intensities. The area is situated between the cities of Geel and Tessenderlo with in between several smaller residential settlements belonging to the municipality of Laakdal (Fig. 4.2). These smaller settlements are connected with roads with houses and domestic gardens on both sides. This ribbon development causes the open space belonging to agriculture and nature to be highly fragmented. Comparable to the BEL-Landscape case, nature areas are mainly concentrated in the valley areas of the rivers 'Grote Nete' and 'Laak' and several scattered forest fragments. Furthermore, the northern border of the study landscape is defined by the highway E313 and a parallel canal ('Albertkanaal') which are flanked by a large industry zone.

The standardised vegetable gardens of 1m² each ('1m²-gardens') are, again, installed along a gradient of landscape composition considering the same land use types described in the general introduction and chapter 2 of this thesis (Fig. 4.2). The design of the 1m²-gardens is nearly identical to the BEL-Landscape case, only radishes were not included because of shortage at the plant nursery and replaced by a second parsley plant (Fig. 4.2, see appendix Table B1 for crop details). The growing medium used in this study consisted of 60% loamy sand, 25% mature compost and 15% of a sustainable variant of peat. The starting material for the latter is wood cuttings. The field campaign in 2021 was conducted from the last week of April until the end of September (identical to BEL-Landscape). The summer months of 2021 were the wettest since 1981 and averagely warm (Fig. 4.1). We irrigated all 1m²-gardens three times with ten litres and eleven times with five litres water (85 litres/garden). Due to the wet season we irrigated less compared to both BEL-Landscape seasons, where we irrigated 210 litres/garden in 2018 and 105 litres in 2019. To support the standardised management of the 1m²-gardens another collaboration was set up with 28 volunteers. Tasks that were easy to communicate and standardise, such as weeding, irrigation and measuring the harvest, were delegated to the volunteers. More details on the participatory trajectory and the learning outcomes thereof are described in chapter 5 of this thesis. Because of the similarity of the methodology, we will frequently refer to the methodology section of Chapter 3 and focus in this section on the differences in the approach.

The aim of replicating the experiment with $1m^2$-gardens in another peri-urban area, was to evaluate the consistency of landscape compositional effects on microclimate, invertebrates and plant performance across different years and regions, and hence to evaluate the robustness of our observation methodology. Both regions were comparable in terms of multi-actor pressure on agricultural land and in terms of fragmented land use: a highly intertwined mixture of agricultural land, nature areas and non-agricultural land usage were observed. We want to stress explicitly that it was not our primary aim to disentangle effects from weather and ecoregion on the consistency of the results. The fact that the experiments were performed in different years for both regions does not allow this. Yet, it remains relevant to study which relationships between landscape composition and agroecosystem functioning are consistent, despite opposite weather conditions and differences in ecoregion. Furthermore and at least as important: we also wanted to evaluate the social dimension of our methodology. The fact that we had to construct a citizen science project starting from a totally different social network in the Merode case, was found highly valuable and enabled us to learn a lot about the feasibility of this combined socio-ecological study framework.

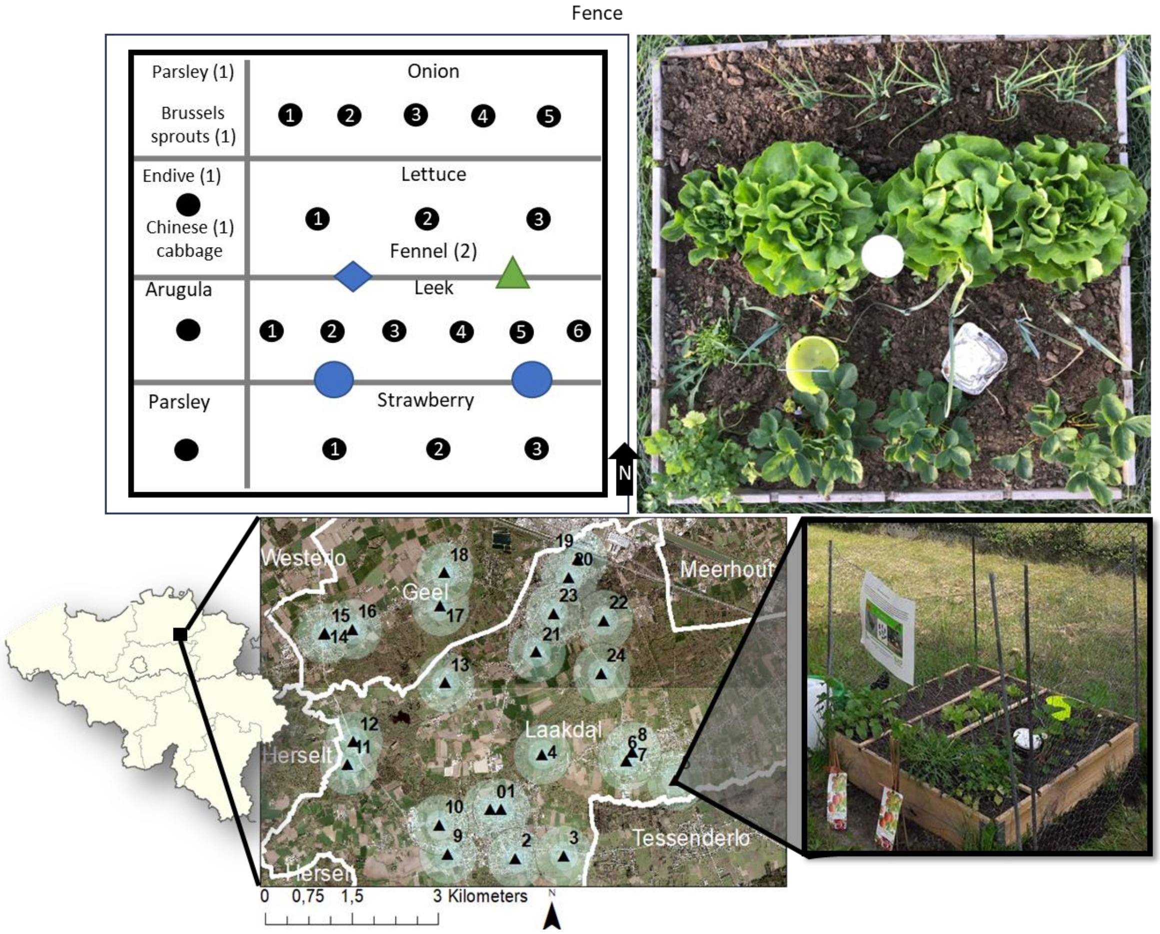


Figure 4.2: *Below: The 'Merode' landscape observatory in Flanders. 25 1m²-gardens are spread in a study area representative for peri-urban Flanders. Above: 1m²-garden design. Blue diamond: sensor for soil moisture and temperature. Blue circles: (1) fluorescent yellow pan trap for flying arthropods (2) pitfall trap for soil dwelling arthropods. Brussels sprouts, Chinese cabbage and fennel are planted after early harvest of parsley, endive and lettuce. Figure adapted from Gerits et al. (2022).*

Land use composition

We determined the proportion of the same six land use categories as in BEL-Landscape around each 1m²-garden at 10, 50, 125, 250 and 500-metre radius, using the same source material (see Table 3.1). In a first phase, 500 metre landscape data were used to sample 25 locations for 1m²-gardens along a gradient of non-crop habitats (Fig. 4.3). Non-crop habitats include all vegetation that is no productive grassland or arable land, being high green vegetation and both biologically valuable and non-valuable, residential low green vegetation. Similar to the BEL-Landscape case, the land use types were correlated (Grab et al. 2018; Billaud et al. 2020), therefore, for the analysis, we reduced the land uses in two orthogonal principal components (Fig. 4.4, see also appendix Fig. C1 for correlation details). The PCA in Merode was highly similar to BEL-Landscape (Table 4.1). 1m²-gardens were installed at locations with as little high green vegetation nearby as possible (10 metre radius) to avoid shade and litterfall. Presence of nearby concrete surfaces was also avoided. The vegetation around the 1m²-garden was kept short to avoid interference. Similar to BEL-Landscape, the nearby vegetation was highly associated with the land-use in the wider environment. For instance, 1m²-gardens in private gardens often had lawns in the 10 m radius. Because there were very few 1m²-gardens in Merode with arable or productive grassland in the 10-metre radius surrounding the location, the models for this scale did not deliver interpretable estimates (in contrast to BEL-Landscape, Fig. 4.5). Therefore, for arable land use and productive grassland, the 10-metre scale was omitted (Fig. 4.6 and Fig. 4.7).

At two locations, two 1m²-gardens were deliberately positioned at close spatial proximity in order to have a replication of those two locations. However, also on other locations there was an overlap between the landscape buffers surrounding the 1m²-gardens, with increasing overlapping areas from 10 to 500 m (Fig. 4.2). The number of overlapping buffers were lower compared to BEL-Landscape. Previous research indicates that overlapping buffers do not necessarily cause statistical dependency or spatial autocorrelation if a robust spatial design is used, avoiding the influence of exogeneous environmental factors (Zuckerberg et al. 2012; Zuckerberg et al. 2020). In chapter 2 the robust design (see Gerits et al. 2021) was validated by an analysis of spatial autocorrelation in the model residuals for all response variables (Dormann et al. 2007; Kühn and Dormann 2012; Zuckerberg et al. 2020) (appendix Table B4).

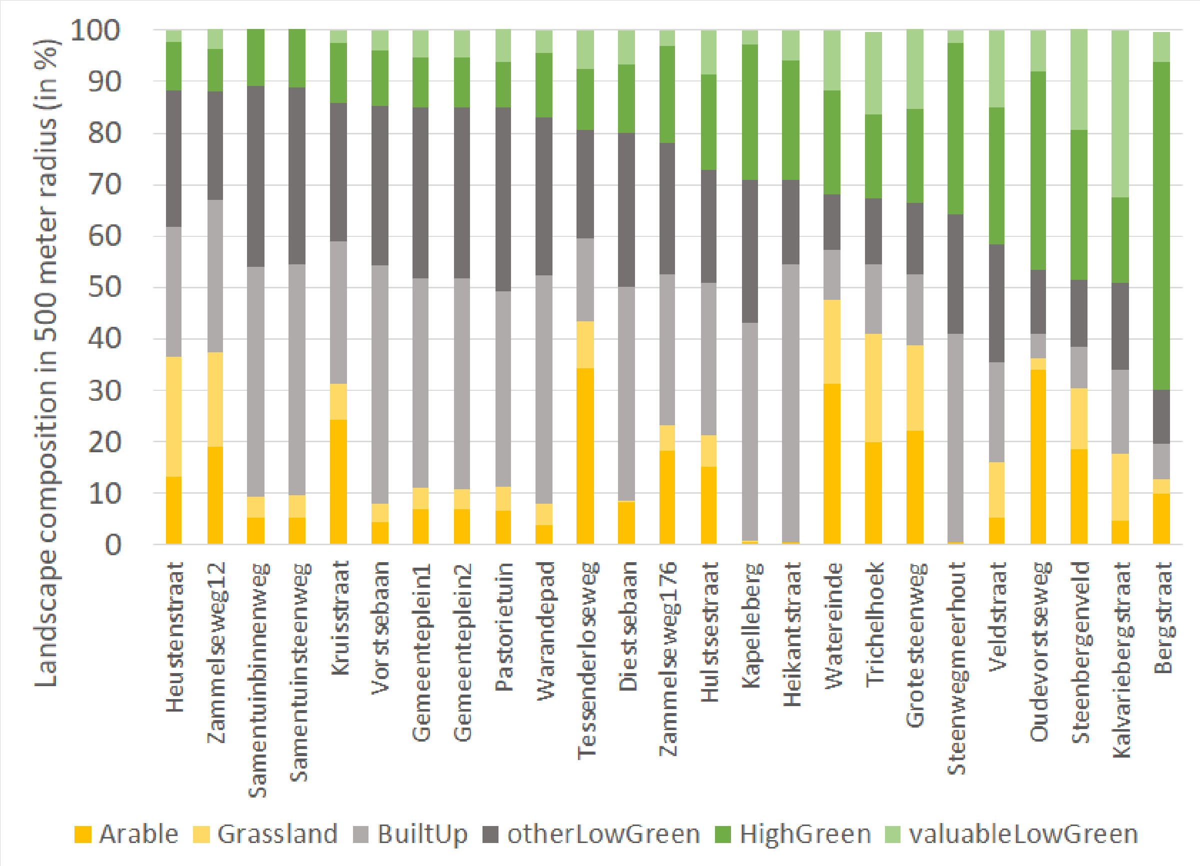


Figure 4.3*: Landscape composition considering six land use types surrounding the 25 1m²-gardens in Merode case at the 500 m radius. The 1m²-gardens are arranged according to the relative proportion of semi-natural habitat (sum biologically valuable low green and high green vegetation) in the 500 meter radius.*

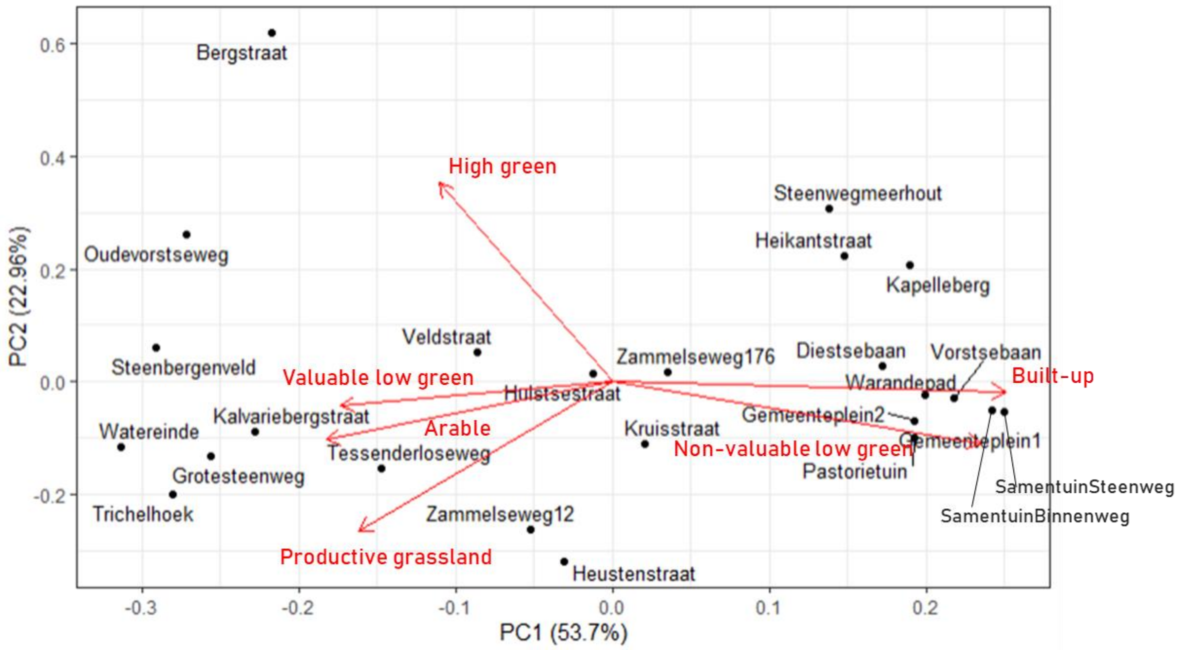


Figure 4.4*: Principal Component Analysis (PCA) of the six land use types characterising the 25 1m²-gardens at a 500 m radius (valuable low green vegetation, high green vegetation, productive grassland, arable land, other low green vegetation and built up area).*

Table 4.1*: Interpretation of the two principal components (PCA 1 and 2) at 500 m radius with indication of the explained variation per axis for both Merode and BEL-Landscape.*

		Merode	**BEL-Landscape**
PCA 1	Description	(+) Built-up, non-valuable low green (-) Productive grassland, arable land, valuable low green vegetation	(+) Productive grassland, arable land (-) Built-up, non-valuable low green, high green
	Variation explained	54%	46%
PCA 2	Description	(+) High green vegetation (-) Productive grassland	(+) High green vegetation, valuable low green vegetation
	Variation explained	23%	22%

The relative proportion of agricultural land use (sum arable and productive grassland) in a 500 m radius around the 1m²-gardens in Merode was 20.5% (max = 47.7%, min = 0.6%) and is considerably lower than the average for Flanders (50%). For high green vegetation the average was 19.1% (max = 64.6%, min = 8.2%). For valuable low green vegetation 8.0% (max = 32.5%, min = 1.1%). For other low green vegetation 23.5% (max = 35.8%, min = 10.7%). For Built-up areas 29.1% (max = 53.9%, min = 4.6%). A comparison to the BEL-Landscape case shows less agricultural land use and more residential land use in the Merode case, with residential land use (other low green) and built-up surfaces (Fig. 4.5).

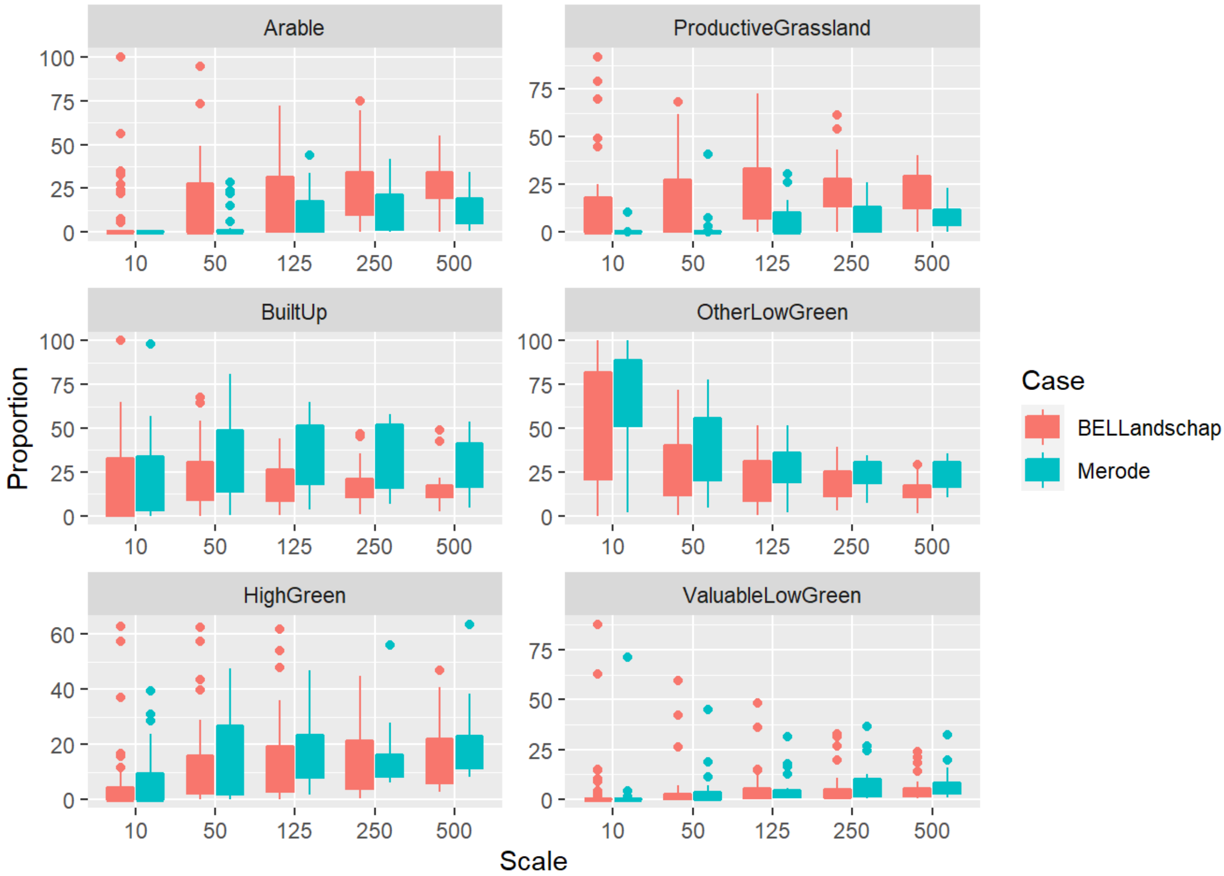


Figure 4.5*: Comparison of landscape composition at different scales between BEL-Landscape (n = 41) and Merode (n = 25) for the six considered land use types. The proportion (in %) on the y-axis points to the relative proportion of the considered land use in a buffer which is defined by the scale on the x-axis. For instance, in a buffer of 10 metre the relative proportion of arable land use is defined as % land use.*

The monitoring procedures for both the abiotic and biotic factors and herbivory and yield as response variables were identical in Merode compared to BEL-Landscape. Therefore, we refer to the methodology section of chapter 3 for a full description. Considering the statistical analysis, different from the BEL-Landscape case, we simplified our models to general and generalised linear models because there was no need to correct for replicated sampling in random terms.

Results

Here we present the results of the Merode case study in an identical way as for the BEL-Landscape case (chapter 3). In the discussion of this chapter, we provide a comparative overview of the results of the two cases and elaborate on the similarities and differences.

Relationship between landscape composition and functional invertebrates

We found a **positive relationship** between the activity-density of **predators** and the relative proportion of biologically valuable low green vegetation (in radii of 125, 250 and 500 m), arable land (in radii of 125, 250 m) and productive grassland (only in the radius of 500 m) (Fig. 4.6). Furthermore, we found a **negative relationship** between the activity density of **predators** and the relative proportion of non-valuable low green (domestic gardens, parks etc.) (in radii of 50, 125 and 250 m) and built-up areas (in radii of 250 and 500 m). There was no relationship with the relative proportion of high green vegetation.

We found a **positive relationship** between the activity-density of **pollinators** and the relative proportion of non-valuable low green vegetation (domestic gardens) (in radii of 10, 50 m) and productive grassland (500 m) (Fig. 4.6). Furthermore, we found a **negative relationship** between the activity density of **pollinators** and the relative proportion of high green vegetation (in radii of 10, 50, 125, 250 and 500 m) and built-up areas (only in the radius of 10 m). There were no relationships with the relative proportion of valuable low green or arable land.

In the appendices we show the model estimates for the different taxonomic groups within the presented pollinator and predator functional groups (Fig. C2, Fig. C3).

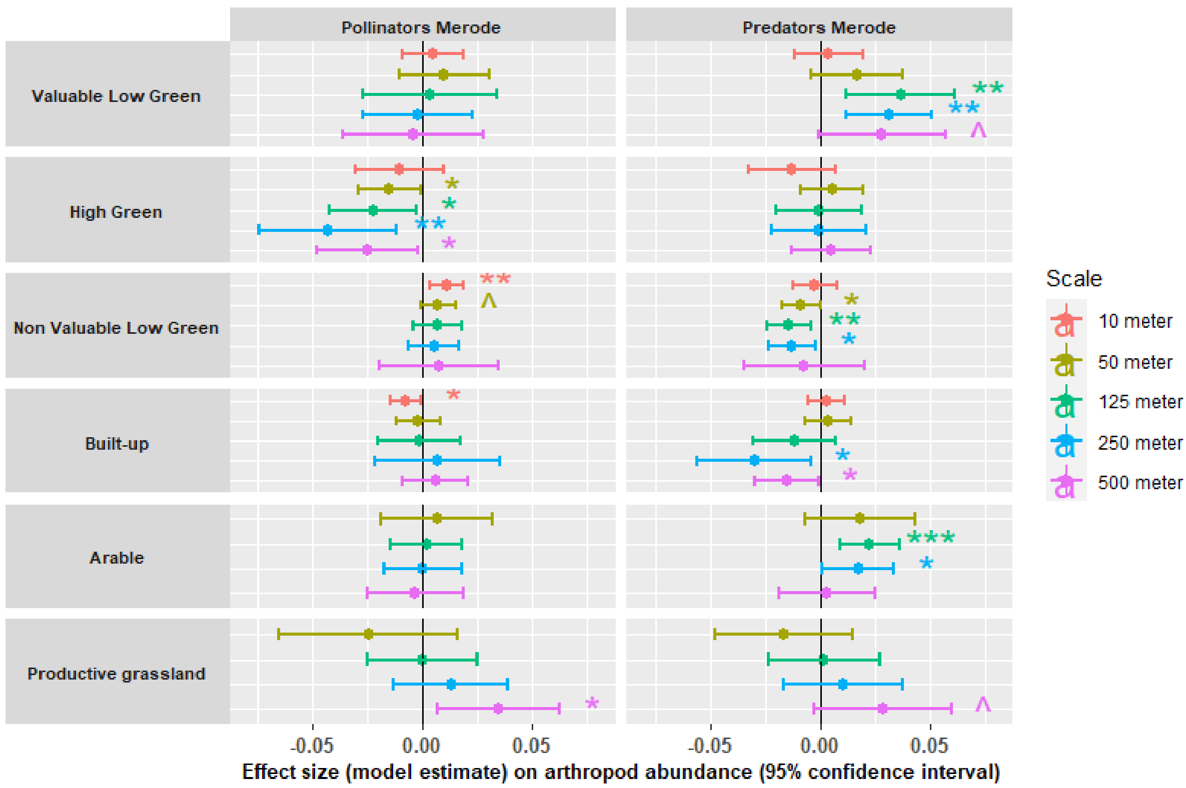


Figure 4.6: *The effect size (model estimate) of landscape composition (the relative proportion of valuable low green, high green, non-valuable low green, built-up, arable, productive grassland) at five different scales on the abundance of predators (spiders, carabids and rove beetles), pollinators (hoverflies and bees). Model estimates and 95% confidence intervals are calculated with a generalized linear model with the relative proportion of the land use variable as explanatory factor. Significance levels are given in the corresponding scale colour (p < 0.001= ***, p < 0.01 = **, p <0.05= *, p < 0.1 = ^).*

Relationship between landscape composition and the microclimate variation

We found a **positive relationship** between the **temperature interquartile range (TIQR)** and the relative proportion of built-up areas (only in the radius of 50 m) (Fig. 4.7). Furthermore, we found a **negative relationship** between the **temperature interquartile range (TIQR)** and the relative proportion of high green vegetation (only in the radius of 10 m). There were no relationships with both the relative proportion of non-valuable as valuable low green vegetation, arable land or productive grassland.

We found a **positive relationship** between the **soil moisture interquartile range (SMIQR)** and the relative proportion of non-valuable low green vegetation (in the radii of 125, 250 and 500 m) and built-up areas (in the radii of 250, 500 m) (Fig. 4.7). Furthermore, we found a **negative**

relationship between the **soil moisture interquartile range (SMIQR)** and the relative proportion of high green vegetation (in the radii of 125, 250 and 500 metre) and productive grassland (in the radii of 50, 125 and 250 m). There were no relationships with the relative proportion of valuable low green vegetation or arable land.

In the appendices we show model estimates for other microclimate variables: Tmin, Tmax, Tmean (Fig. C4, Fig. C5). We found a **positive relationship** between the **mean daily average temperature (Tmean)** and the relative proportion of non-valuable low green vegetation (in the radii of 10, 50, 125 and 250 m). We found a **negative relationship** between the **mean daily average temperature (Tmean)** and the relative proportion of high green vegetation (in the radii of 10, 50, 125, 250 and 500 m). Therefore, the mean daily average temperature seems to be a better predictor than TIQR. For the piecewise structural equation models, we therefore include mean temperature (Tmean) as temperature variable in the models.

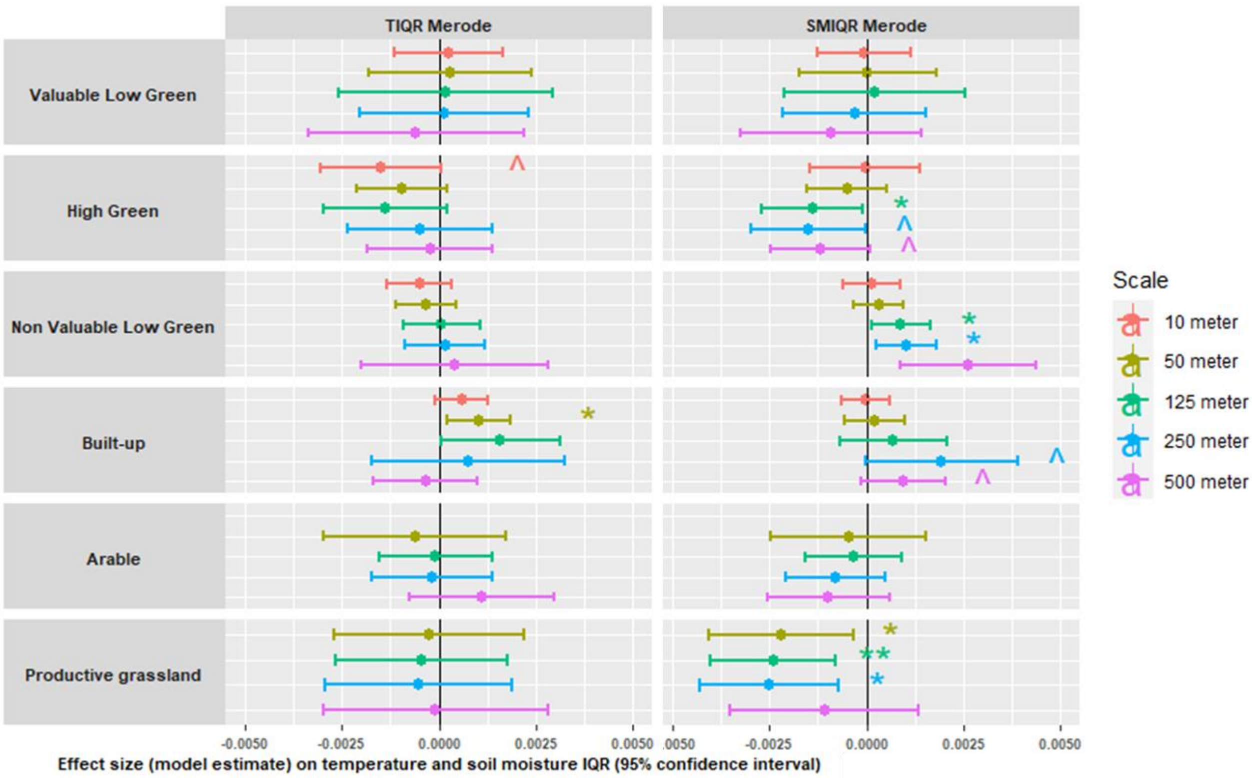


Figure 4.7: *The effect size (estimate) of landscape composition (the relative proportion of the valuable low green, high green, non-valuable low green, built-up, arable, productive grassland) at five different scales on the square root transformed interquartile temperature range (TIQR) and the interquartile soil moisture range (SMIQR). Model estimates and 95% confidence intervals are calculated with a linear effect model with the relative proportion of the land use variables as explanatory variables. Significance levels are given in the corresponding scale colour (p < 0.001= ***, p < 0.01 = **, p <0.05= *, p < 0.1 = ^).*

Relation of landscape composition to crop herbivory and yield

Below we present the results of the multi-crop and crop specific piecewise structural equation models with the land use composition summarised in two PCAs at the 500 m scale as explanatory variables (Fig. 4.8, Table 4.2). We found no relationships between neither of the principal component axes and both the multi-crop herbivory or yield.

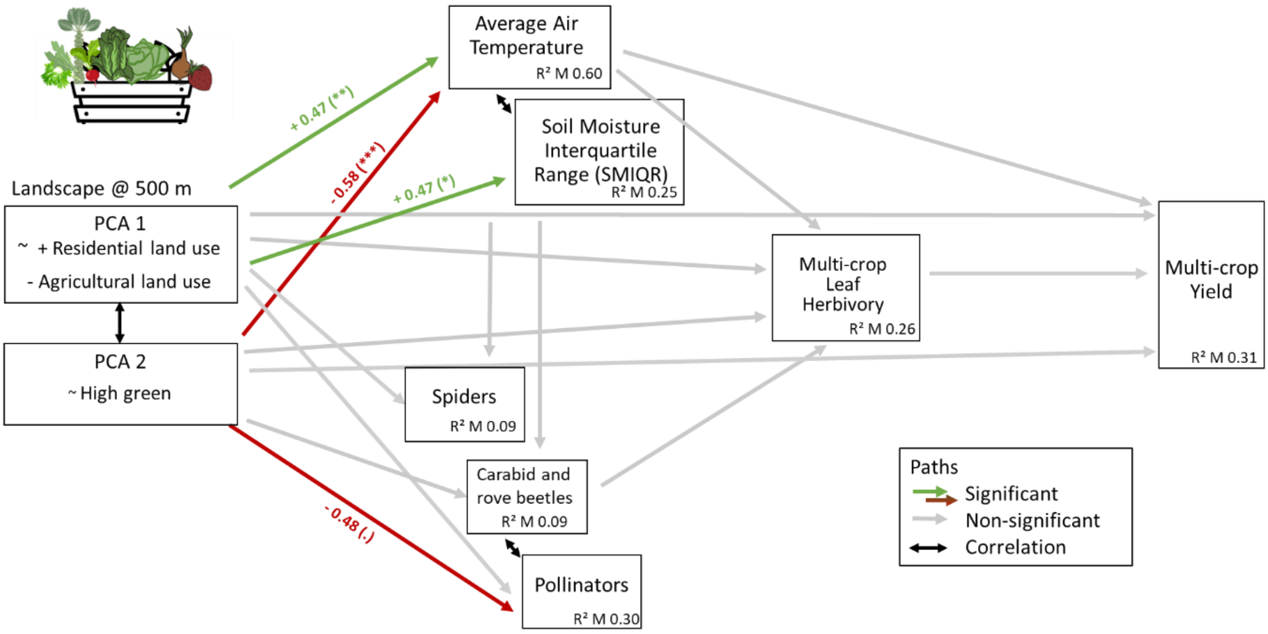


***Figure 4.8**: Piecewise SEM of the determinants of multi-crop yield. PCA1 correlates positively with residential land use (built-up and non-valuable low green vegetation) and negatively with agricultural land use (arable and productive grassland). PCA2 correlates positively with high green vegetation. Coloured standard estimates in the figure indicate significant pathways (negative = red, positive = green, p < 0.001= ***, p < 0.01 = **, p <0.05= *, p < 0.10 = .). The relationships between the abiotic and biotic variables are represented by one set of arrows for simplicity, yet all combinations are included in the model. All non-significant standard estimates are in grey. The marginal R^2 are given for all component models. The overall goodness of fit is P=0.22 with 10 degrees of freedom. The data is resulting from 23 1m²-gardens which is a reduced dataset due to missing yield data in two 1m²-gardens.*

Considering the crop-specific models we found that the yield of strawberry was marginally positively related to the high green vegetation (second principal component). Both the yield of onion and Chinese cabbage were negatively related to residential land use, being private gardens and built-up areas (first principal component). For these three relationships we were not able to reveal a trend via the studied abiotic or biotic pathway. The yield of onion, parsley and lettuce correlated positively with the SMIQR, and negatively with the yield of fennel.

There were no relationships found between crop herbivory as response variable and (TMean, SMIQR, Pollinators, Predators, PCA1, PCA2) as explanatory variables. Therefore, we do not include these pathways of the crop specific piecewise SEMS in the results (Table 4.2).

Table 4.2: *Standard estimates for crop-specific piecewise SEMs. Coloured standard estimates in the table indicate significant pathways (negative = red, positive = green, p < 0.001= ***, p < 0.01 = **, p <0.05= *, p < 0.10 = .). The overall goodness of fit (P) and number of 1m²-gardens (N) per crop. The relationship of pollinators' activity-density is only relevant with the yield of strawberry.*

Response variable			Yield					
Explanatory variable			Herbivory	TMean	SMIQR	Pollinators	PCA1	PCA2
	N	P						
Strawberry	23	0.05				+ 0.67 **		+ 0.48 ^
Leek	23	0.32				/		
Onion	23	0.34	- 0.40 *		+ 0.66 **	/	- 0.53 *	
Parsley	22	0.18	- 0.62 **		+ 0.45 ^	/		
Arugula	23	0.12	- 0.58 *			/		
Lettuce	23	0.21	- 0.62 **		+ 0.45 ^	/		
Endive	23	0.11				/		
Fennel	23	0.12	- 0.40 ^		- 0.61 **	/		
Chinese cabbage	23	0.26	- 0.61 **			/	- 0.59 *	
Brussels sprouts	23	0.19				/		

Discussion

If we now compare BEL-Landscape and Merode as spatially independent cases where the same methodology of 1m²-gardens as phytometers was used, we can consider both consistent and inconsistent relationships between landscape composition, microclimate, arthropod activity-density and ecosystem functioning (Table 4.3). We define a relationship as consistent if it was significant in both case studies, independent of the effect sizes or at which scales the relationship occurs. Considering functional invertebrates, predators show more consistent responses to surrounding land uses than pollinators. Microclimatic buffering of high green vegetation was consistent in both cases, but more prominent in seasons with extreme droughts and heatwaves. Land use types which related positively to microclimate variation were different in both cases. In neither of the cases the leaf herbivory or crop yield related to the relative proportion of any of the surrounding land uses. It might ask some finetuning of measurement approaches to better couple these landscape scale induced processes to local ecosystem service delivery. In this paragraph we discuss and hypothesise why some relationships were consistent in both cases and others were not. Finally, we make recommendations for future design of rural landscapes recognising that some trends are region and weather dependent.

Table 4.3: *Summary of relationships between the relative proportions of the six defined surrounding land use types and the activity-density of predatory arthropods and pollinators, variation in temperature and soil moisture and multi-crop herbivory and yield from both cases (MER = Merode, BEL = BEL-Landscape). '+', '-' and '0' respectively stand for a positive, negative or neutral relationship. A '+' means that for at least one scale a positive relationship was found between the explanatory landscape variable and response variable. For the multi-crop indicators, the six land use types were reduced to principal component axes and focused on the 500-metre scale.*

	Case	Valuable low green vegetation	High green vegetation	Non valuable low green	Built-up	Arable land	Productive grassland
Predators	MER	+	0	-	-	+	+
	BEL	+	0	-	-	+	0
Pollinators	MER	0	-	+	-	0	+
	BEL	0	0	-	-	+	0
Temperature variation	MER	0	-	0	+	0	0
	BEL	0	-	-	0	+	+
Soil moisture variation	MER	0	-	+	+	0	-
	BEL	-	-	0	0	+	0
PCA **(500 m radius)**		Semi-natural habitat		Residential areas		Agriculture	
Multi-crop herbivory	MER	0		0		0	
	BEL	0		0		0	
Multi-crop yield	MER	0		0		0	
	BEL	0		0		0	

Predatory invertebrates respond consistently to the surrounding landscape composition, while the response of pollinators seems to be more context dependent

In both cases, predatory invertebrates (natural enemies of pests in crops) were caught more in environments with higher relative proportions of valuable low green vegetation and arable land use. Biologically valuable non-crop vegetation is described as an important food source for these predatory invertebrates, and also creates shelter and refuge from pesticides or intraguild predators (Lee et al. 2001; Gontijo 2019). Non-crop shelter is also found to be important as refuge both in extreme dry and warm conditions, but also in periods of extreme rainfall (Diehl et al. 2011; Gontijo 2019), possibly pointing out why the beneficial effect of valuable low green vegetation for predatory invertebrates is consistent over both case studies. Second, higher relative proportions of arable land use in the surroundings increases activity-density of predatory invertebrates. This coincides with findings of Rand and Tscharntke (2007) who found that spiders, as generalist natural predators, were denser in simple landscapes. Furthermore, Raderschall et al. (2022) found higher rove beetle activity density with increasing mean size of agricultural fields and Dainese et al. (2019) found higher abundance of carabid beetles with higher arable land cover. These findings are often attributed because of prey availability in arable crops (Rand and Tscharntke 2007; Dainese et al. 2017) and it is suggested that mainly generalist species benefit from “the variety of periodically available, but highly abundant, resources in crops” (Rand and Tscharntke 2007, p. 1359).

We found consistent negative relationships between the activity-density of predatory invertebrates and both the relative proportion of non-valuable low green vegetation and built-up areas. These land use categories largely coincide with domestic gardens or other intensively managed green spaces such as public parks, which typically correlate with built-up areas. This coincides with the findings of Piano et al. (2020) who identified urbanisation (with % built-up area as proxy) as a driver for decline of multiple taxa, including carabid beetles and spiders. One explanation for this trend is found in poor environmental conditions among which the heat island effect (Piano et al. 2020). This heating effect in urbanised regions was confirmed in our data by the positive relationship between built-up area and both temperature and soil moisture, but only in the BEL-Landscape case. This was expected considering the heat waves during the growing seasons in the BEL-Landscape case and average temperatures during the Merode season. Furthermore, this might also explain why the consistent negative relationship between the relative proportion of built-up areas and both pollinators and predators is stronger in BEL-Landscape compared to Merode.

The relative proportion of built-up area is the only explanatory land use variable that consistently relates negatively to the activity density of pollinators. This is in line with the findings of Wenzel et al. (2020) who found that urban sprawl is negative for pollinators and pollination when built-up areas exceed 50% of the relative proportion of the landscape. Levé et al. (2019) also conclude impervious surfaces as unfavourable habitats and join the arguments of Wenzel et al. (2020) that domestic gardens can be beneficial for pollinators. We found inconsistent relationships between pollinator activity density and the relative proportion of residential green. Pollinators were more abundant in areas with a higher relative proportion of local residential green in Merode, while this relationship was strongly negative in BEL-Landscape over all considered scales. Similar inconsistencies were concluded in the relationship between pollinators and the relative proportion of arable land use in the environment. In Merode there was no relationship found, where it was strongly negative over all scales in BEL-Landscape. For the Merode case, we looked separately at both pollinator groups and concluded that hoverflies and bees relate differently to the relative proportion of surrounding land uses. In Merode, bees relate positively to local the relative proportion of residential green and hoverflies to the relative proportion of arable land use. These different responses for dipterans and hymenopterans to urban and rural land uses were also confirmed by Theodorou et al (2020). A last inconsistent result was found in pollinators relationship with the relative proportion of high green vegetation, which was strongly negative in Merode and neutral in BEL-Landscape. This negative relationship in Merode was defined by bees, not hoverflies. Hall et al. (2019, p.1) confirm that "species richness and abundance of bees was greater at sites containing little or no tree cover". The inconsistency of this result in both cases might be due to different forest types or different weather conditions in the considered cases.

Pollinators and predators were not identified at the species level, so we could not examine how communities differ between both cases. Yet, independent of possible differences in species compositions, predators showed highly consistent responses to surrounding land use composition in both cases. Although local microclimate conditions influence the activity density of predators (Diehl et al. 2011; Gontijo 2019), predator trends were consistent over seasons with opposite weather conditions, ranging from historically dry and hot summers to moderately warm but record breaking precipitation. For pollinators the context might be more important. With context referring to both weather conditions and differences in land use characteristics, soil conditions, forest types or species compositions. Furthermore, bees and hoverflies appear to relate different to the relative proportion of land uses while carabids, rove beetles and spiders as ground dwelling predatory invertebrates show more similar responses.

Extreme hot and dry summer seasons aggravate temperature and soil moisture extremes in arable conditions and increase buffering of high green vegetation in the landscape

In the Merode case there were no relationships between the relative proportion of arable land use and the temperature or soil moisture variation, while in BEL-Landscape these relationships were positive. This suggests that during heat waves or periods of drought (BEL-Landscape), arable conditions reach higher extremes considering temperatures and soil moisture. Because of climate change, an increasing exposure of arable staple crops to extreme wetness or dryness and extreme temperatures are expected (Jackson et al. 2021). The average daily maximum soil temperature we measured during the most extreme year (2018) over all 41 m²-gardens in BEL-Landscape, was 27.5° C (max 34.2°C, min 23.1°C) (Gerits et al. 2022). This means that maximum temperatures in many of the 1m²-gardens exceeded the thermal threshold of potato (27°C) and nearly for wheat (28.7°C) (Jackson et al. 2021), which are next to sugar beet and maize the most frequently grown arable crops in Flanders. This points to the severity of the projected exposure to extreme heat and drought in environments with high relative proportion of arable land.

In the Merode case, not the relative proportion of arable land but built-up areas increased the temperature and soil moisture variation. Furthermore, the relative proportion of domestic gardens and other non-valuable low green vegetation increased soil moisture variation. This is partly in line with the urban heat island effect, where built-up areas in urban regions relate positively to land surface temperatures (Morabito et al. 2016). In our case it was however the temperature and soil moisture interquartile range that increased in built-up areas, not the average temperatures or soil moisture contents. The inconsistency of the relationships between the relative proportion of arable land and built-up area with temperature and soil moisture variation might be due to differences in sampling locations for 1m² gardens in BEL-Landscape and Merode. As described in the methodology section, in Merode we sampled at the interface between rural communities and surrounding agricultural land uses resulting in less agricultural conditions compared to BEL-Landscape. In the latter we were able to sample in arable surroundings that are representative for the most intensive agricultural land use in this part of peri-urban Flanders. Yet it is plausible that in moderately warm conditions (Merode 2021), arable lands do not warm up as much as in extremely hot seasons (BEL-Landscape 2018, 2019).

Opposite to the strong buffering effect of high green vegetation for both temperature and soil moisture variation in BEL-landscape, we found only a limited buffering effect for temperature and soil moisture in Merode. For temperature it has been shown that when temperatures become more extreme, the buffering effect of high green vegetation is magnified (De Frenne et al. 2019), which is confirmed by our data. From our research we do conclude that high green vegetation in the landscape buffers microclimate variation, especially in extreme weather conditions. Further research should identify how much high green vegetation is needed to obtain or enhance this effect, and at which scales.

We used a standardised substrate in the m²-gardens on top of the loosened local soil. Despite possible noise caused by variation in local precipitation there were relationships found between soil moisture variation and the surrounding land use composition. This suggests that the soil moisture monitored in the m²-garden is connected with the subsoil and surrounding land use composition. Next to the consistent buffering effect of high green vegetation and inconsistent aggravating relationship of agricultural land use in BEL-Landscape and domestic green in Merode, there were other inconsistent relationships in both cases. In Merode and BEL-Landscape, respectively the relative proportion of productive grassland and valuable low green vegetation relate negatively to soil moisture variation. Relationships between regional land use and soil moisture have been shown in other studies (Wang et al. 2017), often with lower soil moisture contents in woodlands, and higher in arable croplands and grasslands.

An important consideration to be made is about the difference of our standardised soil compared to actual field conditions. It is expected that the effects of drought and heatwaves on soil temperature and moisture are different in the Campine region on sandy soils (Merode) compared to the sandy loam soils in the BEL-Landscape case. The sandy soil in the Campine ecoregion has specific thermal and drainage capacities that could be worse in extreme dry and hot conditions compared to the BEL-Landscape case. We cannot address this point with our standardised soils.

The studied biotic and abiotic variables do not help to explain variation in crop performance

In Merode there were no relationships between landscape composition and multi-crop herbivory or yield. However, for Chinese cabbage and onion there were negative relationships between the relative proportion of residential land use (domestic gardens and built-up surfaces) and crop yield. The studied abiotic or biotic variables did not help explain this direct relationship for either crops. We found that soil moisture variation was higher in surroundings with higher relative proportion of residential land use, and that this correlated positively with the yield of onion. This would suggest a positive relationship instead of a negative relationship between the relative proportion of residential land use and onion yield, pointing that other factors are impacting the yield of onions. We found a positive relationship between strawberry yield and the relative proportion of high green vegetation in the landscape and a positive correlation between pollinator activity density and the yield of strawberry. However, earlier we discussed a negative relationship between pollinators and the relative proportion of high green vegetation in the environment. This would suggest a negative relationship between the relative proportion of high green vegetation and strawberry yield, but we found the opposite. In BEL-Landscape we found a marginal positive relationship between the relative proportion of semi-natural habitat in a 500-metre radius and multi-crop yield, but this relationship is not significant for 2018 and 2019 separately. It seems that the previously discussed landscape effects on microclimate regulation, predatory invertebrates and predators does not explain variation in crop herbivory or yield.

Management implications for the rural landscape

Using the results from both case studies we can make recommendations that are consistent for many peri-urban regions. The weather conditions during the study periods in both cases clearly indicate that future landscapes should be resilient and robust for both heat waves, long dry periods (2018, 2019) and periods of excessive rains (2021). Only in three nearly subsequent years we experienced a taste of what is predicted under the ongoing climate change. Landscape scale high green vegetation shows consistent potential to buffer temperature and soil moisture variation. This potential is highest when temperatures reach higher extremes. Domestic gardens relate consistently negative with predatory invertebrates and variable with pollinators. Yet the built-up surfaces which come along with gardens relate consistently negative with both functional invertebrate groups. Even more, in Merode, impervious surfaces increased temperature and soil moisture variation with potential to aggravate weather extremes. It should therefore be the highest priority to avoid further sealing of the soil in peri-urban areas. Predatory invertebrates and possibly also pollinators actively forage in arable crops. Because this trend is likely caused by generalist species, different actions for conservation of specialist invertebrates might be needed. For ground dwelling predators it is necessary to reinforce and protect valuable low green vegetation in the rural matrix. This means: do not remove wild parts next to roads, keep untidy parts at field borders and infiltrate the arable field matrix with road verges and extensively managed, flower rich grasslands. Where domestic green is already present or unavoidable, intensive garden management should be reoriented towards biologically valuable low green vegetation to support both pollinators and predators while buffering the microclimate.

With this we can contribute to the creation of resilient rural landscapes by supporting regulating agroecosystem services. We clearly found landscape effects on potential abiotic and biotic regulating services related to productivity but we could not uncover the links between these control variables and productivity using our method.

Chapter 5

Participation changed my mindset. Transformative learning about agrobiodiversity in citizen science projects

Adapted from: Gerits, F., H. Cooreman, L. Triste, B. Reubens, K. Verheyen and L. Messely. 2023. Participation changed my mindset. Transformative learning about agrobiodiversity in citizen science projects. Under review at Environmental Education Research.

Frederik Gerits designed the qualitative survey together with Lies Messely, Laure Triste and Hanne Cooreman. All communication was done by Frederik Gerits. The analysis was led by Frederik Gerits with support of Lies Messely, Hanne Cooreman and Laure Triste. Frederik Gerits drafted and submitted the manuscript after in depth revisions by all co-authors.

Abstract

Within citizen science projects, learning about agrobiodiversity can stimulate rural actors to engage with agrobiodiversity. Insight is needed about the ways that citizen science projects facilitate learning outcomes, perspective development and pro-environmental behaviours specifically in favour of agrobiodiversity. In this chapter we present the learning outcomes of both replicates of our 1m²-garden citizen science project where 84 and 28 participants interacted weekly with agrobiodiversity in landscape observatories. Almost all respondents gained knowledge. Most knowledge gains were practical or instrumental, while some were more in-depth. More than half of the respondents changed their views on agrobiodiversity and about one-third changed their actions regarding agrobiodiversity (defined as transformative change). Changed actions for agrobiodiversity as transformative learning outcomes were more likely when participants had less prior knowledge. Participants cited the combination of the tactile tool of the 1m²-gardens and frequent written and informal communication as key learning tools. In conclusion, the key success factors for citizen science

projects to change perspectives and behaviours are: making an effort to engage participants without prior knowledge, combining frequent written communication with self-experimentation, and informal interaction with the research team.

Introduction

Agricultural biodiversity or agrobiodiversity refers to the variety of all living organisms that contribute to agriculture including crops and livestock planned by the farmer as well as associated biota such as weeds, herbivores or pollinators (Jackson et al. 2007). Agrobiodiversity is essential for the transition towards more sustainable agricultural systems (Kremen and Merenlender 2018) and can be seen as a central resource in the rural social-ecological system (Gerits et al. 2021). Today a number of actors make diverse claims on the open space in rural social-ecological systems. Non-agricultural land uses such as private residential gardens, horse pastures and nature conservation shape today's multifunctional rural areas (Kerselaers et al. 2013; Verhoeve et al. 2015; Boeraeve et al. 2020). Actors in the social subsystem can benefit from agrobiodiversity via ecosystem services and can decide to invest in agrobiodiversity either individually or collectively to support the ecological subsystem.

Efforts to reinforce agrobiodiversity are most effective when coordinated at the landscape scale (Tscharntke et al. 2005; Landis 2017). The status and improvement of agrobiodiversity depends upon the behaviour of a broad range of actors. Instead of focusing on farmers alone, responsibility for agrobiodiversity should be shared by farmers, municipalities, rural residents, horse keepers, nature conservation organisations etc. For example, the activity of beneficial arthropods such as pollinators (e.g. bees, hoverflies) and natural pest control agents (e.g. ground beetles, spiders) on individual plots is determined by the presence of shelter and food in the surrounding landscape. These food-rich shelters are often found in semi-natural habitats outside the cropping plots, such as hedges, treelines, flower edges, small forest fragments, grass buffers, etc. Planting and maintenance of habitats to support agrobiodiversity on landscape scale requires multi-actor, collaborative efforts; however, current efforts focus on farmer initiatives at the parcel scale (Tscharntke et al. 2012b; Landis

2017). More research is needed on how to involve other actors with different profiles and motivate them to take (preferably coordinated) action for agrobiodiversity.

As a complement to enforcing top-down measures, research suggests that learning can be a way out of disruptions and challenges in social-ecological systems (Bela et al. 2016; Moyer and Sinclair 2020; Groulx et al. 2021). Among others, Moyer and Sinclair (2020) argue that learning is a more democratic and emancipatory approach and is more effective in achieving sustainability goals. Opportunities to learn about rural ecosystems can take a variety of forms, e.g. learning in school, extracurricular courses and citizen science (CS) projects. To better understand what different people learn from the learning opportunities provided by their participation in CS projects and how, this study was designed to scrutinize the link between these learning opportunities and types of learning outcomes. Of the many suitable learning theories available we chose the transformative learning theory described by Mezirow (1997). This theory appears to be most appropriate for the present research context for the following reasons. Recent literature provides a substantial scientific basis for the application of the transformative learning theory to investigate different educational contexts aiming at sustainable development (Diduck et al. 2012; Boström et al. 2018; Moyer and Sinclair 2020), including natural resource and environment management studies (Stuckey et al. 2013; Moyer and Sinclair 2020). Several recent studies also apply the transformative learning theory to better grasp learning processes connected to different types of learning outcomes (Bela et al. 2016; Groulx et al. 2021; Day et al. 2022). Transformative learning is rooted within an emancipatory approach to education (Mezirow 1997), where the aim is not to prescribe or impose certain knowledge or behaviours, but rather to stimulate meaningful engagement and critical autonomous thinking which can lead to behaviour change.

In a transformative learning process, learners are stimulated to question their deeply-held assumptions and are subsequently changed by the experience (Taylor and Cranton 2012). Personal transformation can act as a foundation towards more environmentally sustainable behaviour (Moyer and Sinclair 2020). Adoption of sustainable practices requires people to change their mindset, such as adopting a more holistic vision of ecosystems and the interplay within the environment. In transformative learning theory, Moyer and Sinclair (2020) detect and describe three intertwined learning outcomes: instrumental, communicative and personal transformative learning. We use these three types of learning to differentiate between the learning outcomes fostered by taking part in the CS project. Instrumental learning is “concerned with learning about how the world works and how to accomplish desired ends (e.g. water management techniques)” (Moyer and Sinclair 2020, p.4). This entails factual knowledge and developing skills to manage problems on a daily basis. Communicative learning “involves interpreting, understanding, and conveying meaning in social interactions, including negotiating norms and desired ends” (Moyer and Sinclair 2020, p.4). Understanding why water is a critical resource for farmers is an example of communicative learning. Critically reflecting on own beliefs and the arguments of others is an important process that leads to learning; such reflection is supported by interactions such as taking part in discussions (Mezirow 2000). Most learning involves an interplay of both instrumental and communicative learning that build upon each other (Mezirow 2012). Personal transformative learning is “rooted in instrumental or communicative learning and may lead to a personal transformation in frames of reference that changes the way that participants perceive their environment and/or act in it” (Mezirow 1997; Sims and Sinclair 2008; Moyer and Sinclair 2020). Adapting one’s water management due to improved understanding of one’s own and others’ influence on water as a resource is an example of personal transformative learning.

Recently, CS projects have increased in popularity as a way of inducing transformative change towards more sustainable practices and pro-environmental behaviour (Bela et al. 2016; Peter et al. 2021; Day et al. 2022). CS projects involve non-professional scientists (Land-Zandstra et al. 2021); have a long history in ecological research (Dickinson et al. 2010; Dickinson et al. 2012); and have recently been applied to agrobiodiversity (Gosling et al. 2016; Billaud et al. 2020). CS has most often been used as a method for data sourcing but recognition of the learning, engaging and transformative potential of CS projects is increasing (Bela et al. 2016; Phillips et al. 2018; Bueddefeld et al. 2022). Frameworks and guidelines have been developed to assess learning outcomes from CS programs (Bela et al. 2016; Phillips et al. 2018), but in many projects these outcomes either remain unevaluated or they focus mainly on factual learning outcomes rather than on the deeper, transformative effects (Bela et al. 2016; Groulx et al. 2021).

Knowledge about which aspects in a CS project facilitate or impede transformation is lacking (Bela et al. 2016; Groulx et al. 2021; Peter et al. 2021). Research with secondary school children has shown that transformative learning is facilitated by transparent and voluntary contributions, a deliberative participatory process and a long-term, flexible project timeline (Ruiz-Mallén et al. 2016). Sims and Sinclair (2008) found that non-formal opportunities between participants and the project team were potentially transformative. Sinclair et al. (2011) and Diduck et al. (2012) suggested that a high level of interaction between the participant and the project team can broaden and deepen learning outcomes. Additionally, Bueddefeld et al. (2022) mention the possible value of post-visit action (take-home messages, follow-up activities, tactile materials or social media prompts) and identify a need for more research on this. Finally, hands-on experiences, i.e. learning through exploration or experimental learning (Kolb 2015), are likely to stimulate transformative learning (Bela et al. 2016; Bueddefeld et al. 2022).

In this chapter we add empirical evidence about the factors that facilitate transformative learning in CS projects about agrobiodiversity. A qualitative assessment of both CS project was used. The aim of the current study is to addresses the lack of evidence for a link between the learning process and the outcomes and methodology used in CS projects. Our overall objective is to identify key aspects of CS that stimulate (transformational) learning outcomes that lead to beneficial actions for agrobiodiversity.

More specifically we explore:

- Whether participation in this CS case study leads to learning outcomes (RO1);
- Whether this learning was transformative and led to action for agrobiodiversity (RO2);
- Whether these learning outcomes depend on the participants’ profile (RO3) and;
- What aspects of the participatory process facilitate or impede learning (RO4).

Two cases of a CS project (chapter 3 and 4) were used in which participants interacted weekly with agrobiodiversity via observation, experimentation, monitoring, reporting, maintaining and experiencing small (1m²) vegetable gardens (Fig. 5.1). Data from a post-project questionnaire were analysed qualitatively using transformative learning theory as analytical framework.

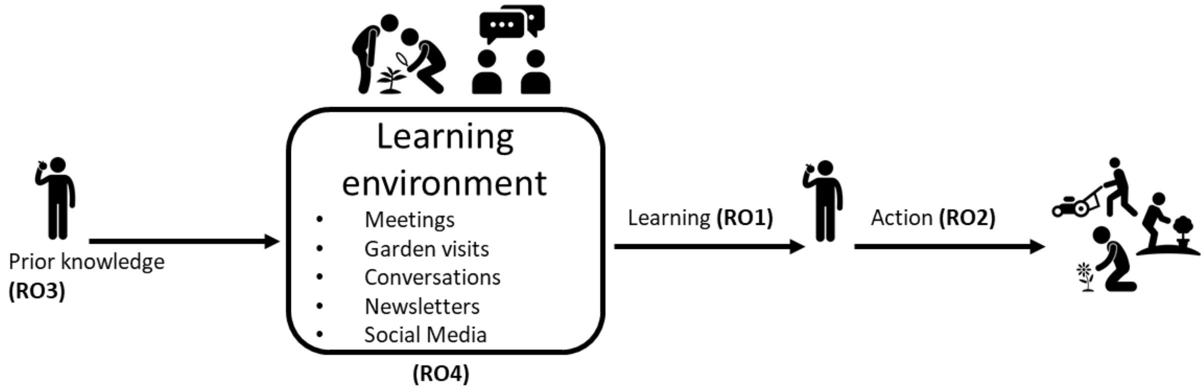


***Figure 5.1**: Research objectives (RO) projected on learning pathway. Participants with different prior knowledge took part in a CS project where they interacted with the learning topic during their garden visits. Other learning opportunities were provided during meetings, conversations with researchers, weekly newsletters and interactions on social media. Icons are used from* Thenounproject.com (2022b).

Methods

The 'BEL-Landscape' and 'Merode' projects are two cases of a CS project in which 84 and 28 volunteer citizen scientists, respectively, interacted weekly with agrobiodiversity in their 1m² gardens (Fig. 5.2). The setup and CS protocols were identical in both cases but they took place in distinct Flemish regions, at different times and with different participant pools. In both cases weekly interactions with the research team took place via various channels (newsletters, informal field visits, email, Facebook etc.) and several in-person gatherings with other participants. In both cases, we used a post-project questionnaire to evaluate the learning outcomes, changes in behaviour and how the project facilitated learning for different participant profiles. We start by introducing both cases and then present the survey method and respondent profiles.

The Data Protection Officer of Ghent University (ADVI-DPO1718/47) approved this study prior to starting the project. The authors obtained written informed consent from all participants.

The BEL-Landscape and Merode cases

As described in the previous three chapters of this thesis, the BEL-Landscape (BEL-Landschap in Dutch) and Merode cases are landscape observatories with 41 and 25 observation points, respectively, used to assess effects of the surrounding landscape. Where the previous chapters present and discuss the ecological data generated by the volunteers and the research team, here we discuss the second purpose which was to involve and bring together local actors and share knowledge about agrobiodiversity. For this purpose, one or more volunteer citizen scientists (‘participants’) maintained a 1m²-garden and gathered data together with the team of scientists. Some participants maintained a garden on their own while others did so in a group of two or more (Table 5.1). We considered participants as members of a group when they shared work with others that were not members of their household and who were equally involved in the project. Participants visited their assigned 1m² gardens weekly for observations and maintenance.

Table 5.1: *Participation in group or as an individual in BEL-Landscape and Merode.*

	BEL-landscape	Merode
Gardens maintained by individual participants	24	22
Gardens maintained by group of participants	17: - 7 groups with 2 participants - 6 groups with 3 participants - 4 groups with > 4 participants	3: - 3 with 2 participants

The main objectives for this CS project were to (1) gather qualitative ecological data from all individual 1m²-gardens and (2) to engage with local actors in the process as well. However, from the beginning of the project it was not strictly defined how this involvement would be, and what social aspects related to the volunteers would be assessed. This is often the case in social research where an inductive approach is used rather than a deductive one. In this inductive approach we step into data assembly without a clear theory and formulate hypotheses along the way. In a deductive way we would have wanted to test a specific theory and might have chosen for a quantitative or mixed-method approach. It is because of our inductive approach that we used a qualitative survey, which allows to formulate theory and hypotheses from survey answers. It was only during the citizen science project that the learning of participants proved valuable to study transformative change in the social part of the framework, but this study objective and hypothesis only grew during the project.

Parallel to the specific target to interact with local actors during the CS project, involvement of local actors was crucial to achieve a sufficient number of independent sites in the rural landscape. Because the follow-up of the $1m^2$ gardens required a considerable, repeated and ongoing effort, it was necessary to recruit committed citizen scientists throughout the duration of the project. Because of the unusually large time investment (more frequent and more time-consuming than the typical CS project) the research team built trust with all participants by investing sufficient time, ensuring close collaboration and providing frequent communication. In addition to these frequent formal and informal researcher-participant interactions, the research team was convinced that the small gardens (tactile learning tool) would keep participants interested because it would also provide valuable information about their own private gardens or fields. Although this was not an initial goal, it became clear in the course of the project that this approach to immersive CS had potential for learning outcomes towards pro-environmental behaviour.

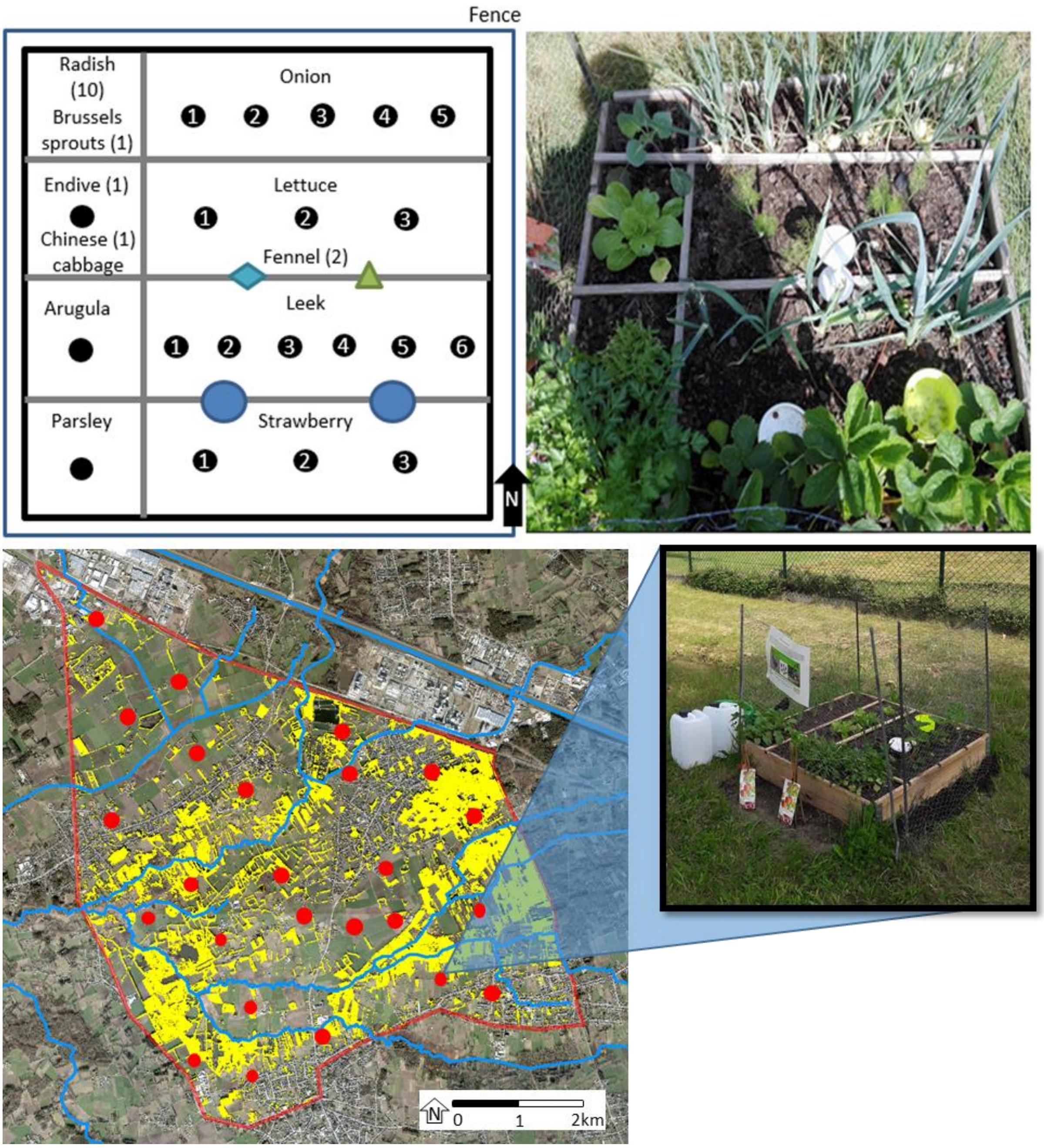


***Figure 5.2**: Setup of a 1m²-garden (identical in both cases). Every 1m² garden contained a set of 10 vegetable crops in a standardised setting. Each garden was also fitted with two invertebrate traps and two microclimate sensors. Distribution of the gardens in the Merode case along a landscape compositional gradient with high green vegetation highlighted as yellow surfaces (hedges, forest patches etc.). Figure adapted from* Gerits et al. (2021)*.*

1m² gardens as a tool to learn about landscape scale agrobiodiversity

Participant visits to the garden always involved watering, removing weeds and making general observations of the plants to examine whether herbivores or slugs had been eating the leaves.

At several time-points, the researchers announced the harvest of specific plants. For each harvest event, participants were informed via the weekly newsletter of a detailed protocol of how to remove the plants, remove dirt, cut non-edible parts, weigh the biomass and register the data. The harvest protocol also included photos and drawings as illustrations. The level of involvement in the project differed between participants. The participants were expected to perform a minimum number of tasks per week to assure standardised follow-up of the 1m² gardens, but several did more than that. Some participants divided the work within a group to assure continuous follow-up of the 1m² garden (Table 5.1). This was often the case for groups of participants following up a garden at their workplace.

In BEL-Landscape, after the first season, three participants decided not to engage in the second year for reasons of time constraints (2) and change of employment (1). Although the research team did not actively recruit new participants, one new volunteer started between the two seasons. During the monitoring seasons there was no complete drop-out of any of the participants, in neither of the cases. In the BEL-Landscape case the researcher had to replace management of only 1 location due to long-term illness of the participant. In some cases, some elements of yield data assembled by volunteers were missing by mistakes or forgotten to register. In BEL-Landscape the yield data was complete for 36/41 gardens (88%) while for Merode this was the case for 23/25 gardens (92%). See Gerits et al. (2022) for reports of the ecological aspects and project results.

Timeline of the BEL-Landscape and Merode cases

Throughout the CS projects, the research team interacted with the participants using various forms of communication and interaction (Table 5.2). For detailed timelines see Table D1, D2 in the appendices. The selection procedure started with an open call for participants after which we coupled the interested people to possible locations for 1m²-gardens regarding the landscape compositional gradient required for ecological data gathering (see chapter 2 and 3). Some participants were asked to maintain a 1m²-garden on their own property, others further away. Participants who preferred not to maintain a 1m²-garden at the proposed location could not be included in the study. This selection was independent of the profile of the candidate participant. Not all participants were present at all events organised during the

CS project. Because these events were potentially important learning opportunities, participants reported on their attendance in the post-project questionnaire.

***Table 5.2**: Summary of the BEL-Landscape and De Merode project timelines.*

CS phase	Date	Participatory steps in this phase
BEL-Landscape (case 1)		
Participant recruitment	January 2018 – May 2018	Press conference – participant selection, information
Season 2018	May 2018 – October 2018	Weekly follow-up of assigned 1m² garden
Season 2019	May 2019 – October 2019	Weekly follow-up of assigned 1m² garden
Discussion and feedback events, workshops	Throughout project	Intermediate feedback event (2018) – feedback and update after first season (2018) – landscape walk (2018) – insect workshop (2019) – closing event (2021)
Merode (case 2)		
Participant recruitment	January 2020 – May 2020	Press conference – participant selection, information
Season 2020	Cancelled (COVID – 19)	Seasonal newsletters to keep participants involved
Season 2021	May 2021 – October 2021	Weekly follow-up of assigned 1m² garden
Discussion and feedback events	Throughout project	Intermediate bike tour (2021) – closing event (planned in Winter 2022)

Regular written and informal communication during 1m² garden seasons

During the kick-off meetings (Table D1, D2), participants received a booklet with information on the research and a detailed description of tasks. This information was updated between the two seasons in BEL-Landscape. Participants also received pictures and information about arthropods that could visit their 1m² gardens and an illustrated list of common weeds. Participant observations were shared with the research team via a researcher-provided link to a personal online folder where the harvest data (noted on-site in a notebook) could be entered into an Excel sheet. The research team could also access the online folder. In addition to the general information in the booklet, the research team sent a newsletter to the participants every Wednesday evening (see example in the appendices Table D3). Every newsletter consisted of a short summary of observations of plants and invertebrate activity from the previous week illustrated with pictures provided by participants and researchers.

The newsletter often provided preliminary results from the research as well. Every newsletter started with a table summarising the tasks for the next visit to the garden. For activities that needed more explanation (e.g. crop harvest) a detailed description was provided in the body of the newsletter. When any participant reported doubts, the research team sent a clarification message to all participants. Researchers regularly contacted participants if their notes in the online Excel were ambiguous or absent.

In addition to participant attendance at formal meetings and learning opportunities, the lead investigator of the research team (‘researcher’) regularly visited all 1m² gardens in both cases. This researcher served as the single point of contact for the participants. During researcher visits, he installed/removed the traps for arthropods, extracted sensor data and performed a standardised observation of leaf herbivory. In the BEL-Landscape case, the researcher visited once a fortnight. Due to time and budget constraints, in the Merode case field visits were fewer, with fortnightly visits occurring at the end of May, the beginning of July and the beginning of August. When the participants were present at the time of the visit they accompanied the researcher and joined him as he made observations in the 1m² gardens. This led naturally to informal interactions with the participants. Finally, participants and researchers interacted in a private Facebook group (46 and 39 group members in BEL-Landscape and Merode, respectively). Participants shared and commented on pictures after receiving the weekly newsletter. In the Merode case there were multiple project partners present in the Facebook group to follow the interactions. Yet, they only followed and did not post content themselves.

Post-project questionnaire to evaluate learning outcomes

The research team sent out post-project questionnaires to evaluate the learning outcomes and the facets of the project that either facilitated or obstructed learning. The questionnaire consisted of 43 questions (Table 5.3). We mainly asked open questions on respondents’ project experiences, lessons learned and changes in perspectives and behaviour. In BEL-Landscape we distributed the questionnaire one year after the end of the season while for practical reasons the questionnaire for Merode was sent only one month after the end of the season (Table D1, D2).

Table 5.3: *Questionnaire outline. Question number (1-43), question topic, description of target information and related research objective (RO). RO1: what was learned, what changed, RO2: learning of different profiles and RO3: what facilitates or obstructs learning. For the full survey see Table D3.*

Question	Topic	Description	RO
1-7	Respondent profile	Information on the profile (age, profession, prior knowledge).	2
8	Reason for participation	Why respondent volunteered in the project.	2
9	Participation in project events	Select the events in which the respondent participated.	3
10 – 11	Experience and memory	What respondents noticed and remembered from 1m² garden visits and events during the project.	1
12	Learning outcomes	What respondents learned about agrobiodiversity, allotment gardening, the landscape or other topics and selection of learning media (newsletters, Facebook, conversation with peers or researchers, internet, insect list, weed list, gathering events, own observation).	1
13 - 18	Vision on agrobiodiversity	If respondents' views on agrobiodiversity changed, what changed, why or why not, due to project or not.	1 + 3
19 – 24	Actions on property	If respondents' actions taken on property changed, what changed, why or why not, due to project or not.	1 + 3
25 – 29	Attention for environment	If respondents' attention for environment changed, what changed, why or why not, due to project or not.	1 + 3
30 – 34	Social network	If respondents' social network changed, what changed, why or why not, due to project or not.	1 + 3
35 – 38	Perception of contribution	If the respondents think that their contribution was valuable for the research team and other participants and why.	3
39 – 42	Communication about project	If respondents communicate about agrobiodiversity, to whom, about what, due to project or not.	3
43	General remarks	If respondents have other remarks or thoughts about their experiences in the project.	/

Coding scheme for analysis of the questionnaires

The framework on transformative learning by Mezirow (1997) guided the qualitative analysis of the questionnaires. All data were analysed through coding in NVivo (Mortelmans 2007). In a first step, the research team developed a coding scheme using existing surveys that apply the transformative learning theory in natural resource and environment management studies (Kerton and Sinclair 2010; Stuckey et al. 2013; Moyer and Sinclair 2020). Three independent researchers discussed a preliminary coding scheme for triangulation (Mortelmans 2007; Baxter and Eyles 2011). They checked for consistency and usefulness of the coding scheme to answer the research questions and triangulated for the categorisation in different types of (transformative) learning.

Mezirow (1997) and Diduck et al. (2012) state that learning outcomes are considered to be part of a transformative process if the learners' perspectives change towards "better justified assumptions, that are more inclusive, discriminating, open, reflective and emotionally able to change, and that are thus more likely to lead us to beliefs and opinions that are more reliable guides for our choices and actions". In our study, we considered that learners at least showed signs of having started a transformative learning process if the respondents reported changes in their vision on agrobiodiversity and/or attention for environment due to the project. We defined that these participants went through a phase of critical reflection, a crucial step in a transformative learning process (Mezirow 1997; Moyer and Sinclair 2020). We categorised respondents as having gone through a complete transformative learning process ("transformation") when the respondent also indicated to have changed his/her actions due to the project.

The criteria for transformation used were rather strict. Respondents who indicated that their view on agrobiodiversity did not change but showed indications of transformative learning in answers to other questions were not counted as transformative. We thus focused on respondents who were self-consciously aware of their own change and indicated this as such (according to Mezirow, 2006). With this procedure we also excluded respondents who changed their actions on their own property but did not change their view on agrobiodiversity or did not report having changed their attention for the environment. These were respondents who, for instance, adapted their vegetable garden management due to new instrumental insights that fit within their current vision on agrobiodiversity.

In addition to this coding scheme, we categorised the open answers to the questions 'what did you learn about vegetable gardening/biodiversity/landscape/other?' into two groups that referred to either instrumental learning outcomes or communicative learning outcomes, respectively. Even though transformative learning theory states that these are intertwined, this distinction was made to provide insights on the type of learning that was stimulated by specific project aspects.

Respondent profiles

For the BEL-Landscape and Merode case, respectively, we received 36 (43% response rate) and 17 responses (61% response rate). The respondents were categorised according to their relation to or activity in the research landscape (Fig. 5.3).

- Residents: participants who live in the landscape and managed a $1m^2$ garden on their own property or on nearby public areas.
- Employees: participants who managed a $1m^2$ gardens at their work environment.
- Farmers managed $1m^2$ gardens located on their fields and nature managers managed them in areas designated for nature restoration.

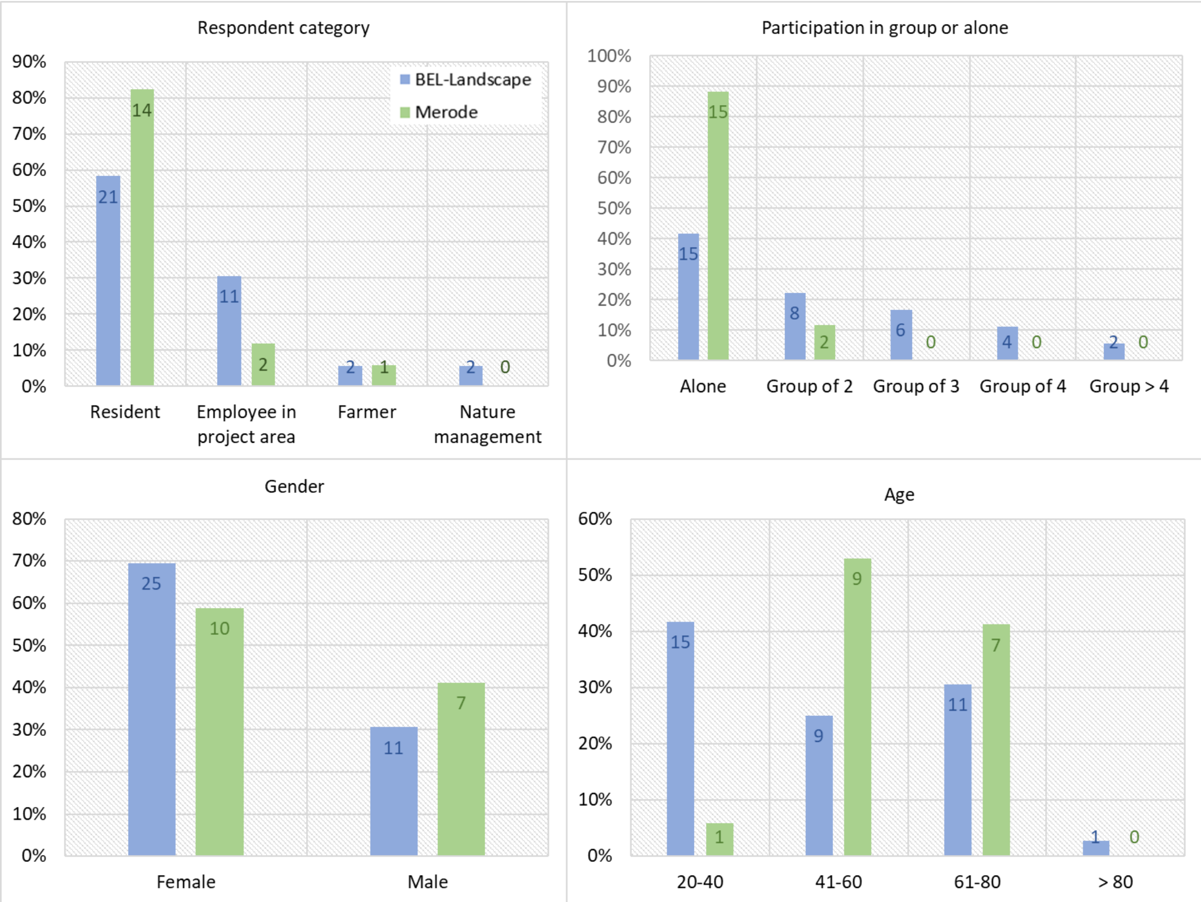


***Figure 5.3:** Categorisation of respondents according to their activities in the research area and whether or not they participated in group or alone. The gender and age of the respondents are also given per case. Percentages on the y-axis are relative distributions per case. Numbers in top of the bars are absolute numbers of participants per case.*

Critical reflections on methodology

The following methodological reflections prevented misinterpretation of the results and overcame possible biases. Lower response rates in BEL-Landscape could be explained by the timing of the distribution of the questionnaire (one year after the season ended), while for Merode this was one month after the end of the season. Despite the differences in timing and number of respondents in the two cases, no differences in answers were observed. In the BEL-Landscape case, respondents showed little difficulty in recalling specific aspects of the project. The analysis of the Merode case was done after finishing the analysis of the BEL-Landscape case, for practical reasons of timing. The data could however be pooled without distinction between cases to minimize the bias of the surveyor. Only in a second round of coding a label could be attributed related to the case to explicitly make the comparison between both cases. The lack of baseline data on knowledge or perspectives of participants before the project was compensated with questions on the respondents' profile and the reasons for participation (question 1-7 and question 8). As participants voluntarily subscribed to an open call from the research team, there was no sampling among different profiles. The second research question is devoted to a possible bias of participants towards people with interests in agrobiodiversity, allotment gardening, etc. A considerable share of the BEL-Landscape respondents were scientists who work at ILVO, Ghent University and University College Ghent (HoGent); all three organisations own or manage properties in the project region (Fig. 5.3). Most researchers maintained their $1m^2$ garden in a team, resulting in a diminished feeling of responsibility and ownership and lower rates of participation in events. The contributing scientists in BEL-Landscape work in a variety of fields of research but none were working on this particular research project. The questionnaires were completed from the point of view of the individual, not the group. It is therefore possible that different volunteers assigned to the same garden responded to the questionnaire. In the Merode case, no respondents were employed in a scientific profession and both employees in the research landscape were municipal staff.

The multidisciplinary research team was comprised of a biodiversity and plant expert from Ghent University and ILVO (Plant Sciences Unit), respectively; one ILVO researcher (Social Sciences Unit) who specializes in participatory trajectories and multi-actor networks on the countryside; and two other ILVO researchers (Social Sciences Unit) with expertise in social learning processes and outcomes. This team supported one PhD researcher who focused full time on the fieldwork and communication during the project. He was involved in all disciplines and maintained intensive involvement and frequent informal contacts with participants. This researcher was also the evaluator of the questionnaires. Objective analysis was assured by anonymization of survey results and triangulation of the results via independent application of the coding scheme on four randomly selected questionnaires by the four researchers from the ILVO Social Sciences Unit (Walter et al. 2007).

Results

Except for one respondent in BEL-Landscape, all remaining respondents show indications of some type of learning (Fig. 5.4). In total, 58% and 47% of the respondents in BEL-Landscape and Merode, respectively went through a perspective change and 31% and 12%, respectively put this new perspective into action and therefore were labelled as experiencing transformative change. Only 8% and 12% of the respondents in BEL-Landscape and Merode, respectively took action without a change in perspective.

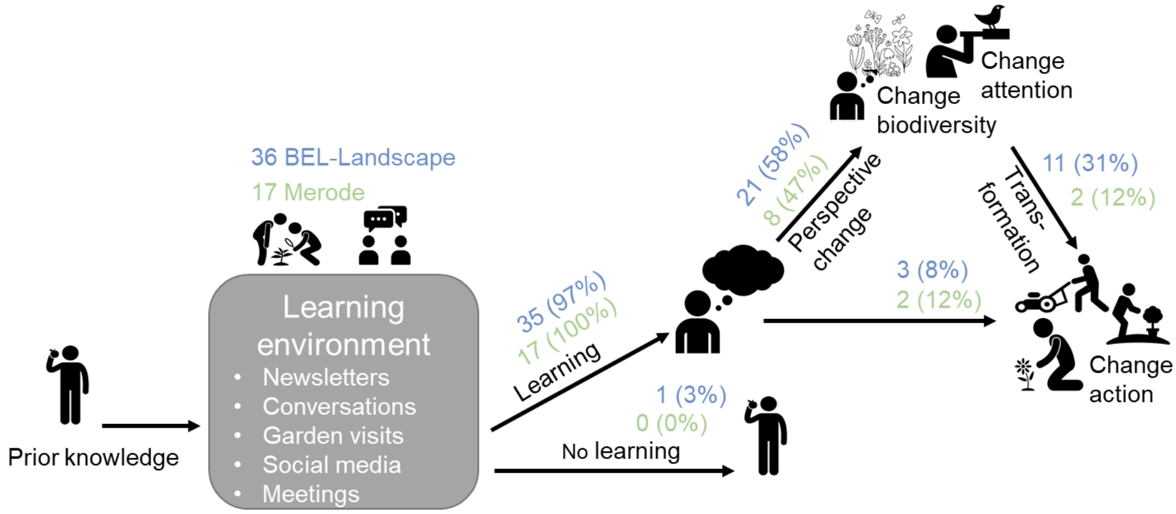


***Figure 5.4**: Trajectories towards learning outcomes of 36 and 17 respondents, respectively by participation in the BEL-Landscape & Merode CS projects. Icons are used from* (Thenounproject.com 2022a).

Learning, changed perspectives and action caused by the citizen science project

Except for one respondent in BEL-Landscape, all 52 respondents reported to have learned about at least one of the three topics: vegetable gardening, biodiversity or the landscape (Fig. 5.4, Fig. 5.5). The reported knowledge mainly represents instrumental, factual knowledge about insects and garden techniques such as watering frequency, crop choice, crop protection or the taxonomy and the functional role of insect species. "It is best not to water every day, because the roots will grow on the surface, rather than in depth." (BEL-Landscape/M/78/retired). Fewer indications for communicative learning were found, such as a better understanding of research processes, the balance in ecosystems and reflection on own knowledge (Fig. 5.5). "I also learned that young people are engaged in research that requires a tremendous amount of work and energy." (BEL-Landscape/F/66/retired).

To the question of why no lessons were learned, “having prior knowledge” was a prominent answer, mentioned 5 and 2 times in BEL-Landscape and Merode, respectively for the topic vegetable gardening and mentioned 4 times in BEL-Landscape for the topic biodiversity. For the landscape or “Other” as topic there were no specified reasons why participants did not learn.

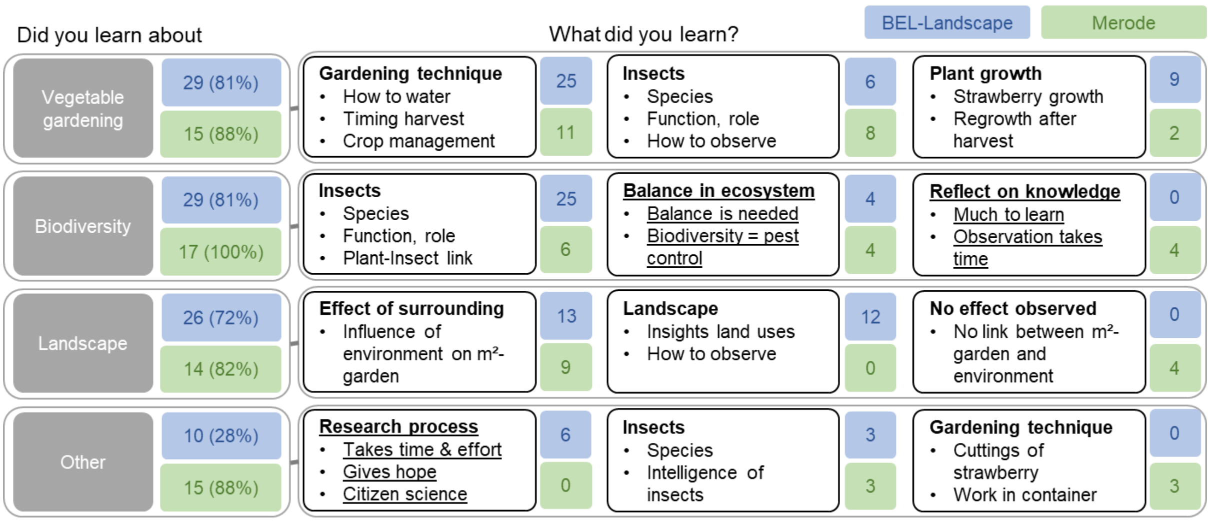


***Figure 5.5**: Answers to the questions on learning about vegetable gardening, biodiversity, the landscape and other topics. Answers were coded and grouped in topics of which labels of the three most mentioned topics are given together with two or three specific topics. The count of coded fragment in each topic is reported per case colour. Communicative learning is underlined, all other topics stand for instrumental learning.*

Our results show that besides instrumental and communicative learning, over half of the respondents changed their view either about agrobiodiversity or attention for the environment (Fig. 5.4, Fig. 5.6). Especially in BEL-Landscape, the changes in view about agrobiodiversity indicated a deeper understanding of the importance of individual efforts for agrobiodiversity and a broadened view on its complexity (Fig. 5.6): “The importance of balancing this diversity starts with the individual gardener.” (BEL-Landscape/M/28/researcher). In Merode, changed views were mainly about gardening techniques, an instrumental topic. However, there were also indications of an increased belief in the importance of agrobiodiversity and the diversity of insects. Changes in attention for the environment were in both cases related to an increased attention for insects, where respondents declare that they better observe and search for insects (Fig. 5.6). The results show that 53% and 24% of the respondents in BEL-Landscape and Merode, respectively changed their actions (Fig. 5.6). In both cases, newly adopted gardening techniques were most mentioned as action: “I'm now making a cultivation plan and don't always turn over the soil, but turn it loose.” (Merode/M/68/retired). In BEL-Landscape, new biodiverse plantings were also mentioned 7 times; e.g. “I started mowing less and sowed a flower meadow.” (BEL-Landscape/F/65/retired).

Similar to the questions on learned lessons, prior knowledge was the most mentioned reason why no changes occurred in the view on biodiversity (respectively 18 and 9 times in BEL-Landscape and Merode).

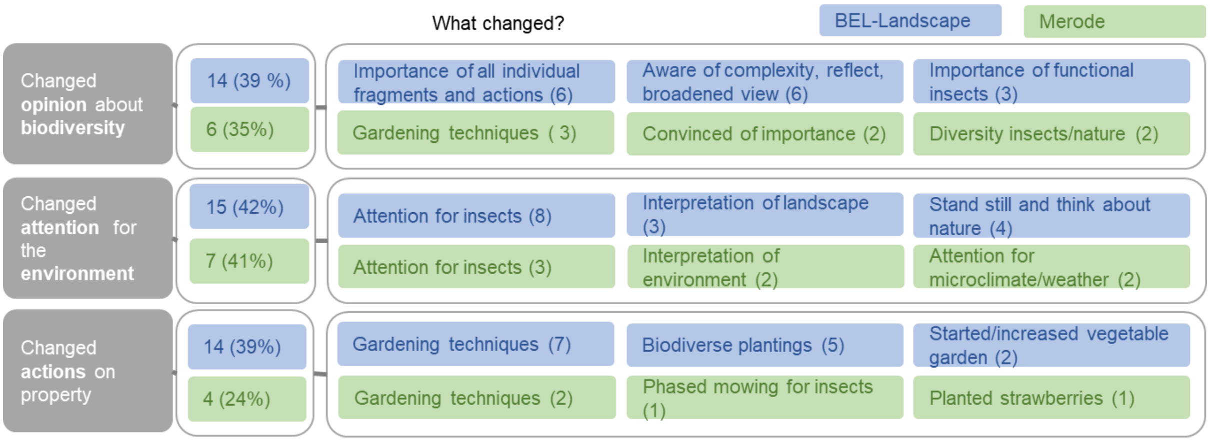


Figure 5.6: *Responses to the question on changed views on agrobiodiversity, attention to the environment and actions on property as a result of the project. Answers were coded and grouped into topics for which the labels of the three most frequently mentioned topics are given. The count of coded fragments in each topic is reported between brackets.*

Learning outcomes depend on prior knowledge

In both cases, respondents started with different prior knowledge about vegetable gardening, agrobiodiversity or agriculture. In total, 29 respondents in BEL-Landscape (81%) and all of the respondents in Merode (100%), respectively indicated to have prior knowledge on at least one of these three topics (Fig. 5.7). Respondents mainly had prior knowledge about agrobiodiversity and vegetable gardening, and to a lesser extent about agriculture (Fig. 5.7).

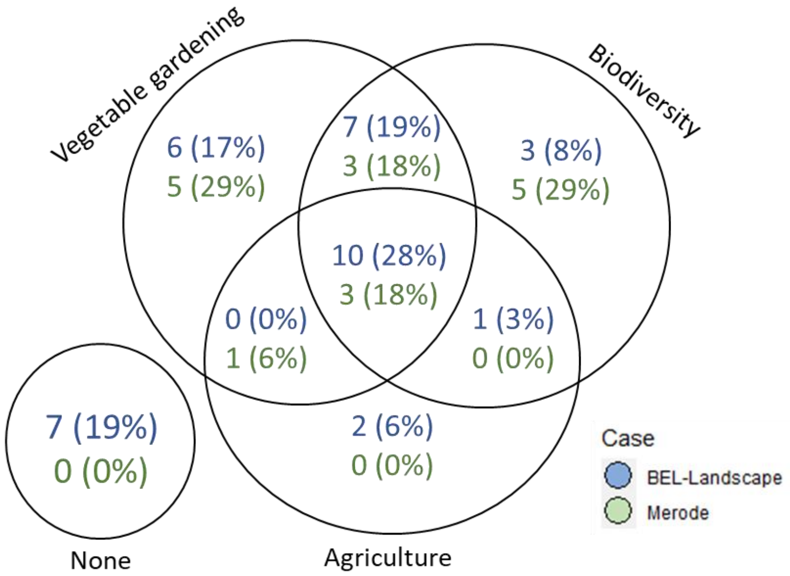


Figure 5.7: *Prior knowledge of respondents in both cases. The number of respondents and percentage is indicated per case in the corresponding compartment of the prior knowledge diagram.*

There was no correlation between the number of topics for which prior knowledge was available and the lessons learned, as almost all respondents learned something (X2 = 2.674, P = 0.445 in BEL-Landscape) (Fig. 5.8). Because all 17 participants in the Merode case learned something, no correlation could be calculated. For BEL-Landscape, the number of subjects with prior knowledge correlated with whether or not perceptions of biodiversity or attention to the environment changed (X2 = 15.947, P = 0.001**) and whether or not transformative change occurred (X2 = 8.802, P = 0.032*). In Merode there were no correlations on the number of topics with prior knowledge with changes in views on biodiversity or attention to the environment (X2 = 3.353, P = 0.187) nor of transformative change (X2 = 1.587, P = 0.452). For both cases, however, almost all respondents who indicated to have prior knowledge on all three topics did not change their view on agrobiodiversity or their attention to the environment, nor were there indications of transformative change (Fig. 5.8).

This is supported by the qualitative data, in which respondents most often cited prior knowledge as the reason why they did not learn about vegetable gardening or change their views on agrobiodiversity (Fig. 5.7): "To be honest, I was familiar with most of vegetable gardening, specifically organic gardening." (BEL-Landscape/M/62/contractor) or "Nothing new actually. After 40 years of owning a vegetable garden." (Merode/M/64/retired).

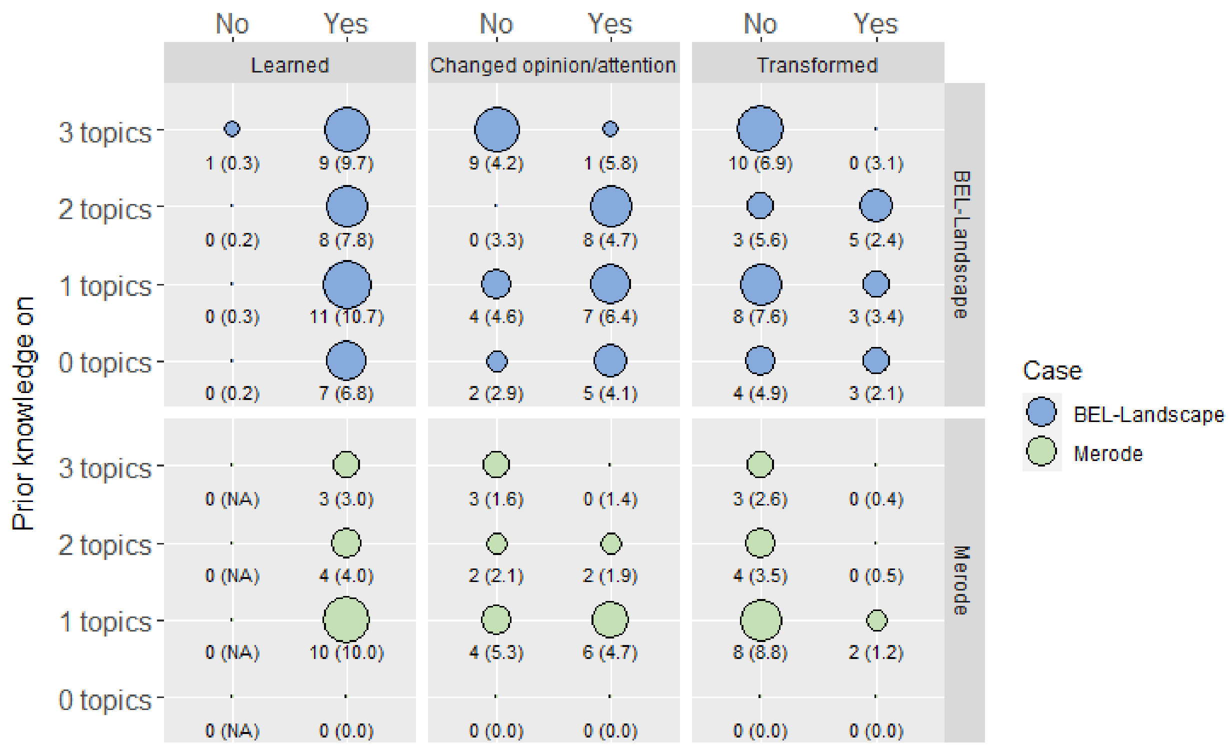


***Figure 5.8**: For both BEL-Landscape and Merode the number of topics for which respondents indicate having prior knowledge before the project in relation to whether respondents (1) indicated having learned, (2) indicated having changed their views on agrobiodiversity or attention to the environment and (3) showed evidence of transformative change through actions on their property. Point size is proportional to the observed frequency indicated under each point along with the expected frequency between brackets. We tested if the calculated expected frequency differs significantly from what we observed. As all 17 participants in the Merode case learned, no expected value could be calculated (NA).*

Because 30% of the respondents in BEL-Landscape work in research (Fig. 5.3), we repeated the analysis with only these respondents. The correlations between prior knowledge and learning outcomes for this subgroup were highly similar compared to the total respondent pool (Fig. D1). This indicates that our findings are not skewed by respondents with a scientific profession that participated in the CS project (Fig. D1).

Which aspects of the citizen science project facilitate learning?

Below we show the importance of the learning media as selected by respondents from the communication means used in this CS project (Question 12, Table 5.3). The top three media are further illustrated with evidence from qualitative answers to the questions regarding why respondents' views on biodiversity and their attention for the environment changed.

Respondents most frequently cited weekly newsletters as the most relevant medium for learning about vegetable gardening, agrobiodiversity, landscape or other topics, followed by their own observations in the 1m² gardens and conversations with the researcher (Fig. 5.9).

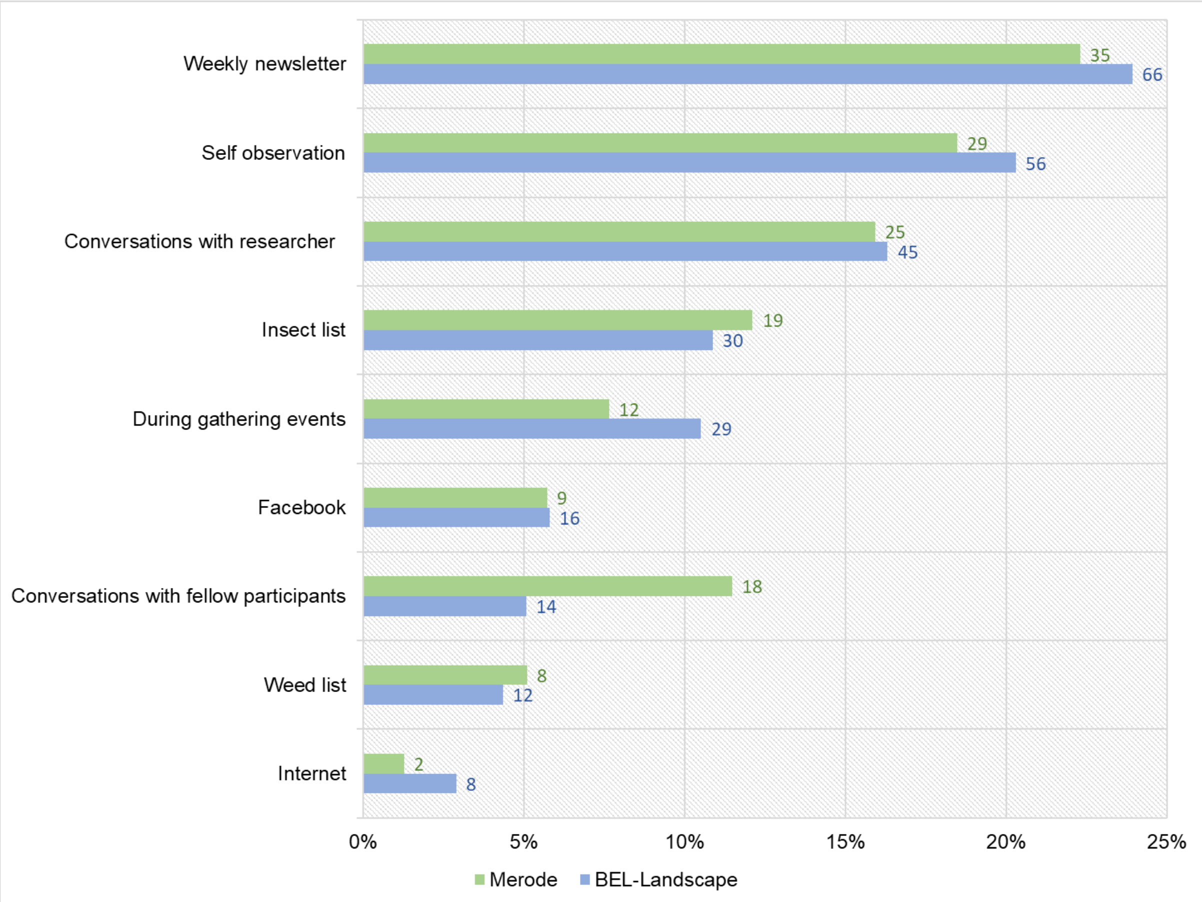


***Figure 5.9**: Counts of learning media summed for learning about vegetable gardening, agrobiodiversity, the landscape or "other" for both cases. The x-axis represents the percentage of the counts of learning indications for that learning medium. The coloured numbers on the right indicate the count of indications per medium, per case, summed over all four learning topics.*

Respondents mentioned self-observation and experimenting in 1m² gardens most frequently as learning medium for changes in views on agrobiodiversity (5 in BEL-Landscape, 4 in Merode): "By the observation in the garden." (Merode/M/68/retired);"Being able to determine in practice, looking at the results of our measurements." (BEL-Landscape/F/61/nurse)

Experiences from the 1m² gardens were the most important learning medium for changes in attention for the environment (5 in BEL-Landscape, 5 in Merode): “The project kind of forced us to look for insects on our plants in the vegetable garden. Before, you were more likely to overlook such things. Now you look for yourself more and your attention is not just drawn to conspicuous things like a plant that has been eaten bare." (BEL-Landscape/F/25/unemployed)

In total, 83% (30/36) and 100% (17/17) of the respondents in BEL-Landscape and Merode, respectively estimated their efforts as valuable for the researchers. In both cases the most important reason mentioned was that they see their contribution as part of the total dataset, and that the comparison with all other participants is valuable for science (12 in BEL-Landscape, 9 in Merode): “Not only my participation, but through the participation of all the gardeners, a lot of information was gathered. The fact that the differences in the yields of the gardens were so great. I tried to follow the guidelines as best I could, so I think the results are representative” (BEL-Landscape/F/42/employee); “Because my results in volume and weight of the harvest was lower than the rest.” (Merode/M/53/chemical inspector).

Discussion

Citizen science facilitates learning and can cause changes in perspectives and action for agrobiodiversity

Our results reveal abundant reporting about knowledge regarding garden techniques such as watering frequency and crop choice. This is in accordance with literature where individual, instrumental learning has been found to be most frequent (Sims and Sinclair 2008; Bela et al. 2016; Moyer and Sinclair 2020). Indications of communicative learning were found regarding a better understanding of research processes, the balance in ecosystems, reflection on one’s own knowledge, interests and a sense of connection to specific locations in the landscape, although the latter type of learning was less represented. In their review, Moyer and Sinclair (2020) found substantial communicative learning, yet it was also less frequent compared to instrumental learning. They attribute this imbalance to the specific context and nature of the projects that focus on specific knowledge and skills (Sims and Sinclair 2008; Moyer and Sinclair 2020), such as vegetable gardening and functional agrobiodiversity. Researchers first assumed that transformative learning and actions for sustainability resulted primarily from communicative learning, but today the importance of instrumental learning is better recognised (Sims and Sinclair 2008; Moyer and Sinclair 2020). Our results confirm that instrumental and communicative learning are often interrelated and when combined can lead to transformative learning (Mezirow 2000; Sims and Sinclair 2008). For instance, learning to observe insects (instrumental) leads to recognition of one's own influences on insect populations (communicative), or vice versa, and resulted in a changed by the participant (transformation). A better balance between both types of learning outcomes could be beneficial to support actions for agrobiodiversity (Day et al. 2022). Transformative learning could be fostered by investing more in facilitated social events to collectively and deliberately reflect on agrobiodiversity (Cooreman 2021; Cooreman et al. 2021).

In BEL-Landscape, the changes in views on agrobiodiversity point to a more profound, critical reflection about the importance of agrobiodiversity. In Merode, respondents changed views mainly on gardening techniques. For instance, a respondent from Merode mentioned that pesticides are not always needed when asked if his/her view on biodiversity has changed, which could be an indication of critical reflection on instrumental lessons. This again highlights the need for instrumental learning as a precursor to transformative learning, whether or not it is related to communicative learning (Mezirow 2000; Sims and Sinclair 2008; Moyer and Sinclair 2020). In both cases there were indications of an increased belief in the importance of both agrobiodiversity and the diversity of insects. Changes in attention for the environment were reflected in respondent statements that they better observe and search for insects. One respondent mentioned for instance that the 'mandatory' search for insects in the $1m^2$ gardens caused this change in attention for the environment. Moreover, the insect observations during the project increased the attention for insects in their daily lives. We interpret these changes as self-conscious transformations or adaptations of respondents' reference frames (Diduck et al. 2012) and, therefore, transformative changes (Mezirow 1997; Mezirow 2006).

Diduck et al. (2012) and Merriam et al. (2020) consider transformative learning as complete when adapted or transformed reference frames are applied in new opinions and actions. In our case, 31% of respondents in BEL-Landscape and 12% in Merode used new insights in their actions. For instance, a respondent mentioned that she had more attention for insects, and that a garden which is not 'tidy' promotes biodiversity (BEL-Landscape/F/65/retired). A conversation with another participant led to stimulation of this changed reference framework and resulted in new actions in the own garden: mowing intensity dropped and flowers were left to grow in the lawn. Consistent with other studies, fewer participants reported having signs of completed transformative learning than participants who reported having gained instrumental or communicative lessons.

Learning outcomes depend on the respondents' prior knowledge

CS reviews often do not specify whether participants have prior knowledge related to the project, despite its recognised potential influence on learning outcomes (National Academics of Sciences Engineering and Medicine 2019). In total, 80% and 100% of the respondents in BEL-Landscape and Merode, respectively reported having prior knowledge in vegetable gardening, agrobiodiversity, agriculture or a combination of these topics. The participant pool in this CS project is therefore considered to be biased towards people with interest in the research topic. The prior knowledge in both cases was mainly about vegetable gardening and agrobiodiversity and only to a very limited extent about agriculture. We argue that this is due to the $1m^2$ gardens that were probably more inviting to people interested in vegetable gardening and agrobiodiversity than agriculture. Although rural residents with prior knowledge are important actors in the countryside, the CS project with $1m^2$ gardens did not attract many farmers, who have the greatest impact on agrobiodiversity.

Despite the open call for participants in newspapers and radio, in both cases, the final participants all had prior knowledge about agrobiodiversity and vegetable gardening. In line with Groulx et al. (2017) and Bueddefeld et al. (2022), we argue that other people who were potentially interested in the project may have encountered time and geographical constraints for participation. Participation required a commitment to take repeated actions over a long period of time, thus favouring people who live or work near the research landscape. Time constraints could explain why, for instance, only three professional farmers participated (van de Gevel et al. 2020). We argue that it is inherent to CS to have a biased respondent group even when an open call for participants is used, which does not provide a representative picture of the society. Whether or not this poses a problem depends on the specific goals of the CS project. As discussed in the methodology section, close collaboration with the researcher, frequent communication and $1m^2$ gardens as tactile learning tool were considered as means to motivate participants and collect a complete dataset, which was a priority in this CS project. In addition to the valuable dataset, this approach showed great potential for learning outcomes toward pro-environmental behaviour. However, there might be a trade-off between the inclusion of participants with prior knowledge who are more likely to stay motivated and compile a complete data set versus and learning or pro-environmental behaviour as project outcomes.

This notwithstanding, we found that all but one respondent improved their (mainly instrumental) knowledge via participation in the project, suggesting that prior knowledge does not hinder citizen scientists from acquiring new knowledge. Indeed, respondents mentioned prior knowledge as the main reason why their views on biodiversity did not change. In this case, however, prior knowledge proved useful in collecting a valuable dataset (Gerits et al. 2022). The research team posited that the limited drop-out rate and successful data collection during this immersive CS project could be partly due to the participants' interest in biodiversity, vegetable gardening or both. Participants' prior knowledge was also often enriching for the researcher, resulting in mutual learning. According to us, the successful data assembly by volunteers was, mainly due to the fact that the volunteers were aware that the researchers were dependent and awaiting their data entries. Through frequent communication about results and findings, the volunteers knew that the researchers were actually using their data and that other volunteers were still involved as well. In addition, the volunteers' data-entries were directly visible to the researcher who quickly responded if elements were missing or unclear. The informal relationship of trust between the researcher and the volunteers certainly boosted the volunteers' motivation to provide the data as accurately and precisely as possible. The qualitative data from the questionnaires clearly showed that participants felt responsible for their data.

According to our data, participants with limited prior knowledge were likely to go through a transformative process and eventually change their behaviour in favour of agrobiodiversity. It is therefore important to differentiate and provide learning opportunities for participants with and without prior knowledge. Additionally, it might be beneficial for (transformative) learning to facilitate interaction between participants with and without prior knowledge. Phillips et al. (2019) also found that social interactions between participants were important for engagement in CS projects and could steer participants toward a leadership role. One example from BEL-Landscape illustrated this. A person (BEL-Landscape/F/61/nurse) without prior knowledge managed a 1m² garden together with a person (unknown to each other) with prior knowledge about vegetable gardening and insects. This participant mentioned: "I was fortunate to work with X, who was very knowledgeable about herbs and insects. Moreover, he also proved to have an excellent camera that provided wonderful close-ups of visiting insects or budding plants. His photo collection will nicely reflect the evolution of our garden."

Scientists and academics often participate in CS projects themselves (Hecker et al. 2018; van de Gevel et al. 2020; CS Track 2021). In contrast to Land-Zandstra et al. (2021), who define citizen scientists as non-scientist participants, our data do not indicate that participating researchers experience CS projects differently than other participants, nor do they appear to follow different learning trajectories or show different outcomes. Learning outcomes of the 11 respondents of BEL-Landscape with a scientific profession were highly comparable to the total respondent pool of that case. The high similarity of the learning outcomes between BEL-Landscape and Merode further confirms this robustness, as the Merode case did not include any professional researchers.

Frequent communication, tactile tools and transparent communication facilitate learning

Based on these results, we believe that pro-environmental behaviour in CS projects is stimulated by a combination of experiences with tactile learning tools and reflection during informal conversations between participants themselves and conversations with researchers, preferably in an authentic learning environment, that mirrors daily life (OECD 2013; Herrington et al. 2014).

In both cases, the weekly newsletter was indicated as the tool that contributed most to the lessons learned. The frequency of the newsletters allowed the research team to be transparent and honest in the scientific process, which in literature appears as a catalyst for learning and uptake of measures (Steingröver et al. 2010; Ruiz-Mallén et al. 2016; Petridis et al. 2017). Furthermore, differentiation between different levels of engagement ("participation ladder") is argued to facilitate learning among a variety of participant profiles (Purcell et al. 2012; Phillips et al. 2019; van de Gevel et al. 2020). For the researchers, the weekly newsletter was the most time-consuming part of the communication plan. An average of three hours per week was spent compiling the newsletter for twenty weeks per year. Along with many other researchers skilled in CS, we therefore support the argument that significant project resources should be provided for communication (Pocock et al. 2014; Lakeman-Fraser et al. 2016; Land-Zandstra et al. 2021). Communication in our CS project was designed to keep participants motivated and enthusiastic about the project and included guidelines for conducting scientific measurements as well as in-depth, accessible information on agrobiodiversity. The weekly newsletters as the main communication tool fulfilled the aim of engaging the participants in data collection. As a spill-over effect it also contributed substantially to learning outcomes.

Direct experience of the effects of agrobiodiversity in the 1m² gardens is the second most mentioned learning medium in both cases. This indicates the value of the theory of experiential learning (Kolb 2015) with the 1m² gardens as a tactile tool, although this theoretical lens is not yet frequently applied to learning in CS projects (Brossard et al. 2005; Phillips et al. 2019). As Gentry (1990) states: "I hear and I forget, I see and I remember, I do and I understand." We underpin this by referring to the recent research of Cooreman (2021) on agricultural innovation demonstrations, who argues that sensory experiences (touching, smelling, tasting, seeing, hearing) can support transformative learning processes (Carolan 2008; Hayden and Buck 2012; Cowan et al. 2015). This is also supported by the research of Anglade et al. (2018), who found that bringing together sensorial perceptive experiences for teaching agroecology could transform beliefs regarding conventional agricultural practices. In addition, research by Cowan et al. (2015) points to the importance of in-person, hands-on extension activities organised in a tactile space.

Our analysis indicates that lessons were often initiated by experiences in the 1m² gardens and in a next step consolidated with information provided by the newsletter (or vice versa). For instance, several participants said they first read in a newsletter that the arugula plant in the 1m² garden could be harvested several times, after which it would grow back easily. Several participants who harvested arugula multiple times during the project have indicated this as an (instrumental) lesson learnt. This shows the complementarity between written communication before or after a hands-on experience, referred to as "post-visit action resources" by Bueddefeld et al. (2022). By providing written information at strategic moments before or after the interaction with the 1m² garden, participants were not overloaded with information during the encounters in the 1m² gardens. This was probably one of the reasons why participants most valued the newsletters as a learning tool.

Communication with the researcher was mentioned as the third most important learning source in both cases. Such communication events took the form of personal, informal contacts in the field where the researcher encountered the participant during the scientific sampling in the 1m² gardens. Informal contacts are valuable learning moments that often remain undervalued (Reed et al. 2010; Triste 2018; Triste et al. 2018; Land-Zandstra et al. 2021). Increased personal contact between participants and researchers helps to create mutual respect and trust (Land-Zandstra et al. 2021) and can deepen learning outcomes and transformative change (Sims and Sinclair 2008; Sinclair et al. 2011; Diduck et al. 2012). Accordingly, the research team experienced that having a full-time researcher dedicated to the CS project was crucial to build an engaged citizen community characterized by mutual trust. The researcher was the single point of contact for participants and succeeded in building an informal connection resulting in a valuable ecological dataset with minimal drop-out of three participants in BEL-Landscape and none in Merode. Trust-building efforts and good collaborations take time, which is not always factored in nor valued in CS projects (Pocock et al. 2014; Lakeman-Fraser et al. 2016). In BEL-Landscape and Merode the informal interactions were mostly with participants who were assigned to a 1m² garden on their own property, often in their own garden close to their house. Others who maintained a 1m² garden further away from their property were often not present at the same time as the researcher. Furthermore, retired participants were present more frequently for informal interactions compared to younger participants or fellow researchers who were at work when the researcher visited the 1m² garden. Therefore, it is likely that learning trajectories differ between participants who had more or less informal interaction with the researcher leading to an unequal chance for learning opportunities.

Finally, our results show that mutual visibility of engagement and actions between participants and researchers made the participants feel like they were part of the research team and helped them understand the extent to which their efforts were appreciated. Phillips et al. (2019) and Day et al. (2022) also found that participants were motivated by knowing that their data were being used to answer questions that were personally relevant and meaningful to them. In our cases, we kept participants updated by frequently sharing lab pictures in the private Facebook group and sharing graphs with preliminary results in the newsletter. This helped participants feel that their efforts were valuable. Furthermore, the researcher frequently checked the online Excel files where participants inserted their data and provided individual, constructive feedback, which Land-Zandstra et al. (2021) also found to be important to build an effectively engaged community.

The role of the principal researcher in the citizen science project was highly determinant for the outcomes of the citizen science approach, both in terms of the quality of the ecological dataset and the learning outcomes. The relatively small number of citizen scientists involved in both cases allowed for an honest, friendly and informal approach to the dialogues that suited the researcher's personal style. The high level of personal involvement, while going through a learning process himself resembles to what Mcareavey (2008) calls becoming embedded in the research field. It is important to mention that prior to his PhD-project, he had limited knowledge about vegetable gardening, agrobiodiversity, landscape ecology or citizen science approaches. He did not consider himself as an expert and took a rather unknowing position alongside the participants, recognizing the usefulness of the citizen scientists' knowledge. The CS literature advocates that this is beneficial for the power balance between researcher and volunteer during the project and allows for smooth and inclusive dialogues where language is not overly specialised (Ozolinčiūtė et al. 2022). In fact, the researcher in the project also took the role as facilitator, linking the expectations from the citizen scientists to himself as a researcher (Eleta et al. 2019; Ozolinčiūtė et al. 2022). The immersive citizen science approach used in this dissertation resembles the field of action research in several ways, as was also mentioned in Chapter 2, where we described our approach in the social-ecological framework.

Action research is defined by Reason and Bradbury (2001, p.1) as "a participatory, democratic process concerned with developing practical knowing in the pursuit of worthwhile human purposes, grounded in a participatory worldview which we believe is emerging at this historical moment. It seeks to bring together action and reflection, theory and practice, in participation with others, in the pursuit of practical solutions to issues of pressing concern to people, and more generally the flourishing of individual persons and their communities". In some ways, this corresponds to our citizen science approach in that it allows us to study the social subsystem while acknowledging peoples' own knowledge, adopting an empathic communication style and taking the time to listen. It also combined theory and practice about agrobiodiversity by combining the information in the newsletters with collaborative experiments in the 1m²-gardens to simultaneously contribute to solving issues (sustainable agriculture, biodiversity crisis) of pressing concern to people (Charles 2011). Moreover, the researcher's non-expert status with respect to vegetable gardening and agrobiodiversity caused him to consciously undergo (transformative) changes as a researcher himself (Brydon-Miller et al. 2003). However, as Smith et al. (2010) discusses, we consider ourselves as university researchers who somehow dictated the course of the citizen science project and the data collection tasks to be performed. This was not democratically decided and although failure or adaptation of procedures were incorporated into the project, this diverges from the dynamic, community-oriented nature in participatory action research. Charles (2011, p. 370) appropriately articulates this by stating that "the partnership between the university and the community requires some flexibility on both sides: the university must accept that genuine participatory action research must allow for unexpected outcomes, and even 'failure', and that participants influence the course of the research; the participants, at least in the case of a PhD study, must recognize and support the responsibility the academic researcher to produce a thesis and other academic outputs." In conclusion, we think that our approach was a combination of citizen science and action research. We dictated the course of the project by aiming for a qualitative dataset, but still recognized values and knowledge of the participants, and aimed to combine both theory and practice in the pursuit of actual change of the social situation. We argue that an 'extreme version' of citizen science projects can become even more like action research by involving participants in the formulation of research questions and research protocols.

Comparison between BEL-Landscape (2018, 2019) and Merode (2021)

As BEL-Landscape and Merode were independent in time and space with no interaction between participants, they can be considered as independent replicates of the project. Despite some important differences between both cases, the results are highly similar. In the Merode case, there were fewer indications of changes in reference frameworks and transformative change. One reason might be that in the Merode the project only went on for one year due to the COVID-19 pandemic. The long term character of projects has already shown to be important for transformative learning (Ruiz-Mallén et al. 2016). Also, BEL-Landscape was located close to the research institutes involved in the project, while Merode was located a long distance (two hour drive) from the researcher's office. This limited the number of opportunities for informal contacts between researchers and participants in Merode compared to BEL-Landscape. Even so, the results indicate that the conversations with researchers are mentioned at a nearly equal level of learning importance in both cases. Finally, in Merode all participants who entered the project had some level of prior knowledge, which might have influenced the learning processes and outcomes in this case.

Conclusion

The goal of this citizen science (CS) project was met, i.e. valuable ecological datasets were compiled while using the help of participant volunteers and involving them in a participatory project (Gerits et al. 2021; Gerits et al. 2022). A CS approach was used with 1m² gardens as tactile tool, weekly newsletters as communication support, and frequent informal contacts by a dedicated researcher as a trust-building approach. This study created a learning space for both instrumental and communicative lessons which led to limited transformative change towards pro-environmental behaviour for agrobiodiversity. Participants were mainly rural residents with prior knowledge about biodiversity and vegetable gardening. Although this prior knowledge did not obstruct learning and was helpful for them to stay motivated to continue data collection, a different approach and search for participants might be necessary when the goal of the CS project is to transform a range of actors towards pro-environmental behaviour. The type of tactile tool and the associated requested scientific actions, in combination with the time required for participation, will create a bias toward a particular rural subpopulation. The approach can be adapted to include a specific target group with high impact for rural agrobiodiversity, but it is impossible to design a CS project that matches the interests of all possible actors. The inclusion of a wide range of actors, many without prior knowledge, could also hamper the collection of a complete, valuable dataset. In the recruitment campaign, an active search for participants with less prior knowledge of the research topic could be useful if behaviour change is sought. Because people without prior knowledge or affinity for the tactile tool might feel hesitant to participate (Land-Zandstra et al. 2021), communication should be done thoughtfully. It will also be necessary to test the participants' prior knowledge before the start of the project. Findings of this chapter could be transferable to learning initiatives outside CS projects (schools, excursions, demonstrations etc.) and could further stimulate engagement for agrobiodiversity in the countryside. We conclude this chapter with transferable guidelines for future CS projects which have (partly) as goal to engage participants for pro-environmental behaviour in favour of agrobiodiversity (Table 5.4).

Table 5.4*: key messages and recommendations for CS practitioners.*

Key findings from research	Recommendations for future projects
Almost all respondents learned. More than half of them changed views on biodiversity or their attention for the environment and one-third changed their actions for agrobiodiversity.	1. When designing CS projects, it is important to consider whether the goal is to increase knowledge or to promote pro-environmental behaviour. These objectives should be incorporated in all project phases, in the selection of participants (recognizing prior knowledge), in the communication of the project (provide both factual and communicative knowledge) and the dissemination of results (frequent, to allow comparison of results).
It is important to recognize participants' prior knowledge and its possible influences on transformative learning processes	2. Reaching participants without prior knowledge might be beneficial but requires extra effort. Acknowledge that participants already involved in sustainability are biased 3. Facilitate interaction among participants with different levels of prior knowledge and experience.
A tactile tool and frequent communication facilitate learning and action.	4. Use a tactile tool to create an in-depth and frequent experience with the topic. 5. Invest in frequent, continuous interactions, combining written information with informal interactions in the field to build trust. 6. Provide sufficient opportunities for informal interactions for all participants. 7. Increase mutual visibility of actions taken by participants and researchers.

Data archiving statement

The original data contains many elements that reveals personal data. As per our agreement with the Data Protection Officer of Ghent University and due to the confidentiality of the data, we are unable to make it publicly available.

Chapter 6

Synthesis of social-ecological findings followed by application to an example case (zoom in) and comparison with other landscapes in Flanders (zoom out)

Agrobiodiversity and the resilience of peri-urban landscapes face multiple challenges related to land use management. On the one hand, agricultural intensification contributed significantly to the simplification of both the composition and configuration of agricultural landscapes and our food production systems today often exceed planetary boundaries (Rockström et al. 2017)**.** On the other hand, a process of actor diversification and fragmentation of land uses is ongoing in peri-urban areas, with urban sprawl and multiple land uses claiming land, often with negative impact on FAB and agroecosystem functioning (Chapter 2). FAB is threatened by both trends, while as a natural resource, it is recognised to be of high value for keeping agroecosystems within planetary boundaries (Jackson et al. 2012). The resource value of FAB should be acknowledged by all actors who could invest in it and co-create a sustainable open space to provide multiple agroecosystem services.

In this thesis we simultaneously addressed the ecological and the social subsystems of our proposed framework (Fig. 2.1), providing new pieces for the jigsaw of sustainable peri-urban landscapes. We studied FAB as central resource in a social-ecological system and used an innovative citizen science approach in two spatially independent case studies in Flanders to measure the impact of landscape composition on multiple agroecosystem services, together with local actors. We disentangled the impact of semi-natural habitats, non-agricultural and agricultural land uses on microclimate, functional invertebrates and crop performance. We also examined how to foster transformative learning among local actors towards pro-environmental behaviour. **The overall objective** of this thesis was to understand how FAB at the landscape scale supports multiple agroecosystem services by the engagement of multiple stakeholders. We confirm our assumption that zooming out to the landscape scale is useful to involve relevant actors for FAB reinforcement. Below we return to the **specific objectives** stated in the general introduction of this thesis and synthesize our main findings. Further on in this chapter we apply these insights on a specific example case of BEL-Landscape.

The first specific objective was to study FAB as a natural resource within multi-actor peri-urban regions in an understandable way using an interdisciplinary method.

- Therefore, in **chapter 2**, we developed a social-ecological framework and innovative toolbox, which we successfully applied for three years;
- We highlighted the usefulness of a social-ecological framework to structure new insights, to keep track of knowledge gaps and to communicate to fellow scientists and to society;
- The 1m²-garden toolbox was useful to reach a subset of the peri-urban population and keep the citizen scientists motivated to compile a standardised ecological dataset.

The second specific objective was to investigate how land use composition at different scales affects a range of agroecosystem services relevant to multiple crops.

- In **chapter 3** we found that agricultural land use, semi-natural habitats and non-agricultural land uses are important explanatory variables for local agroecosystem functioning;
- While domestic gardens and especially built-up areas are consistently detrimental for the functioning of the agroecosystem, the relative proportion of arable farming at several scales related positively to the activity-density of functional arthropods. Semi-natural habitats, in particular biologically valuable herbaceous vegetation, buffer microclimatic variation and support predators;
- We found no clear relationships between multi-crop performance in the 1m²-gardens and surrounding landscape composition. The abiotic and biotic regulatory agroecosystem processes were not explaining variation in crop performance.

The third specific objective was to investigate the generality of the relationships between landscape composition and agroecosystem services when comparing peri-urban regions.

- In **chapter 4** we found some relationships to be more consistent than others when replications of our approach are compared;
- Although the buffering effect of high green habitats in the landscape persists, it is much less pronounced when temperatures and water availability are more moderate;
- Predatory invertebrates seem to be less context dependent than pollinators in their response to the surrounding landscape composition;

- Again, no relationship was found between the landscape composition and the performance of crops considering reduced herbivory or increased plant growth.

The fourth specific objective was to explore the suitability of our immersive citizen science approach to reach different peri-urban land users and encourage engagement in FAB.

- In **chapter 5** we found that citizen scientists learned valuable instrumental lessons about FAB and their (or others') impact on this natural resource. Their views, and to a lesser extent their behaviour transformed, despite their prior knowledge about biodiversity;
- The $1m^2$-gardens were valuable for (mainly instrumental) learning for a subset of the peri-urban population with prior knowledge about biodiversity and vegetable gardening;
- Communicative lessons about understanding of agroecosystem functioning or one's individual role in the landscape were learned and might be first steps towards collaborative governance of FAB;
- The $1m^2$-gardens as tangible tool in combination with frequent written and informal communication and mutual understanding between researchers and volunteers facilitated learning and minimalised drop-out during the project.

The fifth specific objective was to combine previous results into practical social-ecological guidelines relevant to peri-urban regions. Therefore, in what follows in Chapter 6, we will draw from all previous chapters to make a social-ecological analysis for a specific example case.

- In the next section we discuss how a projection of our results from all chapters on a specific sampling site reveals the prevalence of trade-offs between agroecosystem services in peri-urban regions;
- After zooming in, we check the representativeness of the two cases of this thesis by comparing them to three other agricultural landscapes in Flanders.

Zooming in: applying our general results to a specific peri-urban case to highlight trade-offs between agroecosystem services

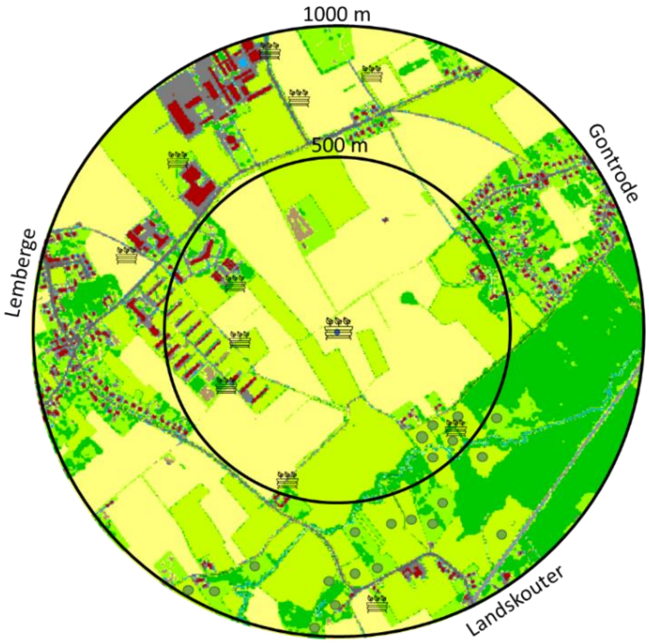
In the previous chapters of this thesis, we presented ecological and social data collected in the 1m²-gardens separately by research discipline. In this section, we combine the insights of both disciplines and use them to do a social-ecological analysis of a spatially explicit peri-urban area (called "**example case**" from here on). In this way, we try to concretise the main conclusions and aim at a better understanding of peri-urban Flanders considering scales, land users and FAB mediated agroecosystem services.

We first present the example case and then elaborate on the actors present at different scales, leading to the understanding of how our social-ecological lens is useful to understand trade-offs between agroecosystem services (Gerits et al. 2021). Finally, we discuss how our citizen science approach in the example case contributed to understanding actors' influences or demands and how this could facilitate collaboration.

Example case selection and characterization

To discuss the interconnected ecological (chapter 3, 4) and social findings (chapter 5) in an understandable manner, we selected a particular location from the BEL-Landscape case based on three criteria: **(1)** the surrounding land uses and extent of agricultural activity, **(2)** the knowledge on the land users and history of the area as it partially coincides with ILVO's Agrifood Research Landscape (ILVO 2022) and **(3)** the presence of social and project dynamics on (future) landscape development with the Rodeland Project (Rodeland 2022). As will appear from the description below, the example case was chosen because both the ecological and social dynamics in this environment have been documented for many years by colleagues of ILVO, which could not easily be achieved in other sampling sites. Understanding land use dynamics requires time and conversations with local land users (stakeholder analysis), which was not feasible in the scope if this thesis. Furthermore, the example site is located in the centre of the BEL-Landscape case with multiple 1m²-gardens in the environment (Fig. 6.1). By analysing this case, we include as many sampling sites as possible. Even more, it concerns a very typical peri-urban landscape in Flanders, with an interesting mix of agriculture, nature protection areas, historical component, etc.

The first criterium for the selection of this case was its usefulness in demonstrating the relevance of the 500-metre scale in peri-urban areas. We project our results on the zone with the most agricultural land use within a radius of 500 metres from both cases, with 80% agricultural land of which 50% is arable and 30% productive grassland (Gerits et al. 2022) (Fig. 6.1). In chapter 3 we mentioned the importance of sampling 1m²-gardens along a full landscape compositional gradient ranging from mainly agricultural land use to areas with more urbanised areas with sealed surfaces and domestic gardens (Pasher et al. 2013; Gerits et al. 2022). In Fig. 6.1 we see that in a 500-metre radius we succeeded in sampling merely agricultural land use (80%), but when zooming out to a radius of one kilometre, three rural municipalities are partly included (Gontrode, Lemberge, Landskouter). Within these municipalities, over 250 private parcels of peri-urban residents with separate domestic gardens and sealed surfaces appear as land users. The amount of land users therefore exponentially rises when going from the 500-metre radius up to 1 km radius in this peri-urban example location.



Land use	Actors in 500 meter	Actors in 1000 meter
Arable	3 farmers, B&B, vineyard	7 farmers, B&B, vineyard, tree breeder
Productive grassland		
Woody vegetation	ANB, domestic garden, ILVO, NP, farmers	ANB, domestic gardens, ILVO, NP, farmers, Ghent University
Valuable herbaceous vegetation	NP, horse keeper, ANB, farmer	NP, horse keeper, ANB, farmers, ecologically managed road verges
Less valuable vegetation (gardens)	Horsekeeper, 4 domestic gardens, ILVO terrain	Horsekeeper, > 250 domestic gardens, ILVO terrains, school
Buildings/roads	Agricultural buildings (ILVO), 8 houses	Agricultural buildings (ILVO), > 200 houses, roads, railway

Figure 6.1: *The example case (central garden icon) and the related land uses in a 500 m and 1000 m radius. In the surroundings there were several other sampling locations, indicated with a smaller garden icon (further supports the choice for this specific example case). The legend of the map is coupled to a description of the actors present in the different landscape scales. ANB = Forest and Nature Agency in Flanders, related to the Department of Environment, ILVO = Flanders Research Institute for Agriculture, Fisheries and Food, NP = 'Natuurpunt' is a nature organisation.*

Gontrode, Lemberge and Landskouter are no recent settlements, because cores from rural land use have been there at least since 1771 - 1778 (Ferraris) (Fig. 6.2). Yet, earlier they were condensed in settlements, while now there is considerable ribbon development in between them, with domestic gardens intertwined with agricultural fields. Evaluations of these and other locations in both BEL-Landscape and Merode suggest that infiltration of domestic land uses is common in Flanders and other peri-urban regions (Verbeek and Tempels 2016; Pisman et al. 2021). Infiltration of non-agricultural land uses in between fields introduces demands from the agroecosystem that go beyond regulatory services studied in this thesis to create resilient food production. Areas for nature conservation or residential land users, for instance, could demand for forestation or recreational infrastructure (walk or bike trails). This leads to trade-offs between agroecosystem services leading to different opinions about the required FAB at the landscape scale (Zasada 2011; Kerselaers et al. 2013; Lefebvre et al. 2015).

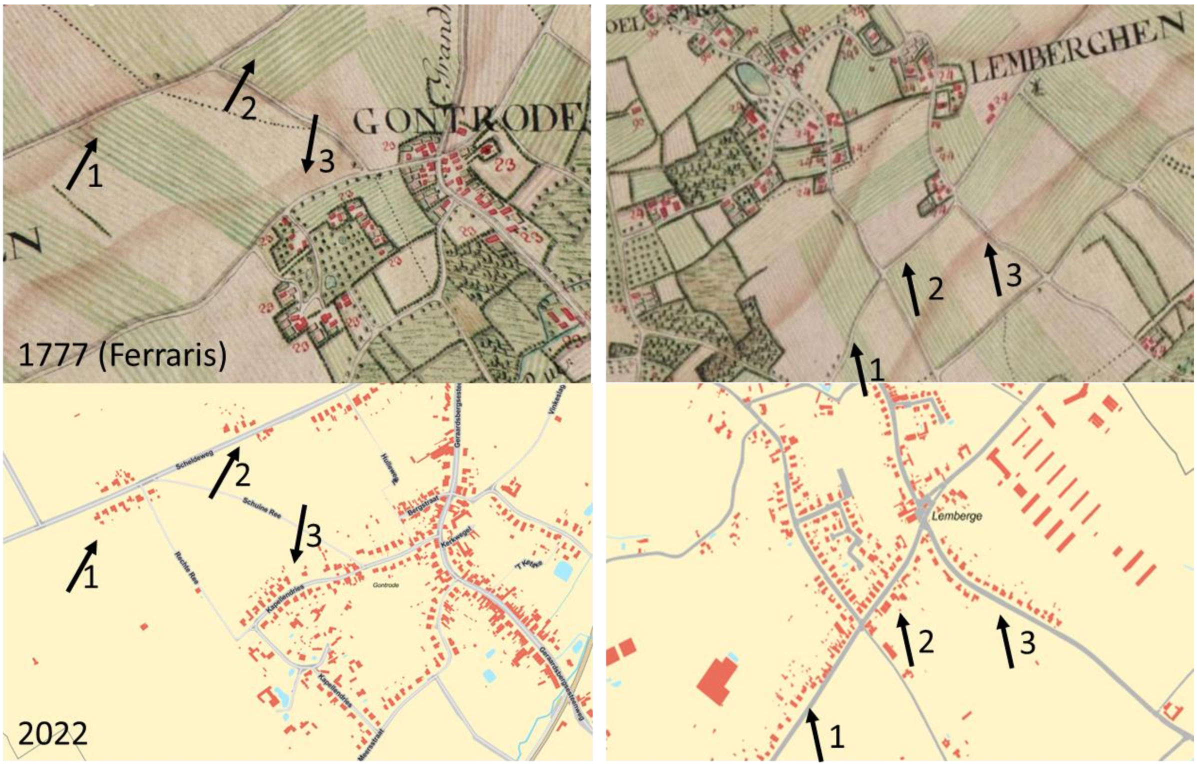


Figure 6.2: *Illustration of ribbon development between 1777 and 2022 in Gontrode and Lemberge with hotspots indicated by arrows.*

The second criterium for selecting the example case was the research team's knowledge of the history and non-agricultural land uses (other than residential ones) in the example case. Within the 500-metre radius there are three farmers (including ILVO, representing a farming business) working on 80% of the area. There is also a semi-professional vineyard, a bed and breakfast, a recreational horse keeper and a World War I monument in between the agricultural fields. On the outside of the central agricultural zone, there are several domestic gardens and adjacent to the Gondebeek stream, the local nature organisation (Natuurpunt) manages the single considerable patch of valuable, low green vegetation in the studied 500-metre area: extensively managed, wet and species rich grasslands flanked by pollarded willow trees. High green vegetation is absent in the central agricultural zone. The only high green vegetation present in the example case is concentrated close to the Gondebeek, close to the buildings of ILVO, the bed and breakfast or in domestic gardens (Fig. 6.1). The above shows that many actors in an area of only 0.8 km^2 (500-metre radius) have their own requirements for the peri-urban area, creating possible trade-offs.

The third criterion for selecting this example case was the start of the Rodeland project which launched multi-actor partnerships to jointly manage the peri-urban landscape (Rodeland 2022; Terpstra and Vaneenooghe 2022). The BEL-Landscape case presented in chapter 2 and chapter 3 lies within the working area of the Rodeland project, that started in 2020 after the 1m^2-garden seasons. Both ILVO and Ghent University (research team leading this thesis) were involved together with 18 other partners including several other research institutes, the involved municipalities, the province of East Flanders, Flanders' Agency for Nature and Forest, Flanders' Department for Agriculture and Fisheries, several landscape networks, famer organisations and nature organisations. The involvement of the research team as partners allowed for close monitoring of the project and it's possibility of spatially organising FAB for multiple agroecosystem services and trade-offs between the demands of a high variety of rural actors. Next to the Rodeland project, many other social dynamics are at play in these surroundings, as described in the thesis of Terpstra and Vaneenooghe (2022). There is considerable pressure of governmental agencies for afforestation on grassland, and nature conservation organisations are aiming for the connection of nature areas in the landscape.

Trade-offs between agroecosystem services demanded by multiple actors

In this section we build further on the characterisation of the example case from before and discuss how trade-offs occur between local microclimate regulation, functional arthropod community, provisioning agroecosystem services but also other ecosystem services appearing from other non-agricultural land users. We learned from chapter 3 that arable areas were prone to high variability in soil temperature and moisture content during extreme drought and heat waves (Fig. 6.3 left). Extreme microclimatic conditions were registered in the middle of the open arable zone that we discuss here as example case (Fig. 6.1). Additional to the sensor data, the research team experienced these microclimatic extremes through fast drying out of pan traps relatively to traps in 1m²-gardens in other locations. Such severe temperature and drought extremes in the arable landscape occurred in 2017, 2018 and 2019 and will become more frequent under the predicted climate change. Furthermore, the results of both chapter 3 and 4 confirmed that high green vegetation in the landscape can buffer both temperature and drought extremes.

Figure 6.3: *Left: open arable conditions in the 500-metre radius. Right: the Gondebeek-valley with permanent, wet and species-rich grasslands for biodiversity conservation, flanked by forest fragments and pollarded willows.*

From our brief land user characterisation earlier in this section we learned that the inner agricultural part of the example location is managed by three farming businesses, a semi-professional vineyard an a recreational horse keeper. So in fact, no other than these actors could increase the high green vegetation in between their fields or crops to buffer the microclimatic variation. This would ideally ask for collaboration among these actors because actions of one will affect the others. While current buffering high green vegetation is mainly present on the outer sides of the inner agricultural area (Fig. 6.3, right), introduction of high green habitats might not be beneficial considering other agroecosystem processes. The trapping data from our research suggests that the activity-density of functional arthropods is in fact highest at the location where they are expected to perform their pest control and polination services (arable areas). It is likely that it concerns generalist species which can use a variety of food sources and survive in many different habitats. In chapter 4 we learned that high green vegetation might also be distracting pollinators from pollination in arable zones or that general foragers prefer more open arable regions to forage.

Our results therefore suggest a possible trade-off between the agroecosystem services studied in this thesis, where high green vegetation could be implemented in agricultural areas to buffer the microclimate but could distract functional arthropods in their function for the agroecosystem at the right place and the right time. Also, where high green vegetation is close to crops, competition for light, water en nutrients occurs (Van Vooren et al. 2017; Pardon et al. 2020). Yet a smart implementation of high green vegetation in the landscape could optimise different agroecosystem services at the landscape scale. Although beyond the scope of this thesis, previous studies have shown that high green vegetation is also useful for many other agroecosystem services, such as erosion control and flooding due to excessive rainfall (Pardon 2018). This 'wet side' of climate extremes is equally important because its likelihood is also increasing due to climate change. In the case of Merode, we faced such extreme wet conditions in 2021 (chapter 4), with the known catastrophic outcomes for agriculture, people and society.

Trade-offs considering FAB at the landscape scale in the studied example case go beyond the agroecosystem services studied in this thesis. Considering nature conservation, for instance, several red list bird species adapted to foraging in open arable regions. Even more, these often ground nesting-birds (e.g. lapwing, skylark) do not benefit from nearby lookout posts in nearby trees for crows, magpies or gulls (Game & Wildlife conservation trust 2022). Also, there is often historical and cultural value attributed to open arable landscapes (Van Berkel and Verburg 2014; Plieninger et al. 2015). In our example there is a war history (WWI) where scattered bunkers in the open agricultural landscape remind visitors of what happened in the twentieth century (Atlantikwall Belgium 2012). Moreover, the agricultural area in the example case has always been a traditional open pasture area (Fig. 6.2) with distant views over the gently rolling terrain in which churches are seen as anchor points in the landscape.

However, for the horse farmer, on the other hand, climate extremes increase the need to provide shade for the animals in this open terrain.

Clearly, it is difficult to optimise all agroecosystem services in specific locations because of trade-offs. Especially in peri-urban areas where pressure from multiple non-agricultural land uses is high (Verhoeve et al. 2015). The research in this thesis highlights the possibility that some goals may require zoning at a relatively small landscape level, which could be no more than a composite of multiple individual plots. For example, if it is not beneficial to establish high green vegetation in the open arable regions to buffer the microclimate, we should mainly focus on drought-resistant crops or crops that are less sensitive to extreme temperatures or precipitation. Crops that are more vulnerable in terms of climate extremes could be planned in areas that are enriched with high green vegetation in the 500 metre-radius or perhaps in an agroforestry context, maybe next to domestic gardens who contribute to these circumstances. However, the combination of several '500-metre-landscapes' makes it possible to combine all these objectives in a relatively small landscape anyway. Think of it as a multifunctional strategy at a larger landscape scale (>500 m) but zoning on a micro-scale (<500 m).

In addition to possible trade-offs, our research revealed opportunities for FAB-enhancement at the landscape scale to promote multiple agroecosystem services. Natural pest control could be useful for farmers, decreasing their dependence of expensive agrochemical crop protection (Steingröver et al. 2010; Tschumi et al. 2015). We show in this thesis that valuable low green vegetation has potential for stimulating ground dwelling predators, in different regions and different weather conditions. Furthermore, it is probably beneficial for many more agroecosystem services not studied in this thesis (detritivores, biodiversity conservation, carbon sequestration, aesthetic value etc.) (Van Vooren et al. 2018). There are currently small strips (<1 metre width) of non-crop low green vegetation in between the agricultural fields in the example case. Although they contain wild flora, these habitats in the example location are not yet managed for FAB nor biodiversity conservation although they have potential to provide useful habitat in the agricultural matrix. These habitats are there because they are not reachable for crop production due to local elevation or situated close to fences, small roads or walking trails.

The arable crops that are currently rotated in our example location are not pollinator-dependent (maize, wheat, potato, sugar beet, temporary grassland). However, there is a growing demand from society for plant based proteins and research is promising for growth of legumes in Flanders for this purpose (Vilt 2020). Different types of beans, but also chickpea, soybean and lentils could facilitate the protein shift from meat-based to plant-based and increase the sustainability of our food production. Most of these crops are, at least partly, dependent on insect-pollination and functional natural enemy community. It is therefore useful to anticipate a high dependency of future crops of insect pollination and natural pest control and to optimise FAB for both increased pollinator and natural enemy activity.

Encouraging various actors to adopt pro-environmental behaviour for agroecosystem services

In this final part of the example case illustration, we look at which actors we reached with the 1m²-garden citizen science approach in and around the example case and whether lessons were learned on how to facilitate transformative learning or pro-environmental behaviour. With our 1m²-garden approach, in both cases, we involved many rural residents (chapter 5). As we discussed before, their cumulative impact on FAB is significant in Flanders, since more than 12% of the total area in Flanders is domestic garden (Dewaelheyns et al. 2016; Pisman et al. 2021). In the 1000-metre surrounding of the example site, next to several rural residents, the semi-professional vineyard farmer, two volunteers with the nature organisation (Natuurpunt) and several researchers from ILVO were involved as participants. In contrast, none of the three other farmers were involved, despite their decision-making power over the farmland that makes up 80% of the example case. ILVO provided several sampling sites on the Agrifood Research Landscape that were either managed by employees or by rural residents living nearby. Although these actors had no decision-making power over the landscape around their sampling site, many of them showed an increased understanding of agroecosystem functioning and how FAB should be improved to support it (communicative learning). Although our 1m²-garden approach involved only a small subpopulation of the peri-urban study landscape, we showed that the tactile tool and informal, frequent communication led to transformative lessons about FAB. As an immersive citizen science project with whole peri-urban areas is not realistic, we need to draw lessons from our citizen science project that are transferable to approaches to encourage rural actors to participate in the management of FAB in their surroundings.

Our approach stimulated individual communicative learning but did not facilitate steps towards actual collaborations in the field. Specific aspects of our citizen science approach might however be useful to stimulate interactions between farmers, nature organisations, the municipality, horse keepers and rural residents towards collaborative governance for FAB. If we want to reach people with different prior interests in their surroundings, we should find a common ground in knowledge or concerns (Rogge et al. 2013). Stimulating frequent informal interaction using collaborative experimentation with a tactile tool could then facilitate dialogue and transformative learning. Common grounds in peri-urban landscapes could be drought and heat under the predicted climate change or pressure on the open space (Vilt 2022), which is understandable language for all actors. Starting from mutual interests creates trust before entering topics where dialogue is more difficult (high green vegetation, fertilisation, pesticides, garden preferences, garden sizes, infrastructure etc.). Organisations that lead participatory processes (such as Rodeland), could therefore design collaborative programs that coincide with the prior knowledge and interests of rural actors to get them on board, being aware of time constraints. It seems hard to develop a common ground and tactile tool that suits the high variety of actor groups with their prior knowledge in peri-urban areas. In our 1m² approach, there was a trade-off between encouraging individual learning and keeping participants motivated for their citizen science tasks on the one hand and facilitating collaboration and networking on the other. The questionnaires (chapter 5) confirm a clear lack of networking activities during the project, but also after it ended. Although several networking events were organised (feedback event, landscape walk and bike ride, insect workshop, etc.), these were focused to stimulate motivation for the citizen science project and were not designed to promote dialogue and cooperation among participants. Yet, the 1m²-garden approach has the potential to provide a platform to discuss trade-offs between agroecosystem services and landscape management with different actors.

Zooming out: representativeness of BEL-Landscape and Merode for peri-urban and rural areas

In the previous section we zoomed in on a specific sampling location of the BEL-Landscape case. Here we zoom out again and compare the peri-urban land uses in BEL-Landscape and Merode to three other agricultural landscapes in Flanders. The objective is to check to what extent our results are applicable in other contexts and landscapes, because the demand for agroecosystem services can be different between agricultural landscapes. Furthermore, relationships between land use composition and FAB-mediated agroecosystem services can be dependent on the overall agricultural intensity of the agricultural region, as we discussed in chapter 3 and chapter 4. For this thesis we sampled in two provinces (East Flanders and Antwerp) and different agricultural regions (sand and Campine ecoregion). For the comparison with other agricultural landscapes, we searched for communities with the highest shares of agricultural land use in the three other provinces in Flanders (West Flanders, Vlaams-Brabant and Limburg) and other ecoregions (sand-loam and loam regions) (Fig. 6.4). With this we focus on the agricultural end of the landscape compositional gradient because the starting point for this thesis is the study of agroecosystem services with sustainable food production as main target. With the sampling design of our 1m²-gardens in both cases we included locations with much residential land use (private gardens and built-up areas) and semi-natural habitats (extensive grasslands in valley areas) in the environment. This points out that we might have underexplored areas that are more intensively used for agriculture in our study. This further justifies our comparison to landscapes with high agricultural land use.

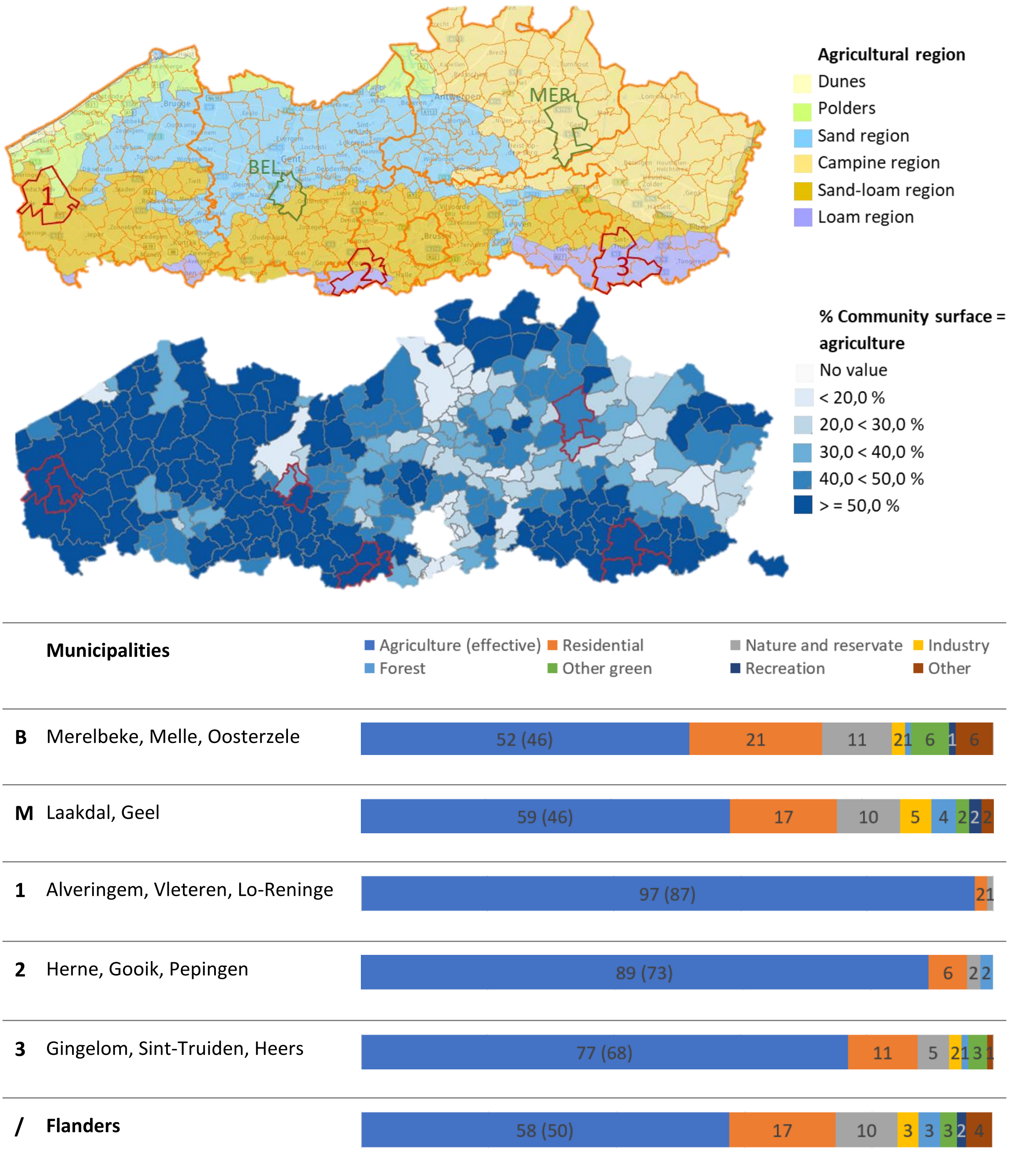


Fig. 6.4: *Comparison of BEL-Landscape and Merode to three other agricultural landscapes in Flanders, Belgium. For each region, data are aggregated for three municipalities on the share of the total area (in %) of the following planning designation categories: agriculture (grassland and arable), residential (housing and gardens), nature and nature reservates (also forests), industry, forest (not designated as nature or nature reservate), other green, recreation and other designations. For agriculture we also give (between brackets) the proportion of what is factually used for agriculture according to the agricultural parcel identification system* (ALV 2018). *The difference between the designated and factual proportion agriculture is an indication for what is defined as virtual farmland (designated for agriculture, but occupied by a non-agricultural land use or apparent farmland)* (Verhoeve et al. 2015). *Data were retrieved from: https://provincies.incijfers.be/dashboard/dashboard/landbouw.*

From this we learn that BEL-Landscape and Merode were examples of true peri-urban areas, close to the average agricultural land use for the whole of Flanders. In all three comparative agricultural landscapes, we find municipalities with significantly higher shares of agricultural land use (up to 87.8% in Alveringem, West Flanders) (Fig. 6.5). The share of agricultural land use for the first comparative agricultural landscape is comparable to the sampling point with the highest share of agricultural land use at a 500-metre radius in BEL-Landscape (Fig. 6.1, 80%). But in peri-urban landscapes when we zoom out to a radius of 1000 and 2000 metres, agricultural land use decreases sharply and non-agricultural land use increases (Fig. 6.5, right). Several settlements with associated domestic gardens appear, as well as built-up, industrial areas and highways. Furthermore, there are multiple forest fragments located in this landscape. The built-up surfaces in the first comparative agricultural landscape are mainly farm buildings scattered in between arable land and productive grasslands (Fig. 6.5, left). The road density is lower and forest fragments are very scarce leading to a very limited non-agricultural land use in this agricultural landscape. Therefore, as we discussed in chapter 2, what we defined as high shares of agricultural land use in our case studies, is rather low compared to agricultural land use in other landscapes. Moreover, to include a high proportion of agricultural land use in a landscape composition gradient in peri-urban areas, a radius of up to 500 metres is required. It is possible that in areas with a higher share of agricultural land use, the relationships between landscape composition and microclimatic extremes or activity-density of functional invertebrates differ from what we found in our case studies. For further research it is therefore advised to include landscapes which proportionally have a higher share of agricultural land use in the surroundings (discussed in the last section of this thesis 'Avenues for future research').

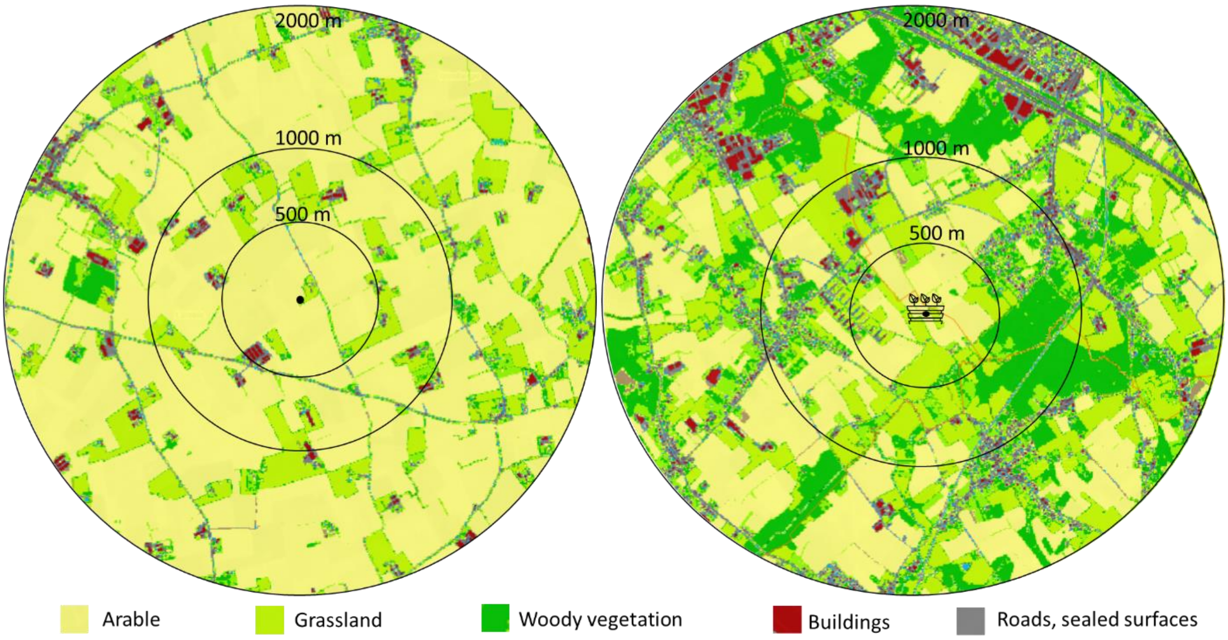


***Figure 6.5: Left**: an agricultural landscape with high share of agricultural land use (Alveringem, West Flanders). **Right**: the sampling point in the BEL-Landscape case with the highest share of agricultural land use in a 500-metre radius. This sampling location coincides with the example case on which we projected our results in the previous part of the general discussion.*

Within the Merode case, as mentioned in chapter 4, the sampled landscape compositional gradient contained even higher shares of non-agricultural land uses. Possibly we were thereby underestimating the effect of agricultural intensification because we did not measure in the most outer end of the gradient at larger scales. We only measured in the most intensive agricultural zones within landscapes with strong infiltration of non-agricultural land uses. Therefore, we suppose that the results from this thesis are representative in peri-urban areas, where there is a certain sprawl of non-agricultural land use in between farmers' fields. Practical recommendations for rural and peri-urban landscapes should therefore consider to what degree landscapes are rural, with low pressure from non-agricultural land uses from nearby urban regions or rather have a peri-urban context. Because the approach to improving FAB may differ in agricultural landscapes with different non-agricultural land uses. For instance, in landscapes with high shares of agricultural land use there might be a higher need for high green vegetation in the landscape to buffer the microclimate, which can be organised among mainly farmers. While in peri-urban areas, where more non-agricultural land uses are present, the responsibility for high green vegetation in the landscape can be coordinated among different actors.

Chapter 7

General discussion on practical implementations, research methodology and avenues for future research

In this last chapter we reflect on practical implications of our results at different levels, going from individual actors (farmers, rural residents, nature organisations, horse keepers, municipalities) to governments and landscape organisations. Finally, we reflect on the 1m²-garden toolbox and discuss avenues for future research.

Practical implications for enhancing FAB in peri-urban areas

In the previous chapter we used our insights from the social-ecological approach in this thesis (Gerits et al. 2021) to zoom in on a specific sampling site from the BEL-Landscape case (Gerits et al. 2021; Gerits et al. 2022). By then zooming out, we confirmed that both cases concern densely populated peri-urban areas, which are probably more representative of Flanders than sparsely populated agricultural landscapes. In this first section of the general discussion, we provide recommendations to enhance FAB for different levels of the social subsystem in peri-urban areas: individual actors (different actor groups), governments (EU, national, regional and local), landscape networks and researchers.

Farmers as individual actors

For individual actors, we first recommend looking around and explore who is present in your surroundings. Break through individualism and connect with fellow land users. It helps to understand each other's expectations of the landscape you share, set common goals and integrate knowledge (Rogge et al. 2013). During this thesis we learned that **farmers** are important beneficiaries of FAB-based agroecosystem services, but they are by no means the only ones, nor the only ones who could contribute to FAB in the landscape**.** Non-agricultural land users such as rural residents and horse keepers could also benefit from a buffered microclimate by integrating high green vegetation in the landscape. Establishing valuable low green vegetation in between fields encourages the activity of predators at locations where their service is demanded and likely promotes other agroecosystem services as well (e.g. soil moisture buffering in some cases, biodiversity conservation). These services are useful for all actors in peri-urban areas, and not only for farmers. A well-connected network of such semi-natural habitats is shown to perform better and requires collaboration between farmers (referred to as configurational heterogeneity by Fahrig et al. 2011). Current government regulations impose a cultivation-free strip from ditches or watercourses to avoid nutrient leakage into the environment. Currently, the required width for these strips is one metre, but there is a debate to increase this to meet the waterway quality prescribed by EU standards. Together with buffer strips for erosion and verges next to walking trails or larger roads, these margins provide potential to create and manage a network of biologically valuable low green vegetation for agroecosystem services without extra loss of productive areas. Additional to these linear structures, patches of extensively managed, permanent grasslands with biological value are also beneficial for natural pest control (chapter 3 and 4), but also carbon sequestration, biodiversity conservation etc. (Huber et al. 2022). Furthermore, high green vegetation buffers the microclimate and although not confirmed in this thesis, this might lower drought and heat stress for different crops. Our results cannot predict at what scale or proportion high green vegetation should be implemented, but working at the landscape scale could optimise multiple agroecosystem services because trade-offs occur between them. To stimulate collaboration among farmers, participatory approaches (possibly citizen science) can be designed that start from local knowledge and demands for agroecosystems services in which farmers frequently experiment with a tactile tool that is close to their practices (authentic learning environment). Frequent interactions with each other and the research team to discuss results and spatial organisation could increase transformative learning and motivation to jointly work on FAB at the landscape scale.

Peri-urban residents as non-agricultural actors

Peri-urban residents, as important non-agricultural land users in peri-urban areas, should be encouraged to become aware of their role in the surrounding landscape. We learned in the fifth chapter of this thesis that experimentation during an immersive citizen science project can contribute to this awareness. This increased awareness should include knowledge on the necessity to avoid sealing surfaces at all costs, as this is detrimental to both the microclimate and the functional invertebrate community in agroecosystems. We learned that predators were more active in m²-gardens with more valuable low green vegetation in the environment and less active in environments with more domestic gardens (chapter 3 and 4). This highlights possibilities for the domestic garden complex to contribute to FAB and related agroecosystems by changing the management towards ecologically valuable habitats. Where our definition of valuable low green vegetation encompasses many different types of habitats (see Table 3.1), there is much literature available with specific details on how to change the management of local gardens or parks in favour of agrobiodiversity (Goddard et al. 2013; Beumer and Martens 2015; Breed et al. 2022). Furthermore, in Flanders, a programme of Garden Rangers has been launched to guide residents towards nature-friendly gardens (Tuinrangers 2022). This could be an opportunity to increase awareness of rural residents of the embeddedness of their garden in the environment, and more specifically on the interface with farmland. Some of our findings on transformative learning in Chapter 5 could be applied to such programmes. Through frequent informal interactions, garden rangers can build trust with rural residents. Furthermore, providing frequent information about the gardeners' impact on FAB and agroecosystem services in their surroundings, followed by observation and experiments in their own gardens and reflections with the garden ranger or other participants, could facilitate management to pro-environmental behaviour. Yet, as our results in chapter five indicate, these programs will probably reach only a subpopulation with certain prior knowledge, interests and motivation. Therefore, the question is whether it is necessary to adapt the programme to the specific requirements of the owners of residential land that we want to involve.

Other non-agricultural land users

As discussed before, non-agricultural land users other than peri-urban residents, such as **nature organisations, municipalities or horse keepers** have an impact on FAB as well. Nature organisations contribute to the intrinsic conservation of species described in the European Birds and Habitat Directives, which are often rare and endangered (Bianchi et al. 2013). This implies that goals for nature conservation can be different than functional agrobiodiversity since the latter focusses on instrumental support for agroecosystem services (Kleijn et al. 2011; Bianchi et al. 2013). In zones where nature conservation areas intertwine with agricultural fields, it might be beneficial to check for possible win-wins between species conservation and functional agrobiodiversity (MacFadyen et al. 2012). Yet these win-wins are not plentiful according to MacFadyen et al (2012, p.693) who predict that “a focus on biodiversity conservation will sometimes support ecosystem services, but a pure focus on ecosystem services will not generally provide good biodiversity conservation outcomes.” While authorised nature reserves cover 15.000 ha in Flanders, road verges cover an area of more or less 25.000 ha due to a very dense road network (Maelfait 1997; Statistiek Vlaanderen 2022b; Statistiek Vlaanderen 2022a). Flanders’ Agency for Roads and Traffic and municipalities manage 33% and 66% of the road verges, respectively, and much work has been done to increase species diversity in these verges with focus on nature conservation. However, at locations of interests, where roads intertwine with agricultural fields and demand a buffered microclimate and/or activity of functional invertebrates the management could be adapted towards optimal functioning for the agroecosystem (Steingröver et al. 2010; Phillips et al. 2020). Finally, the impact of land used for professional and recreational horse keeping cannot be underestimated since it was estimated on 70.000 ha (5% of Flanders), making up one third of the grassland in Flanders in 2011 (Bomans et al. 2011) and still appears to be increasing strongly in all provinces (Degezelle et al. 2022). Moreover, this trend (called ‘horsification’) is spatially concentrated in peri-urban areas (Bomans et al. 2011), which is consistent with our experience from both case studies. The non-profit organisation Regional Landscapes (Regionale Landschappen 2021) recognises the importance of the horse pastures for biodiversity and provides clear information to horse owners on how to enhance biodiversity. However, the advice does not include coordination with other land users in the area. Furthermore, the findings of our fifth chapter could be used by Regional Landscapes to facilitate transformative changes of horse owners towards collaborative management of FAB in their environment.

Spatial coordination by governments and landscape organisations

Spatial coordination appears to be a key concept for FAB-based agriculture. Such coordination requires a thorough stakeholder analysis, finding common objectives among stakeholders, defining demands for agroecosystem services, building social capital[3], designing participatory approaches, and therefore often requires support (Prager et al. 2012; Prager 2015; Westerink et al. 2017a; Westerink et al. 2017b). This support can be provided by governments at different levels or by landscape organisations. A combination of both is often needed to create good conditions for joint action for FAB as a natural resource (Westerink et al. 2017a).

Governments and policy makers at different levels (EU, regional, province, municipalities) can define science-based boundaries of sustainable production based on the findings of researchers. For example, in Flanders there is currently debate about a draft version of a renewed manure action plan ('MAP7') which starts from science-based limits on nutrient leakage to the environment (OECD 2021). Another example of a restriction by regional and local policies in Flanders is a block on further taking and building on open space (see Fig. 1.2 and Fig. 1.3). This is a highly necessary action as we learned from chapter 3 and 4 in this thesis, which is pursued by the 'building shift' policy Flanders in which local governments are encouraged to avoid further occupation of remaining open space through their spatial planning (Vlaamse Regering 2022). The defined hard limits are 3 ha per day of loss in 2025 and 0 in 2040, while Flanders is still losing 5 ha of its open space per day today (Vlaamse Regering 2022). While there is finally a draft decree, there is justified criticism on the proposed term (2040 is too late) and 'accounting approach' where high-value open space can be taken by offsetting open space elsewhere (Vilt 2022). The protection of open space is one of the few cases where nature conservationists, farmers and researchers find each other, which could reopen the dialogue on joint management of agricultural landscapes.

Whereas stopping further occupation of open space may seem primarily a policy issue, we believe that greater awareness of society on the matter, additional to strong decisiveness of governments, is paramount. This thesis shows that establishing high green and valuable low green vegetation in the right locations and proportions requires joint action by land users.

[3] Social capital by definition of Westerink et al. 2017a, p. 178: "We consider social capital as the soft qualities of networks and relationships that enable groups to achieve things together, including trust, access to knowledge and support, shared values and the capacity to learn and innovate as a group."

Defining the right locations and proportions should result from combining (1) insights from science that predict how landscape scale FAB impacts multiple ecosystem services with (2) the demands formulated by local land use actors that organised themselves in their environment. The results from this thesis provide first insights in how different land uses are influential, but research needs to dive deeper in modelled simulations linking landscape composition to agroecosystem services (see last section of this chapter on avenues for future research). Governments at all levels should therefore support local, bottom-up initiatives for FAB governance. The EU Common Agricultural Policy (CAP) creates possibilities for joint arrangements between farmers and other land-managers (Westerink et al. 2017a). National or regional policy makers should translate these opportunities for governance from the CAP in regional funding abilities for the creation of multi-actor networks that engage for FAB (Gerits et al. 2023). For instance, Swiss researchers reported in 2018 on three case studies where farmers were allocated a network bonus on top of individual payments to coordinate their efforts spatially (Krämer and Wätzold 2018). Their effectiveness for biodiversity was found higher than uncoordinated measures and there were positive findings around 'learning' between farmers and constructive contacts with nature organisations. Multi-actor cooperation must be facilitated by different government levels (EU, national, regional and local) that can reinforce each other. In addition to incentives from governments, research shows that **landscape organisations**, which could be civil society organisations, non-profit organisations or non-governmental organisations, can facilitate FAB governance processes (Westerink et al. 2017a).

The diversity of actors and the tensions between them asks for a bottom-up approach with recognition of the opinions and knowledge of all actors. Because spatial planning is a complex task, it is often done by organisations with a degree of professionalism (Westerink et al. 2017a). The degree of professionalism should maintain social capital between different actors, yet acquire sufficient organisational and institutional capacity. A promising organisational structure is where smaller groups function in a larger professionalised community (Ostrom 1990; Westerink et al. 2017a). It is important that the coordinating organisation takes a role as objective catalyst which is trusted by all actors. There are numerous organisations or networks in Flanders that could take on the spatial coordination of FAB. Regional landscapes (Regionale Landschappen 2021) are a non-profit organisation active in almost all Flanders' municipalities and state their goal as enhancing nature, landscape, heritage, regional identity and recreation together with residents, associations and governments. Urban Landscape Leie and Scheldt (Stadlandschap Leie en Schelde 2022) is an initiative of the province of West Flanders and has similar objectives to the Regional Landscapes, but is situated in the landscape defined by the rivers Leie and Scheldt. Farming Nature Flanders (Boerennatuur Vlaanderen 2022)[4], works with local operational groups of farmers on agricultural landscape management (e.g. collaborative management of hedgerow network in the landscape). The latter is an example of a nested organisational structure (Ostrom 1990; Westerink et al. 2017a), but with focus on farmers as the main landscape actor. Moreover, a process for the decretal recognition of three landscape parks is ongoing in Flanders, which could be another parallel forum to strengthen FAB-based agroecosystem services at the landscape scale. All these examples involve professionalised organisations with (multiple) full-time jobs and considerable institutional and organisational capacity. The organisations discussed here, together with many others, start from regional identity of the project area and should be capable of spatially organising FAB enhancing efforts at the landscape scale. Making a choice between many parallel networks or organisations or even start a new one might seem arbitrary, but should be guided by the capability of building social capital and involve and combine scientific knowledge with the involved actors in peri-urban landscapes.

In this thesis, we underexplored the potential for collaborative governance of FAB at the landscape scale and focused on individual learning towards pro-environmental behaviour (Fig. 5.4). In the questionnaire (chapter 5), respondents cited multiple times that there was a lack of networking opportunities and social contact. With the 1m²-garden approach we were able to stimulate learning and individual management actions for FAB, but not coordination among actors. Although there was definitely social capital (mutual trust, safe space for knowledge sharing), we as research team did not actively take the role for spatial coordination but focused on ecological and social tasks related to the citizen science project. In both case studies there were organisations present (other than the organisations described in the previous paragraph) that could actively take the role of spatial coordinator of FAB efforts.

[4] Previously named 'Agrobeheercentrum Eco²' which is described in the comparative analysis of Westerink et al. (2017a)

More specific, the BEL-Landscape and Merode cases were situated in the working area of the Rodeland Project (Rodeland 2022) and Landscape Park Merode (Landschapspark De Merode 2022), respectively. These organisations are comparable to the Urban Landscape Leie and Scheldt which we described above, but they are active in different specific landscapes, with different organisational and institutional capacities and starting from different goals. The goal of Rodeland Project was, for instance, to increase the connectedness of semi-natural elements in the landscape for biodiversity. Yet, this starting definition might already hamper the building of social capital with actors other than nature conservationists. Research teams could assist these landscape organisations by providing objective information on land use decisions related to FAB and how to reach, involve and engage different actors. An example from the Netherlands, 'Hoeksche Waard', shows how researchers can take an active role in spatial collaborative governance of FAB to optimise natural pest control (Opdam et al. 2006; Steingröver et al. 2010; Opdam et al. 2015). In this thesis we show that researchers themselves can work as part of a learning community and catalyse tranformative change but might not be the right partner to take the role as spatial organisator of landscape scale FAB.

The priority of researchers in this type of project could be to provide the most accurate data possible to address the challenges that limit sustainable food production in peri-urban landscapes. This does not mean that researchers could not engage in building social capital, facilitating transformative change or spatial organisation. Looking back on our scientific work as a prior task, we end this discussion by reflecting on the performance and improvement of our 1m²-garden toolbox and avenues for future research.

Reflection on methodology and avenues for future research

In the final section of this thesis, we (1) evaluate the suitability of the 1m²-garden toolbox both in terms of its role of as phytometer (ecological monitoring role) and its role as tactile learning tool (social role) and (2) define future avenues for research based on newly identified knowledge gaps.

The 1m²-garden toolbox

First we discuss the 1m²-gardens function as local phytometers to capture the influences of landscape scale FAB. The exact setup of the measurement point, considering crop composition or sensory toolbox could be adapted to local demand for agroecosystem services. The crop composition can, for instance, be adapted to a 'pollination-focused' toolbox with crops of different plant families that require different pollinator species (bumblebees, honey bee, hoverflies, butterflies, moths etc.) or pollination by wind. Researchers, policy makers or civil society organisations can be creative with this approach and should understand that the 1m²-gardens are interconnected in a landscape observatory and results should always be interpreted through a relative comparison between points in the same landscape (Gerits et al. 2021). The toolbox we used was specifically for FAB and related agroecosystem services, and could also be extended with other variables such as: weed pressure, decomposition rate using teabags, light intensity throughout the day, daily precipitation, wind speed or evapotranspiration other sampling methods for more functional invertebrate taxa (netting, beating, trembling) or a recently developed automatic sampler (Hadi et al. 2021). In the appendix of the second chapter, we provide references to different variables that could be measured in the 1m²-garden toolbox (Table A1).

Yet it is not possible to measure all agroecosystem services in one tool that might be valuable at a certain location. We therefore advocate that it is good practice to do a pre-experimental survey with all relevant stakeholders to collaboratively determine the setup of the measurement tool in line with the prioritised demands considering agroecosystem services. This would be a form of citizen science where actors are involved in defining the research questions, gathering data and debate the results towards practical outcomes (Veeckman et al. 2019). It is likely that when such trajectories are supervised by an objective team of researchers, this could foster constructive debate between otherwise conflicting land users. For instance, collaboratively designed measurements for biodiversity conservation, weed pressure, pest abundance and agroecosystem services could offer a constructive new dialogue between nature conservationists, rural residents and farmers present in peri-urban areas. Yet, before debating demanded agroecosystem services, a profound stakeholder analysis is essential to study which actors should be involved (Reed et al. 2009).

Each measurement method used in 1m²-garden toolbox has its practicalities and risks on which a reflection should be made. Considering the invertebrate sampling we used the trapping methods mostly used for this type of research (pitfall traps and pan traps). Advantages are the time efficiency of collection of specimens in the field (passive sampling) and the possibility to do it in all 1m²-gardens simultaneously. However, processing of samples and determination should not be underestimated and requires time and skill. As discussed in chapter 2, with these methods we only collected a part of the invertebrate community locally present and discussions and conclusions should recognise this. Correct setup of traps is important and care should be taken that the trapping method is as identical as possible in all 1m²-gardens, so that a meaningful, relative comparison can be made between measurement points (McCravy and Willand 2007; Skvarla et al. 2014; Portman et al. 2020). For pan traps, simultaneous to the trapping period, a vegetation survey of flowering species in the immediate surrounding should be done to estimate possible concentration effects (discussed in chapter 3). Considering the TMS4 sensors (Wild et al. 2019) used for microclimatic measurements we found good performance for temperature measurements but not for comparison of absolute soil moisture contents, which was confirmed by Jackisch et al. (2020) in an open field trial. However, data could be useful when variation in soil moisture is used as variable to compare between measurement points (in this thesis). There are multiple possibilities to increase the chance of detecting linkages between landscape-mediated biotic and abiotic processes to variation in crop herbivory and performance. One can focus on a specific plant-herbivore-predator/parasitoid link. For instance, Tschumi et al. 2015 focused on the cereal leaf beetle as herbivore on winter wheat. Yet, by focussing on one pest species of one crop, researchers could miss other important drivers for plant performance. Furthermore, unwanted local variation on crops could be excluded by increasing the depth of the wooden container so that roots will be further divided from the local soil underneath the standardised soil mixture.

Considering the work of the citizen scientists it is good practice to only delegate tasks that are easily to communicate and standardise (such as weeding and harvesting). Furthermore, close involvement of the research team to follow-up and give feedback avoids mistakes and drop-out, while increasing informal contacts. Development of a smartphone application would be useful (see Ghent University 2022 for an example), because the data entry in the online Excel file was sometimes perceived difficult by the volunteers. An extra advantage of this is the possibility of real time feedback of results to participants or even more a comparison of their results to others (CurieuzeNeuzen 2022). The latter works motivating because it makes the volunteers feel part of a team and makes them aware that their data is being used for valuable comparisons to others.

Beyond providing feedback for the citizen scientists, a deeper reflection on the social function of the 1m²-garden toolbox is needed. To facilitate wider and faster transitions of peri-urban areas towards recognition and enhancement of landscape scale FAB, it might also be useful to have a 'light version' of the 1m²-gardens to include more actors and scale up with less time investment. While this increases the numbers of land users reached, it will likely decrease chances on transformative learning about biodiversity while increasing drop-out of participants. This is because the more participants are involved in a participatory project, the fewer the research team can have informal conversations, feedback moments troubling a trust bond between volunteers and the research team. In both cases in this thesis, it appeared that for me as principal researcher, time was lacking to provide equal informal learning moments for all participating citizen scientists, while we learned that this was essential to build trust and confidence. One way to cope with this lack of time is to delegate informal interactions to the community itself and stimulate social learning (Reed et al. 2010). From the questionnaire from both cases, it appeared that participants experienced a lack of networking with peer volunteers, and especially when the project ended, all contacts ended. It might be beneficial to stimulate community building and informal interaction between volunteers that could create a sustainable forum, also for after the projects end.

Avenues for future research

A better differentiation between land use types would improve the understanding of linkages between landscape structure, FAB and local agroecosystem processes. For this thesis we worked with the latest available, freely accessible digital spatial information. However, today many useful geographical resources become available for researchers, and this continues to develop more. Future research should always inform on the latest available geographical information on land uses and review the ecological relevance of it prior to experiments. An example is the recently delivered spatial dataset with refined differentiation between semi-natural habitats (hedgerows, treelines, forest edge etc.) in between agricultural fields (Informatie Vlaanderen 2017). Also, within this thesis, we did a separation of low green habitats in valuable or not valuable, based on mapping material provided in the biological valuation map (Vriens et al. 2011). This delivered a category of low green vegetation that was assumed not to be ecologically valuable and largely coincides with domestic gardens. For now, there was no detailed geographical information on the ecological value of domestic gardens, which would have been useful. Although, much ongoing research is suggesting this data would become available rather soon (Baker and Smith 2019; Yan 2020).

Future research should reveal the scale at which land-use composition should be considered to optimise multiple local agroecosystem processes. In this thesis we could not do this because land uses were often correlated along scales. For instance, sampling locations with much high green vegetation in the 10-metre radius were sometimes also rich in high green vegetation in wider scales, not allowing to see at what scale it was most important. There were certain trends showing that land uses had the highest effect size with highest significance at certain scales, but we could not decisively state that this is independent from our semi-experimental approach. So, from this thesis we know how land uses influence multiple agroecosystem services, or don’t, but we cannot conclude upon how much we need, and even more important, at what scale. To better highlight this, the scales should be decoupled and studied orthogonally. For instance: measurement points at locations with high and low share of local high green vegetation in the area, and this both at locations with and without high green vegetation in the wider surrounding area. But this would mean loss of generality again by focusing on one or a limited set of land uses.

It would be interesting to replicate our approach in agricultural areas with few non-agricultural land users in the wide surroundings (Fig. 6.5, left). The relationships we found between the use of arable land or domestic green and the activity of predators and pollinators might be different if a more intensively used agricultural landscape is sampled. Yet it would be challenging to do this with the current setup of the 1m²-gardens because it requires people who can do the weekly follow-up and provide irrigation. Even more, the current design is proven to be less motivating for the main actors of rural areas: farmers. A different version of our toolbox could be a 'light version' of the 1m²-garden setup that needs less follow-up, is more stand-alone and according to the demands of the farmers for FAB in these rural landscapes. Yet, as discussed before, drawbacks of a less immersive citizen science approach are a lower potential for learning and transformative change due to fewer moments of experimenting or fewer interactions, discussions with peers and the research team.

With this we come to a final statement in this thesis. We now have a first version of a toolbox that can assemble a scientifically sound dataset on FAB while stimulating learning and collaborative awareness of its importance and each one's roles to enhance it. In the ever-increasing social complexity in densely populated peri-urban areas this has great potential to increase the resilience of future peri-urban agroecosystems.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Curriculum Vitae

Personal data

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Education and experience

2023 – Today	Scientific collaborator
	Flanders Research Institute for Agriculture, Fisheries and Food (ILVO)
2019 – 2022	FWO SB personal doctoral grant
	Flanders Research Institute for Agriculture, Fisheries and Food (ILVO)
	Faculty of Bioscience engineering, Ghent University
2017 – 2018	Start PhD project as scientific collaborator
	Flanders Research Institute for Agriculture, Fisheries and Food (ILVO)
	Faculty of Bioscience engineering, Ghent University
2015 – 2017	Master in Bioscience engineering, forest and nature systems
	Faculty of Bioscience engineering, KULeuven
2012 – 2015	Bachelor in Bioscience engineering, land management
	Faculty of Bioscience engineering, KULeuven
2006 – 2012	Secondary school, science – mathematics
	Heilig-Hart College Lanaken

Peer-review scientific articles included in Web of Science (A1)

Published

Gerits, F., L. Messely, B. Reubens, and K. Verheyen. 2021. A social–ecological framework and toolbox to help strengthening functional agrobiodiversity-supported ecosystem services at the landscape scale. *Ambio* 50: 360–374.

Gerits, F., B. Reubens, L. Messely, P. De Smedt, D. Landuyt, A. Loos, and K. Verheyen. 2022. Disentangling the interrelated abiotic and biotic pathways linking landscape composition and crop production. *Journal of Applied Ecology* 59 (11): 2742 – 2755.

Under review

Gerits, F., H. Cooreman, L. Triste, B. Reubens, K. Verheyen and L. Messely. Participation changed my mindset. Transformative learning about agrobiodiversity in citizen science projects. *Under review at Environmental Education Research.*

Gerits, F. B. Reubens, L. Messely and K. Verheyen. Consistency of landscape compositional effects on microclimate, invertebrates and plant performance across different years and regions. *Under review at Landscape Ecology.*

Peer-reviewed conference papers (C1)

Amery, F., **Gerits, F.,** Huygens, J., Lakkenborg Kristensen, H. & Willekens, K. 2021. Influence of compost characteristics and compost:soil ratio on soil properties and growth of Vicia faba. *Acta Horticulturae* 1317: 271-280

Peer-reviewed book chapters (B)

Gerits, F., L. Messely, B. Reubens, S. Schelfout, and K. Verheyen. 2023. Nieuwe kansen voor biodiversiteit in het landbouwgebied. In Tot de Bodem. Ed: Maïka De Keyzer. KULeuven University Press, Leuven, Belgium.

MSc. Thesis

Gerits Frederik. How are functional tree traits related to productivity in a young biodiversity experiment? 2017**.** Thesis, KULeuven, Leuven, Belgium. Supervisors: Prof. dr. ir. Bart Muys and Prof. dr. ir. Kris Verheyen. Tutor: Dr. ir. Thomas Van de Peer

Scientific activities

Oral presentations

Gerits, F., H. Cooreman, L. Triste, B. Reubens, K. Verheyen and L. Messely. 2022. Participation changed my mindset. Transformative learning about agrobiodiversity in citizen science projects. SciVil Netwerkdag 2022, Bruge, Belgium.

Gerits, F., B. Reubens, L. Messely, and K. Verheyen. 2022. Disentangling the interrelated abiotic and biotic pathways linking landscape composition and crop production. IALE 2022 European Landscape Ecology Congress, Warsaw, Poland (online).

Gerits, F., B. Reubens, L. Messely, and K. Verheyen. 2018. Ontwikkelen van socio-ecologische richtlijnen ter versterking van de biodiversiteit en ecosysteemdiensten op landschapsschaal. Startersdag Bos en Natuur, Brussels, Belgium. **Awarded second best presentation**

Poster presentations

Gerits, F., B. Reubens, L. Messely, and K. Verheyen. 2022. Participation changed my mindset. Transformative learning about agrobiodiversity in citizen science projects. IALE 2022 European Landscape Ecology Congress, Warsaw, Poland (online). **Awarded with third best poster**

Gerits, F. 2017. How are functional tree traits related to productivity in a young biodiversity experiment? Startersdag bos en natuur, Leuven, Belgium.

Tutor of master dissertations

Thoen Céline**.** Vierkantemetertuintjes als meetinstrument voor de effecten van landschapscompositie op ecosysteemdiensten. 2018**.** Thesis, UGent, Gent, België. Supervisors: Prof. dr. ir. Jan Mertens and prof. dr. ir Kris Verheyen. Tutors: **Ir. Frederik Gerits**, dr. ir. Bert Reubens and dr. ir. Lies Messely.

Loos Annelies. 'Functionele' tuintjes als meetinstrument voor biodiversiteitsgerelateerde ecosysteemdiensten in rurale landschappen. 2019. Thesis, UGent, Gent, België. Supervisors: Prof. dr. ir. Kris Verheyen, dr. ir. Bert Reubens and dr. ir. Lies Messely. Tutor: **Ir. Frederik Gerits**

Van Heghe Benedikte**.** Functionele tuintjes als meetinstrument voor ecosysteemdiensten langs een landschappelijke complexiteitsgradiënt op het platteland. 2020. Thesis, UGent, Gent, België**.** Prof. dr. ir. Jan Mertens and prof. dr. ir Kris Verheyen. Tutors: **Ir. Frederik Gerits**, dr. ir. Bert Reubens and dr. ir. Lies Messely.

Scientific courses

Participated in Specialist Course organised by The Graduate Schools for Production Ecology & Resource Conservation (PE&RC) and for Socio- Economic and Natural Sciences of the Environment (SENSE): Bugs at your Service. 31 March - 5 April 2019. 1.5 ECTS. Course leader: Dr.ir. Felix Bianchi– Farming Systems Ecology, Wageningen University

Transferable Skills Seminar: Correcting work of students and provide feedback (begeleiden van schrijftaken) organised by the Ghent University Doctoral Schools (teaching cluster).

Transferable Skills Seminar: Project management organised by the Ghent University Doctoral Schools (career management cluster).

Transferable Skills Seminar: Making smartphone videos and Facebook posts by the Ghent University Doctoral Schools (Wolfram Carlier 'I Like Media') (science communication cluster)

Scientific projects

BEL-Landscape

https://ilvo.vlaanderen.be/nl/dossiers/biodiversiteit-en-ecosysteemdiensten-van-en-voor-landbouw

FABulous farmers

https://www.fabulousfarmers.eu/nl

Appendices

The appendices to this thesis can be consulted digitally on the author's ResearchGate page. The appendices are open access and available via the following QR code and link:

https://www.researchgate.net/publication/368810576_Appendices_to_the_doctoral_dissertation_of_Frederik_Gerits_Understanding_the_impact_of_landscape_composition_on_agrobiodiversity_in_a_peri-urban_context_learnings_from_a_citizen-science_approach