



MAGYAR AGRÁR- ÉS  
ÉLETTUDOMÁNYI EGYETEM

APPLYING LANDSCAPE METRICS TO  
ASSESS THE EFFECTS OF LANDSCAPE  
STRUCTURE

Thesis of PhD Dissertation

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# **1 BACKGROUND AND OBJECTIVES**

## **1.1 Relationships between the structure of the agricultural landscape and insect communities**

In the last few decades, agricultural intensification and the expansion of agricultural areas at cost of (semi-)natural habitats resulted in an alteration and destruction of the natural landscape structure in many parts of the world. The consequence of these processes was a decline in insect abundance, biomass and diversity (WAGNER 2020; RAVEN & WAGNER 2021; SÁNCHEZ-BAYO & WYCKHUYS 2021). However, the presence of many insect species, which often occupy important roles in ecosystems, is important for the maintenance of different ecosystem processes. Some of these ecosystem processes, which are provided by several different insect groups and species, are very important for humans, especially for securing crop production and quality in agroecosystems (ALTIERI 1999). Two well-known examples for such beneficiary services, which are also called ‘ecosystem services’, provided by insects are the protection of crop plants from insect pests by predatory or parasitoid insects (= biological control by natural enemies; JONSSON et al. 2014; BENGTSSON 2015) and the pollination of crop plants by insect pollinators such as (wild) bees (MELATHOPOULOS et al. 2015; FIJEN et al. 2018) or sometimes even the provision of both ecosystem services at once, like in case of hoverflies (DUNN et al. 2020).

Besides their important roles in ecosystems, many insect species are sensitive to changes in the natural landscape structure, which makes them especially suitable for detecting and monitoring such effects. Several studies have been conducted in the last few years, which investigated the relationships between the composition and configuration of the agricultural landscape, with an especially strong emphasis on the proportion and structure of semi-natural

habitats, and different ecosystem services provided by insect species or groups. The results of these studies, however, are far from clear. For example, a study conducted in soybean (*Glycine max*) fields (MITCHELL et al. 2014) found that in more complex agricultural landscapes, where the soybean fields were smaller and narrower, not only predatory insect species were more diverse and abundant, but the aphid numbers were also significantly higher. The results of another study (ZIÓŁKOWSKA et al. 2021), which investigated the effects of insecticides and landscape structure – more precisely the number of grassy field margins – on the carabid beetle *Bembidion lampros*, showed that the reduction of the insecticide-driven lethality had larger positive impacts on beetle density and occupancy than increasing the abundance of field margins (only). In contrast to these findings, the results of a study carried out in Ethiopia (KEBEDE et al. 2018), which investigated the effects of landscape structure on the natural enemies of maize stemborers (*Busseola fusca*), indicated that a more complex landscape structure with larger hedgerows had positive effects on the abundance of predatory natural enemies, while the numbers of parasitoids and parasites remained unaffected.

The relationship between the structure of agricultural landscape and different traits regarding insect pollinators has also been analysed in some studies. For example, the results of a study, which was conducted in a high-intensity agricultural landscape in Germany (JAUKER et al. 2009), showed that an increasing distance from semi-natural habitats had a negative effect on the number of wild bees, but a positive effect on the number of hoverflies. Furthermore, the diversity of wild bees only decreased with an increasing distance from semi-natural habitats, when the proportion of grassland around the sampling transects was quite low (<10%). Another study, which was conducted in pumpkin (*Cucurbita maxima*) fields (PFISTER et al. 2018), found that the flower visiting frequency of bumble bees (*Bombus* spp.)

decreased with an increasing proportion of agricultural areas in the studied landscape sectors. The presence of semi-natural habitats, which could be found around the studied fields, however, did not have any significant effect on the bumble bees.

In summary, it can be said that – despite the results of these and other similar studies – we still know far too little about the relationships between the structure of the agricultural landscape and the insect species and groups providing ecosystem services related to crop production and quality in agroecosystems.

## **1.2 Quantifying landscape structure**

The term “landscape ecology” was first coined by the German biogeographer Carl Troll in 1939 (TROLL 1971). His work was influenced by the technical advances in aerial photography and the newly evolving concepts of ecosystem science at the time before the Second World War, which helped him to develop several early concepts of landscape ecology (CUSHMAN et al. 2010a; KUPFER 2011). The main focus of landscape ecology is on analysing the relationship between the spatial pattern of a studied area or landscape unit and the ecological processes happening within this area (TURNER 1989; WIENS 2002). The research field of landscape ecology, which is strongly reliant on computer models, has profited much from the ground-breaking advances in the computational capabilities of modern computers and broadly available, high resolution satellite imagery in the last few decades (CUSHMAN et al. 2010a). These innovations in computer sciences, remote sensing and GIS have even resulted in a “lagging-behind” of the discipline of landscape ecology (CUSHMAN et al. 2010a).

Landscape metrics or indices are mathematical tools, which are used in landscape ecology to quantify the landscape structure of a studied landscape unit or more precisely to measure the composition and configuration of different landscape elements situated within the borders of this unit. Depending on the intensity of human influence on the structure of the studied area or ecosystem, there are basically two major types of landscape structure, which can be distinguished: a) The “primary” landscape structure of (semi-)natural ecosystems, which is largely unaffected by human activities and predominantly formed by the abiotic and biotic natural conditions encountered at the studied site. b) The “secondary” landscape structure, which has been significantly altered from its original primary structure by human interferences and activities. If this secondary landscape structure is a result of both natural influences and traditional, sustainable human activities carried out over a longer time period (= several hundreds or thousands of years), it is also referred to as a “cultural” landscape (WALZ & SYRBE 2013).

The scientific approach to quantify landscape structure, as the discipline of landscape ecology itself, was developed after the Second World War. Initially, most studies analysed the characteristics of the primary landscape structure (MEZŐSI & FEJES 2004). However, from the end of the 1970s and especially from the 1980s investigations focused more on functional questions like analysing how changes in the landscape structure caused by humans affect different ecosystem processes (MEZŐSI & FEJES 2004). In order to quantify the structure of landscapes the so-called “patch-corridor-matrix” model was developed (FORMAN & GODRON 1986; FORMAN 1995), which is strongly based on the theory of island biogeography by MacArthur and Wilson (MACARTHUR & WILSON 1967). This model differentiates between three landscape elements based on their shape, which can be found in a studied landscape (FORMAN & GODRON 1986; FORMAN 1995):



- a) Patches: Non-linear, discrete areas, which are relatively homogenous and differ from the surrounding environment.
- b) Corridors: Linear, strip-shaped areas, which differ from the surrounding environment and usually connect patches. Corridors can be physically interconnected with patches or be separated from these. They can be of the same type as the patches or differ from these.
- c) Matrix: The most dominant and spatially extensive patch type in a studied landscape. It can be seen as a background area, in which all other patches and corridors are embedded.

Landscape models, which are based on the theory of island biogeography, usually focus on single patch types in their analyses. Patches and corridors are treated like islands located in an ocean. Here, the ocean corresponds to the matrix and is, from the view of the studied organism(s), an ecologically hostile or neutral background (CUSHMAN et al. 2010b). However, as a contrast to the rather static island biogeography model, there exists a second, different kind of approach to characterize landscape structure: the so called “landscape-mosaic model” (WIENS et al. 1993; WIENS 1995). The more dynamic landscape-mosaic model dismisses the dichotomy of habitats or patches vs. matrix and views landscapes as spatially heterogeneous, complex entities, so to speak as mosaics of different patch types (CUSHMAN et al. 2010b).

A large number of landscape metrics or indices have been developed to analyse the proportion, spatial structure and distribution of different patch types within a studied landscape unit (e.g. LI & REYNOLDS 1993; MCGARIGAL & MARKS 1995; JAEGER 2000). Basically, in a landscape pattern analysis, no differentiation is made between patches and corridors, that means all patches are treated equally (BOGAERT et al. 2014). If there is a need to distinguish between linear and non-linear landscape elements, then they have to be

preliminary classified as distinct categories. Usually, if the matrix is dominant and fills out the studied landscape, then it is excluded from a landscape pattern analysis. However, if the matrix is not a true background and cannot be separated such clearly from the other patches or patch types, then it is treated as a patch itself.

The most widely-used software to analyse and quantify landscape structure is the FRAGSTATS program developed by McGarigal and Marks (MCGARIGAL & MARKS 1995). This software uses raster-data to measure and analyse spatial patterns occurring in a studied landscape unit that is to conduct a landscape analysis. A landscape analysis can be conducted at three different levels of heterogeneity:

1. At the patch-level, if we study the spatial characteristics of individual patches.
2. At the class-level, which describes the spatial characteristics of all patches of the same type in a studied landscape.
3. At the landscape-level, where the spatial characteristics of all patches in a studied landscape are calculated as integrated or combined metrics.

Even though many different landscape metrics exist, basically all of them describe either the composition or the configuration of a studied landscape or, in some cases, both characteristics at the same time. Furthermore, since the calculation of most metrics is based on the same geometric attributes of patches, like patch area or edge, the intercorrelation between these metrics is frequently high, making the majority of them redundant. With other words, most metrics describe the same spatial characteristics of a studied landscape. Several studies have already been conducted that tried to find and sort out redundant metrics (e.g. LI & REYNOLDS 1995; MCGARIGAL & MCCOMB 1995; RIITTERS et al. 1995; CUSHMAN et al. 2008). The results of these

studies showed that the majority of landscape metrics are indeed highly intercorrelated and that usually a few of them suffice for a comprehensive description of a studied landscape unit. However, the results also indicate that the correlation between the metrics often strongly depends on the pattern of the analysed landscape itself and that there is no specific set of metrics that can be applied in each single case. Therefore, the choice of metrics is primarily dependent on the scientific questions, which we want to answer.

Finally, I also want to highlight the importance of the spatial scale chosen for the landscape analysis. In case a landscape unit is analysed as a raster-image, the spatial scale consists of two main components: The spatial extent on the one hand and the spatial resolution or pixel-size of the analysed raster-image on the other hand (FORMAN & GODRON 1986; TURNER et al. 1989; WIENS 1989). The preliminary choice or setting of these two parameters can have considerable effects on the values of the calculated landscape metrics and the results of the landscape analysis. Besides these two spatial components of scale there also exists a third, non-spatial one, which should not be ignored: The thematic resolution, which is the number of distinguished patch types in a studied landscape unit. This parameter can also have considerable effects on the results of the landscape analysis. Usually, the finer the thematic resolution, the more precise is the picture we get about the studied ecological phenomena or processes, but the more complicated and difficult to implement gets the analysis at the same time.

### **1.3 Main objectives of this thesis**

Among the main objectives of all three studies presented in this thesis was the investigation of the relationship between the spatial structure of the agricultural landscape around the study sites and different parameters concerning insect groups or communities. The spatial structure of the landscape around the study sites was quantified with the FRAGSTATS software mentioned in the previous chapter using landscape metrics. The first two studies were carried out in a high-intensity agricultural landscape in the central part of Hungary, where the landscape is dominated by arable land (= large fields of agricultural crops) and the proportion of semi-natural habitats is quite low. In contrast to the high-intensity agricultural landscape, which served as the study area in case of the first two studies, the third study was conducted in the low-intensity agricultural landscape of Transylvania, located in the central part of Romania. In this landscape, the proportion of semi-natural and natural habitats (like flower-rich pastures, meadows and forests) compared to the proportion of agricultural areas is much more balanced than in the central part of Hungary. In the first two studies, besides uncovering different effects of landscape structure, I also investigated some methodological issues concerning landscape metrics, which were discussed in the previous chapter. For example, in the first study I applied a new selection procedure for finding and sorting out redundant metrics – that is, to find the landscape metrics with the highest explanatory power. Moreover, in the first two studies I also tested the effects of different spatial scales applied in the landscape analysis. The main concepts and aims of these three studies are presented in the next three subchapters:

### 1.3.1 Concepts and aims of Study 1

The larvae of the cereal leaf beetle (*Oulema melanopus* L., CLB; Chrysomelidae, Coleoptera) are one of the most important insect pests of cereals, especially winter wheat (*Triticum aestivum* L.) (HAYNES & GAGE, 1981). Both the CLB (CASAGRANDE et al. 1977; PHILIPS et al. 2012) and many natural enemy species of crop pests (e.g. TAKÁCS & FRANK 2009) are connected with woody landscape elements, which are either used as transient (e.g. for overwintering in case of the CLB) or permanent habitats. Study 1 was carried out in a high-intensity agricultural landscape located in the central part of Hungary, where basically two different types of woody landscape elements can be encountered: Linear elements like shelterbelts and hedgerows with a biologically and structurally diverse understory on the one hand (TAKÁCS & FRANK 2009), and areal elements like plantations of poplar (*Populus tremula*) and black locust (*Robinia pseudoacacia*) monocultures, usually with a strong canopy closure as well as low biological and structural diversity of the understory on the other hand (WEIH et al. 2003; VÍTKOVÁ et al. 2017). The main objective of Study 1 was to assess the pest-reduction effect of natural enemies on CLB larvae in winter wheat fields close to either linear or areal woody landscape elements. For this, the relationship between the spatial features of the linear or areal woody landscape and the CLB herbivory suppression by natural enemies was evaluated in exclusion experiments.

### 1.3.2 Concepts and aims of Study 2

Sunflower (*Helianthus annuus* L.) is the second most important oil crop after rape and turnip rape in the European Union (= EU-28), grown on more than 4 million hectares (EUROSTAT 2018). In Hungary, sunflower is the most important oil crop, cultivated on more than half a million hectares since 2005

(KSH 2019). Even though sunflower is capable of self-pollination, cross-pollination by insect pollinators often results in better quality seeds and higher yields (HEVIA et al. 2016; TERZIĆ et al. 2017; SILVA et al. 2018), up to 40% at field scale (PERROT et al. 2019). Globally viewed, managed honey bee (*Apis mellifera* L.) colonies are the main insect pollinators of sunflower (e.g. GREENLEAF & KREMEN 2006; NDERITU et al. 2008; CERRUTTI & PONTET 2016; MARTIN & FARINA 2016). The presence of wild bees was also found to affect sunflower yield, but their own pollinator activity is rather marginal compared to honey bees. Their most important effect regarding the pollination of sunflower is indirect, by enhancing the movement (= disturbing) and thus increasing the pollination efficiency of honey bees (GREENLEAF & KREMEN 2006; CARVALHEIRO et al. 2011; SARDIÑAS & KREMEN 2015). This effect seems to be especially important in hybrid sunflower systems, where male-sterile (i.e. female only) plants require a polliniser movement for effective pollination (GREENLEAF & KREMEN 2006; OZ et al. 2009; MARTIN & FARINA 2016). Therefore, in sunflower production in general, it is important to know, which aspects of landscape composition and structure enhance the abundance and species richness of wild insect pollinators. The influence of landscape context on wild insect pollinators visiting sunflower, however, has been rarely investigated. The results of those few studies, which dealt with this topic, indicate that a higher amount of semi-natural habitats in the landscape surrounding sunflower fields has an enhancing effect on the abundance and species richness of wild insect pollinators (BENNETT & ISAACS 2014; RIEDINGER et al. 2014; BIHALY et al. 2018). The relationship between more complex and sophisticated landscape metrics, like the proportion and spatial configuration of different landscape elements around the studied sunflower fields, and the sunflower visiting frequency of wild insect pollinators, however, has not yet been investigated in any study.

For this reason, the aim of Study 2 was to fill in this knowledge gap. That is, to quantify the structural parameters of the landscape surrounding the studied sunflower fields and to examine the effects of these parameters on the sunflower visiting frequency of insect pollinators.

### *1.3.3 Concepts and aims of Study 3*

Trap-nests are not only useful tools to assess the abundance, diversity and trophic interactions of cavity-nesting Hymenopterans, but also to study the effects of landscape structure on this group (e.g. STECKEL et al., 2014; STANGLER et al., 2015; STAAB et al., 2018; MAYR et al., 2020). The increasing agricultural expansion and intensification as well as urbanization in densely-populated regions of the world like Western Europe have caused a decline in insect abundance, biomass and diversity, mainly due to a loss or fragmentation of the insects' habitats (e.g. PIANO et al. 2020; WAGNER 2020; RAVEN & WAGNER 2021; SÁNCHEZ-BAYO & WYCKHUYS 2021). Therefore, additional knowledge about cavity-nesting Hymenopteran species and the influence of landscape context on them may provide help in measures for their protection. The majority of previous studies, which were assessing cavity-nesting Hymenopterans in different Western European countries, were conducted in high-intensity agricultural landscapes (e.g. HOLZSCHUH et al. 2009 and 2010; FABIAN et al. 2013 and 2014). In contrast to this, studies from Western Europe dealing with the abundance and diversity of cavity-nesting Hymenopterans in low-intensity agricultural or (semi-)natural areas are comparatively rare (e.g. ALBRECHT et al. 2007; SOBEK et al. 2009; BUDRYS et al. 2010; KREWENKA et al. 2011). Moreover, the number of studies conducted in Eastern Europe concerning this topic is also very low (e.g. BUDRYS et al. 2010; BIHALY et al. 2021).

Therefore, we decided to conduct a study using trap-nests in the central part of Romania, where the impact of humans is relatively low and the landscape is still rich in semi-natural habitats. The aims of this study were to assess the abundance and diversity of cavity-nesting Hymenoptera and the spider prey of the predatory representatives of these groups in the context of the proportion and edge-density of low-intensity agricultural areas located around the study sites.

## **2 MATERIALS AND METHODS**

### **2.1 Study 1: Linear woody landscape elements may help to mitigate leaf surface loss caused by the cereal leaf beetle**

The field experiments took place in the north-western part of the Great Hungarian Plain, the Jászság region, and were carried out over two years (2014 and 2015). In each year 17 wheat fields were selected as focal fields. In 2014, on each field, three transects (wheat rows, perpendicular to the field edge) were designated for the experiments at 10 m distance from each other, plus a fourth one, 2 m left or right of the central row. In each of these four transects individual plants were selected at “transect distances” 2-25-50-75 m away from the field edge. Both male and female CLBs were collected with sweep nets and five specimens were placed on these individual plants (2380 in total), which were isolated under a mesh supported by an iron frame. After 4–7 days, when the eggs were laid by the females, the adults were removed. Subsequently, except for the additional central row (= “caged” treatment), the cages were not placed back on the plants (= “open” treatment), thus allowing the action of natural enemies. In 2015, in an otherwise identical experimental setup, only three rows were set up per field with the central row receiving the caged treatment and the lateral rows serving as the open treatments. CLB



herbivory was quantified as leaf surface loss per experimental wheat plant ( $LSL_{PLANT}$ ), which was visually determined as an average ratio of skeletonized leaf area in relation to the whole leaf area for 10 flag leaves of the plant. The difference between the mean leaf surface loss ( $LSL_{DIFF}$ ) of the caged and open treatments was used to calculate a single response variable that describes “herbivory suppression” in a given field. The surroundings of the 34 wheat fields were digitised in QGIS, differentiating between linear (= shelterbelts and hedgerows) and non-linear (= monocultural plantations) woody landscape elements. Raster images were created in form of circular polygons starting with radii of 150 m and consecutively increasing by 50 m up to 500 m radii around the wheat fields. These raster images were analysed with FRAGSTATS in order to calculate 36 landscape metrics of the two types of woody landscape elements. As a next step, this large number of metrics was reduced with a two-phased selection procedure checking first for correlations between the metrics to identify a manageable subset of metrics. Finally, automated model selections were performed based on linear models, which used the square-root transformed values of  $LSL_{DIFF}$  as dependent variables and the preselected subset of standardized metrics of woody SNHs as explanatory variables. These automated model selections were able to find the most important metrics. This selection procedure and all other statistical analyses were conducted in the R statistical software.

## **2.2 Study 2: Landscape structure affects the sunflower visiting frequency of insect pollinators**

The study area was the same as in Study 1 and located in the central part of Hungary (Jász-Nagykun-Szolnok county), in an intensively used agricultural landscape. The field experiments were carried out in randomly selected sunflower fields over two years (2014 and 2015), with 18 fields examined in

each year. The sampling of the pollinators was performed by visual observation between 9:00 and 17:00, adapted to the daily activity of bees. The sampling was carried out alongside two transects perpendicular to the field edge, running parallel 10 m from each other. Along a single transect, there were four sampling points located at 5, 25, 50 and 75 m from the edge of the field. At each of these sampling points nine flowering sunflower heads were chosen for observation and monitored for 10 min. We differentiated between honey bees, wild bees and non-bee pollinators. The surroundings of the sampled sunflower fields (focal fields) were mapped in QGIS. For testing possible scale-dependent effects, circles of 13 scales with differences of 50 m in radius were created around the centre point of one of the transects (at 37.5 m), ranging from 150 to 750 m. We distinguished between herbaceous SNH patches, like grass strips and pastures, and sunflower fields, including the investigated focal fields. In order to quantify the composition and spatial configuration of the landscape sectors regarding the two landscape element types, we calculated three specific landscape metrics with FRAGSTATS using the raster images of the landscape sectors: The metrics ‘Percentage of Landscape’, ‘Edge Density’ and the negated values of the metric ‘Aggregation Index’, which we renamed ‘Dispersion Index’. To test the effects of the spatial properties of the two studied landscape elements on the sunflower visiting frequencies of the three pollinator groups, we applied generalized linear mixed models (GLMMs) assuming a Poisson distribution. For this, the sunflower visiting frequencies served as dependent variables and all three metrics mentioned above were added as explanatory variables in the Poisson GLMMs, for each two landscape element types separately. All these statistical analyses were carried out in R statistical software.

### **2.3 Study 3: Preliminary assessment of cavity-nesting Hymenopterans in a low-intensity agricultural landscape in Transylvania**

The study took place in a hilly mountainous area around the Vargyas-gorge at the border of the two counties Harghita and Kovászna (Transylvania, Romania). The eight study sites were located between 530 and 630 m a.s.l. in three valleys. Two sites were established in the Northern Vargyas valley (NV1–NV2) and three sites each in the Southern Vargyas valley (SV1–SV3) and Körmös valley (K1–K3). The Northern Vargyas valley is mostly used for extensive grazing and is dominated by meadows and pastures, while the Southern Vargyas valley, due to its remoteness, is much less used for grazing and more dominated by forest patches. The Northern and Southern Vargyas valleys are separated by the Vargyas-gorge. Compared to the two Vargyas valleys, the Körmös valley is more strongly influenced by humans with arable land in its southern part. As a result of these differences in the intensity of land use, the ratio of low-intensity agricultural areas to the natural woodland and other areas in the close surroundings of the eight study sites also differed from site to site. Four trap nests each were installed at the study sites at the end of May 2018. The trap nests consisted of PVC tubes of 12 cm diameter and 23 cm length. The tubes were filled with front-back open reed stalks of approx. 22 cm length. The trap nests were collected at the end of August 2018 and stored outdoors at a shady, dry place. In January 2019, the trap nests were put into a refrigerator. After this, all stalks were cut open and in case of each occupied stalk (= nest), the following parameters of the stalks and nests were recorded: (a) diameters of the reed stalks; (b) number of occupied brood cells, filled

either with Hymenopteran offspring (larvae or cocoons) or spider prey; (c) type of nesting material; (d) colour of larvae or cocoons. Based on the parameters (c) and (d), we were able to identify seven groups of nest types. From each of these seven groups, we also took at least two nest samples and reared them at room temperature in plastic bags. After the emergence of the adults from these samples, at least two specimens from each nest sample were collected and identified at genus level. We were able to identify the following eight genera: *Ancistrocerus*, *Auplopus*, *Dipogon*, *Hylaeus*, *Megachile*, *Osmia*, *Symmorphus*, and *Trypoxylon*. Except for the two genera *Ancistrocerus* and *Symmorphus* of the subfamily of Eumeninae (= potter wasps), which could not be visually distinguished based on the nest type, each genus was assigned to a specific nest type. If present, spider prey specimens were collected from the nests and taxonomically identified at family level and attributed to the three taxons of the spider-hunting wasp (= *Auplopus*, *Dipogon* and *Trypoxylon*). The landscape surrounding the eight study sites was mapped as landscape sectors of 250 m radius in QGIS, differentiating one single landscape element, the so called 'low-intensity agricultural areas', which consisted of meadows, pastures and small patches of arable land. For calculating the landscape metrics 'Percentage of Landscape' and 'Edge Density' in FRAGSTATS the vector layers of the landscape sectors were rasterized. GLMMs assuming a Poisson distribution were applied to analyse the effects of the spatial properties of low-intensity agricultural areas, described by the two landscape metrics, on the seven cavity-nesting Hymenopteran taxa and the most commonly preyed spider families. In these GLMMs, the number of occupied brood cells per site was used for all seven cavity-nesting Hymenopteran taxa and the number of preyed spider specimens per site for the most frequently preyed spider families. The relationship between the proportion and edge density of the low-intensity agricultural areas and the Shannon diversities per site for both Hymenopteran

taxa and *Trypoxylon* spider prey was analysed with linear models. All statistical analyses were conducted in R.

### 3 RESULTS

#### 3.1 Study 1: Linear woody landscape elements may help to mitigate leaf surface loss caused by the cereal leaf beetle

The leaf surface loss caused by the larvae of the cereal leaf beetle was considerably higher in case of the wheat plants protected by isolator cages ( $= 64.9 \pm 35.7\%$ ) than in case of the wheat plants, where the cages were removed ( $= 14.3 \pm 19.7\%$ ). This difference was highly significant according to the results of a Welch Two Sample t-test (t-value = 15.542, d.f. = 168.05, p-value < 0.001). The distance from the field edge, however, did not have any significant effect, according to linear models, on the extent of the leaf surface loss in case of the two different treatments.

Both types of woody landscape elements showed significant but contrasting effects on CLB herbivory suppression. In case of woody linear patches, the metric 'Aggregation Index', which measures the degree of compactness of a particular patch class, showed positive, significant effects on CLB herbivory suppression at the majority of the studied spatial scales. The effects of the metric 'Edge Density' were also positive, but only significant at the two smallest spatial scales (150–200 m). In contrast to woody linear patches, the metric 'Percentage of Landscape' of woody areal landscape elements had significant, negative effects on CLB herbivory suppression at all scales between 200 and 500 m, with a peak value found at 250 m.

### **3.2 Study 2: Landscape structure affects the sunflower visiting frequency of insect pollinators**

Over the two sampling years we observed 2993 potential pollinators on the investigated sunflower heads. The vast majority (85.2%) of them were managed honey bees (*Apis mellifera* L.). In comparison, the number of wild pollinators was rather low, with wild bees only making up 7.8% (n = 233) and non-bee pollinators 7.0% (n = 209) of the total number of observed pollinators.

Honey bees, which were the most abundant sunflower-visiting pollinators, were significantly positively affected by an increasing proportion and dispersion of herbaceous semi-natural patches within the studied landscape sectors. These effects were scale-dependent and the strongest at scales between 350 and 500 m. The spatial properties of sunflower fields in the landscape had no significant influence on the visitation frequency of honey bees. Similarly to managed honey bees, the visitation frequency of wild bees was also positively affected by both an increasing proportion and dispersion of herbaceous semi-natural patches. These effects were scale-dependent and while the effects of the dispersion were stronger at smaller scales (150–350 m), the effects of the proportion were stronger at larger scales (550–750 m). An increasing edge density of sunflower fields had significant negative effects on the visitation frequency of wild bees at larger scales (500–700 m). In comparison to the group of wild bees, the visitation frequency of non-bees was only significantly affected by the dispersion of hSNH patches. This positive effect of the dispersion of hSNH patches was clearly scale-dependent, reaching a peak value at 450 m. Similarly to the group of honey bees, the spatial properties of sunflower fields had no significant impact on the visitation frequency of non-bees.

### 3.3 Study 3: Preliminary assessment of cavity-nesting Hymenopterans in a low-intensity agricultural landscape in Transylvania

In total, we found 990 nests in 4,857 reed stalks. The majority of the nests were built by solitary wasps ( $n = 888$ ). From these, the genus *Trypoxylon* ( $n = 560$ ) was the most abundant nest-building taxon. This was followed by the genus *Dipogon*, with 158 nests, by representatives of the subfamily of potter wasps (Eumeninae), with 152 nests, and by the wasp genus *Auplopus* with 18 nests. The number of nests built by solitary bees was considerably lower than those built by solitary wasps ( $n = 102$ ). From these, 61 nests were built by the genus *Hylaeus*, 23 nests by the genus *Osmia* and 18 nests by the genus *Megachile*.

Regarding the identifiable spider prey, we found 1,471 specimen in total preyed by the genus *Trypoxylon*, from which the majority were Araneidae ( $n = 1,118$ ), 99 specimen in total preyed by the genus *Dipogon*, from which the majority were Thomisidae ( $n = 93$ ), and one specimen of Clubionidae in total preyed by the genus *Auplopus*.

The cell numbers of the Hymenopteran taxa of *Auplopus*, *Megachile*, and *Osmia* were significantly correlated with both the edge density and proportion of low-intensity agricultural areas around the study sites. The strongest, significant effects were found for the solitary bee genus *Osmia*, where an increasing edge density and proportion of low-intensity agricultural areas both had negative effects on its cell numbers. The cell numbers of the *Auplopus* spider wasp (Pompilidae) genus were significantly, positively correlated with an increasing edge density, but negatively with an increasing proportion of low-intensity agricultural areas. The cell numbers of the *Megachile* solitary bee genus were significantly, positively correlated with both landscape metrics. From the preyed spider families, only the numbers of Thomisidae were significantly, negatively correlated with an increasing proportion of low-

intensity agricultural areas. The Shannon diversities of the *Trypoxylon* spider prey were significantly, positively affected by the same landscape metric.

#### **4 CONCLUSIONS AND RECOMMENDATIONS**

The main goal of this thesis, as the title suggests, was to assess the applicability of landscape metrics to quantify the effects of landscape structure. I found statistically significant effects of landscape structure for all three insect-related studies presented in this thesis, which were all testing completely different hypotheses and using completely different sampling methods. Therefore, the results of the three studies unequivocally able to demonstrate the applicability of landscape metrics in this direction.

One of the main topics of Study 1 was the selection of landscape metrics regarding the herbivory of cereal leaf beetle larvae. In this selection procedure, besides the more often used testing for (inter-)correlations between the metrics that formed the first part of the procedure (e.g. LI & REYNOLDS 1995; MCGARIGAL & MCCOMB 1995; RIITTERS et al. 1995; CUSHMAN et al. 2008), I applied a model-selection based on AICc-values as the second part of the procedure, which is a seldomly used method in landscape analysis (e.g. SCHINDLER et al. 2015; LUSTIG et al. 2017). The results of this new, two-phased selection procedure showed that the majority of the studied metrics were strongly correlated with each other or did not provide enough explanatory power in the models, so most of them were redundant. Of course, the results of such a selection procedure depend largely on the response variables – that is the scientific questions we want to answer. For example, in case I would have planned to find those landscape metrics, which best describe the temporal changes of landscape structure (like in LAUSCH & HERZOG 2002), the same selection procedure certainly would have delivered different results. Based on



these results I recommend that it is enough to preliminary select a few landscape metrics with easy biological interpretability to quantify the effects of landscape structure and in case we already find significant effects for these metrics, then it is unnecessary to search further. Since the calculation of most metrics in FRAGSTATS is based on the same geometric attributes of patches, like patch area or edge, it is advisable to start with metrics closely connected to these two properties like the ‘Percentage of Landscape’ or ‘Edge Density’. This method was successfully applied in both Study 2 and Study 3, as significant effects were detected for all preliminary selected metrics.

In Study 1 and Study 2, in order to point out the importance of the applied spatial scale in landscape analysis, I used landscape sectors of different sizes. In most cases, the effects of landscape structure were strongly scale-dependent. The scale-dependency of landscape structure effects has already been investigated by studies dealing with both plant protection issues (e.g. THIES et al. 2003; ROSCHEWITZ et al. 2005; THIES et al. 2005) as well as topics concerning insect pollinators (e.g. STEFFAN-DEWENTER et al. 2001; WESTPHAL et al. 2006; SCHERBER et al. 2019), but only rarely with such a high resolution as in Study 1 and Study 2. Moreover, none of the previous similar studies used such a high number of different landscape metrics. In Study 1 and Study 2, the strongest landscape structure effects were often found at scales smaller than 500 m. Sadly, spatial scales of such small sizes are usually ignored in similar studies. Therefore, I suggest that similar future studies – at least those dealing with insects – should additionally focus on these smaller scales, too.

Finally, I want to summarize the findings of the three studies presented in this thesis regarding landscape structure effects and what kind of conclusions can be drawn from these results:

- a) The results of Study 1 indicate that CLB herbivory suppression was stronger in wheat fields with both long and extensive linear woody landscape elements (= broader shelterbelts) nearby. Whereas, CLB herbivory suppression was weaker in wheat fields surrounded by larger woody areal patches (= monoculture tree plantations). Based on these results I conclude that while broader shelterbelts are most likely serving as habitats for the natural enemies of the CLB, larger monoculture tree plantations are not, or at least not so suitable for them.
- b) The results of Study 2 point out the importance of landscape structure in a high-intensity agricultural landscape for insect pollinators, especially for wild bees. An increasing proportion and/or dispersion of herbaceous semi-natural habitats around the investigated sunflower fields showed a positive relationship with the sunflower visitation frequency of all studied pollinator groups, while an increasing edge density of sunflower fields – that is an increasing number of sunflower fields within a landscape sector – had negative effects on wild bees. This result indicates that for securing the successful pollination of sunflower in a high-intensity agricultural landscape it is important to have herbaceous semi-natural habitats of sufficient area and dispersion around the sunflower fields. Besides this, the sunflower visitation frequency of insect pollinators can also be enhanced if the sunflower fields are not located in close proximity to each other.
- c) However, the effects of herbaceous semi-natural habitats are not always positive. For example in Study 3, an increasing proportion and edge density of low-intensity agricultural areas (also including herbaceous semi-natural habitats) had negative effects on the nest cell numbers of the solitary wild bee genus *Osmia*, but an increasing proportion had positive effects on the diversity of the *Trypoxylon* spider

prey. So, it can be concluded that the results of any study strongly depend on the studied species or organism groups and on the environment, in which the study was conducted. This way, structurally or functionally similar landscape elements can have a different or even the opposite effect in different environments.

## **5 NEW SCIENTIFIC RESULTS**

### **Study 1:**

- Development and successful testing of a new, two-phased selection procedure to find and sort out redundant landscape metrics.
- The results of the first study showed that the herbivory of cereal leaf beetle larvae was more strongly suppressed in wheat fields with linear woody landscape elements located within 200 m from the border of the studied fields.
- This effect was the strongest near long, but also more extended patches of linear woody landscape elements (= broader shelterbelts).
- Whereas, the presence and increasing proportion of areal woody landscape elements (= monoculture tree plantations) within 250 m from the border of the studied fields had an enhancing effect on the herbivory of cereal leaf beetle larvae.

### **Study 2:**

- The results of the second study showed that an increasing area and/or dispersion of herbaceous semi-natural habitat patches, like grass strips and pastures, around the studied sunflower fields enhanced the visitation frequencies of honey bees, wild bees and non-bee pollinators.

- These positive effects of herbaceous semi-natural habitat patches were scale-dependent and the scales, where the strongest effects were found, corresponded well with the mean foraging distances of the observed bee pollinators.
- In contrast to the positive effects of herbaceous semi-natural habitat patches, an increasing edge density of sunflower fields, which were located around the sampling points, resulted in considerably lower visiting frequencies of wild bees.

### **Study 3:**

- The results of the third study demonstrated that the cell numbers in the nests of the Hymenopteran taxa *Auplopus*, *Megachile* and *Osmia* were significantly correlated with both the edge density and proportion of low-intensity agricultural areas around the sampling sites.
- The numbers of Thomisidae spider prey found in the nests of *Dipogon* were significantly, negatively correlated with an increasing proportion of low-intensity agricultural areas.
- Whereas, the Shannon Diversity Index of the *Trypoxylon* spider prey was significantly, positively affected by an increasing proportion of low-intensity agricultural areas.

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## 7 PUBLICATIONS RELATED TO THE TOPIC OF THE THESIS

### 7.1 Publications in scientific journals

LAJOS, K., DEMETER, I., MÁK, R., BALOG, A., SÁROSPATAKI, M. (2021): Preliminary assessment of cavity-nesting Hymenoptera in a low-intensity agricultural landscape in Transylvania. *Ecology and Evolution*, 11(15). doi: 10.1002/ece3.7956

LAJOS, K., SAMU, F., BIHALY, Á. D., FÜLÖP, D., SÁROSPATAKI, M. (2021): Landscape structure affects the sunflower visiting frequency of insect pollinators. *Scientific reports*, 11. doi: 10.1038/s41598-021-87650-9

LAJOS, K., CSÁSZÁR, O., SÁROSPATAKI, M., SAMU, F., TÓTH, F. (2020): Linear woody landscape elements may help to mitigate leaf surface loss caused by the cereal leaf beetle. *Landscape Ecology*, 35, 2225–2238. doi: 10.1007/s10980-020-01097-3

BIHALY, Á., VASKOR, D., LAJOS, K., SÁROSPATAKI, M. (2018): Agrártájba ékelődött természetközeli élőhelyfoltok hatása a napraforgót megporzó rovarregyütesekre. *Tájökológiai Lapok / Journal of Landscape Ecology*, 16(1), 45–52.

### 7.2 Conference articles and abstracts

BIHALY, Á. D., LAJOS, K., SAMU, F., FÜLÖP, D., SÁROSPATAKI, M. (2021): A tájszerkezet hatással van a napraforgót megporzó rovarok viráglátogatási gyakoriságára. In: 12. Magyar Ökológus Kongresszus - Előadások és poszterek összefoglalói (p. 144).

LAJOS, K., BIHALY, Á., SÁROSPATAKI, M. (2019): Effects of semi-natural habitats on the abundance and distribution of insect pollinators in

sunflower fields in Hungary. In: 10th IALE World Congress - Book of Abstracts (p. 399).

LAJOS, K., BIHALY, Á., SÁROSPATAKI, M. (2018): Féltermészetes élőhelyfoltok tájmetriai jellemzőinek hatása napraforgótáblákban megporzást végző rovarközösségekre. In: 11. Magyar Ökológus Kongresszus - Absztraktkötet (p. 53).

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SZALAI, M., TÓTH, F., AMBRUS, G., LAJOS, K., PAPP, K. J., SZEDER, F., et al. (2016): Féltermészetes élőhelyek hatása a biológiai kártevő-szabályozásra: a veresnyakú árpabogár példája. In: 62. Növényvédelmi Tudományos Napok – *Konferencia kiadvány* (pp. 33).

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