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COMPLEX EVALUATION OF ECOSYSTEM SERVICES AND SUSTAINABILITY IN PERMACULTURE, ORGANIC AND CONVENTIONAL FARMING SYSTEMS

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1. INTRODUCTION

There is less and less fertile land available for the production of food for the growing population of humanity, moreover, its loss is significantly accelerated by the progress of soil degradation, so the remaining land is increasingly endangered. Therefore, the importance of agricultural land has increased, thus many studies in recent decades have focused on the impacts of agriculture on natural resources and several concepts have emerged on how to harmonise the survival of ecosystems with production needs. One of these concepts is sustainability (ST) and sustainable agriculture (STA). This concept has been present in agriculture for several decades, and many attempts have been made to put it into practice and find solutions and technologies that are in line with its principles. One of the key steps in the transition to ST is to try to assess and then monitor and evaluate the performance of ST on a given farm. Under the umbrella of STA, several types have now emerged, some of which continue to use conventional practices (e.g. chemical control, use of fertilisers in precision or integrated farming), while others abandon them altogether and try to find ecological solutions (organic farming, biodynamic farming, agroecology). The latter also takes a holistic view of STA and integrates social aspects in addition to environmental and economic ones (e.g. worker management, support for disadvantaged people, multifunctional agriculture, etc.). The other, more recently developed concept is ecosystem services (ES: the tangible and intangible benefits derived from natural ecosystems that are useful to humans) and its consideration in farming. The concept aims to take into account such ESs in landscape management (e.g. regulatory: biological control, mineralisation; cultural: landscape aesthetics) that go beyond the primary function of agriculture (production), since society, decision-makers and policy-makers have increased their expectations of agriculture. Conventional agriculture focuses on the provisioning ESs, including food and feed production, and largely neglects the role of other ESs, while other systems such as organic farming or permaculture take the latter much more into account (e.g. soil formation, water purification, aesthetic value of the landscape, habitat protection, recreation, etc.).

The objectives of the two concepts (ST and ES) are very similar, as both seek to balance the functions of agriculture and harmonise the impact of humans on the environment, but within a different conceptual framework. The common problem is how to measure and demonstrate, also communicate to society, how well individual farms or (on a larger scale) landscapes/regions are able to meet these principles in practice. This is why, research on the relationship between the two concepts, their overlaps and divergences, seemed to me relevant and actual. Also comparing the sustainability performance and ecosystem-service capacity of permaculture, organic and conventional farms seemed a promising empirical research goal. In Hungary, no such holistic, farm-level empirical research has yet been carried out, nor has there been any attempt to compare permaculture farms with other farming systems (conventional, organic).

The objectives of my research were:

C1. to compare the concepts of ecosystem services and sustainability based on the literature and to attempt to harmonise them in relation to agriculture.

C2. to compile a methodological framework to assess small-scale horticultural farms against the concepts of ecosystem services and sustainability.

C3. to conduct a complex assessment of five permaculture, five organic and five conventional small-scale horticultural farms using a combination of natural and social science methods.

C4. to assess the ecosystem service potential and sustainability of the three studied farming systems.

2. MATERIALS AND METHODS

For the field research, 5 permaculture, 5 organic and 5 conventional farms (PERM, ORG and CONV) were selected, mostly of similar size (0.3–2 ha) and agroecological characteristics in north-central Hungary, in Pest and Nógrád counties, all producing for selling (no self-sufficiency or hobby farming), mainly horticultural (vegetable) profile, growing a wide range of crops, mainly for fresh market(Fig.1.).

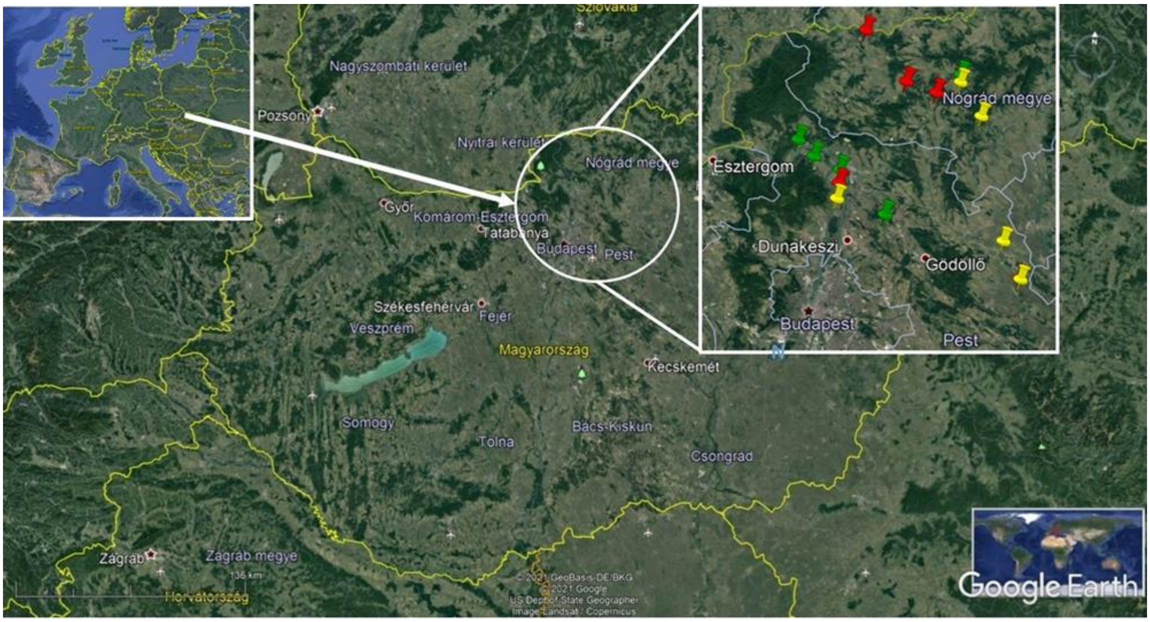

Figure 1. Location of the studied farms (Source: Google Earth Pro 2020, in one location (Zsámbok) the yellow overlaps the red point). Green points indicate PERM farms, yellow ORG farms, and red points indicate CONV farms.

Four main criteria were taken into account when selecting the farms: 1) production profile (not only greenhouse, but also open field production), 2) farm size (small scale, less than 3 ha), 3) location (I tried to select farms in such a way that an organic and a conventional horticulture farm are close to a PERM farm, but at least in the adjacent area, with similar soil and climatic conditions). Finally, (4) the characteristics of the production methods (ORG farms should be certified by a national inspection body; CONV farms should use chemical inputs not allowed in organic production - fertilizers and synthetic pesticides).

The **indicators** assessed during the research were defined according to the two concepts' (ES and STA) framework for agriculture. Based on the available literature, I first identified the ESs that can be measured in the field and the relevant

STA topics. My starting point was that elements of both concepts can be assessed using the same biophysical indicators (Fig. 2.).

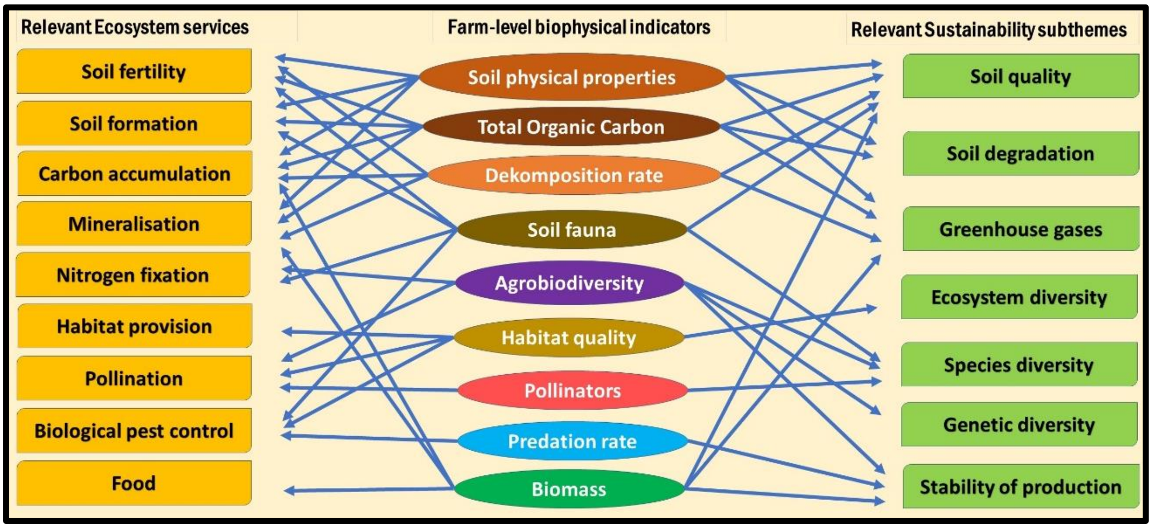

Figure 2. Farm-scale biophysical indicators and their relation to the ES (TEEB) and STA (SAFA) frameworks.

2.1. Methods of field research

Six sampling points on the farms were marked with a red flag during the first visit, to carry out the measurements multiple times in 2020. I randomly selected the sampling points on the farms taking into account the following criteria: 1. I excluded sampling in greenhouses, 2. sampling points were evenly distributed so that I had a picture of the whole farm, 3. I tried to sample several crops, preferably the same crops as on the other farms, 4. I avoided sampling on footpaths, other disturbed areas and near manure stocks.

The soil was sampled with a Pürckhauer-type soil sampler. Between 11 and 13 September 2020 I sampled one point on each farm. I determined the colour and thickness of the soil layers, in particular the thickness of the humic layer, the lime content, physical texture, moisture content and compaction of each level. Finally, I determined the soil type based on the observations. An extended soil test was carried out in an accredited laboratory on 5 samples from each farm. The five samples were taken from open field areas (0–30 cm layer) in each farm on 11–13 September 2020. I tried to cover the typical homogeneous patches of the farm with the five samples, taking into account my general sampling criteria. The samples were then dried at room temperature and sent to the accredited laboratory (HL-Lab, Debrecen). In the extended test, the samples were analysed for one physical parameter (Arany-type texture, MSZ-08-0205-2:1978) and 13 chemical parameters - humus content, %, MSZ 08-0210:1977, MSZ-08-0452:1980), pH (KCl), total salt (%), CaCO3 (%)

(MSZ-08-0452: 1980), N-NO2-NO3, Mg, S, K2O, P2O5, Na, Cu, Mn, Zn (all the latter in ppm, according to MSZ 20135:1999) were measured.

Soil resistance was measured with a digital penetrometer (Eijkelkamp Penetrologger GPS, type 06.15.SA) in the upper 80 cm of soil, while soil moisture was measured with a 4-pin Soil Moisture Sensor Theta Probe attached to the penetrometer in the upper 5–10 cm, following Mesoro et al. (2018). Measurements were carried out between 21–23 September 2020 at 6 points on each farm. The penetrometer recorded both the GPS coordinates of the sampling and the data series.

To investigate the **fresh organic matter decomposition** capacity of farm soils, the so-called litter bag method (plant residue bag) was used following Burgess et al. and Kriaučiūnienė et al. 2012. I used *Elymus repens* (Couch grass) chips collected from a single location (Kóspallag, Hungary) in spring and air-dried in a dryer (50°C for 48 h). The grass cuttings were shredded with scissors, and then stuffed into plastic canvas bags, filling a total of 540 bags. The bags were individually coded, and then each bag was filled with between 1 and 2 g of biomass and recorded together in a database. I placed the bags in the sample plots on 21–23 May 2020, 6 bags per farm at 6 points, which I fixed to the soil surface with loop sticks and toothpicks. Where there was a continuous cover of plants, I removed the plants and in all cases fixed the bags to bare soil. I collected the bags intermittently on three occasions (16–18 July first time, 27–29 August second time, 21–23 September third time), 2 bags per point each time. Afterward, I first stored the bags at room temperature for a few weeks and then air-dried the bags again with the residues in a drier. Finally, I measured the remaining plant residues from the bags in the laboratory using an analytical balance.

Earthworms were counted in 25×25×25 cm soil cubes at 6 points on each farm in spring (21–23 May 2020) and autumn (11–13 September 2020) according to ISO 2006 standard. The excavated soil sample was hand-sorted on a plastic foil and earthworm individuals were collected in coded jars. I recorded the earthworm counts in the field, then recounted them in the laboratory after the field day, separated adult and juvenile individuals, measured them, and then they were killed in 70% ethanol and left to stand in 4% formalin for one week. Finally, the individuals were placed back in 70% ethanol. Adult individuals were identified by external characteristics based on the descriptions of Csuzdi and Zicsi (2003) and Csuzdi (2007). Soil samples for **nematodes** were taken with a cylindrical sampling device with open sides, using a so-called nematode sampling rod in spring (21–23 May 2020) and autumn (11–13 September 2020), in parallel with earthworm sampling. Composite samples were collected at 6 points in the study plots, from three subsamples (within 2 m^2). About 100 g of soil per point was collected, of which 30 g per sample was weighed out in the laboratory, from which nematodes were extracted by gravity using the Baermann funnel method (Szakálas et al. 2015). I placed 2 layers of paper towel discs in the plastic filters and poured the soil sample onto them. The filters were placed in a glass funnel, pre-filled with distilled water and sealed at the bottom with a plastic clamp so that the filter was just in contact with the water surface. After 48 hours, the distilled water was drained into 50 ml Falcon centrifuge tubes, into which the nematodes migrated by gravity while the soil particles were trapped by the paper and filter. Samples were stored in a refrigerator and nematodes were counted within two weeks, as most of them were still alive within this time, making counting easier and more reliable. The soil trap method was used according to Császár et al. (2018) to survey the **soil surface fauna** on two occasions (May and September) in 2020. I placed 6 traps per farm at the preselected sampling points and then collected them after 10 days. The soil traps consisted of a 500 ml clear plastic cup and a white plastic cover sheet, the latter fixed to the soil with 100 mm plastic sticks about 3–5 cm above the soil surface. I placed a 120 ml plastic container and a funnel made from the cut tops of plastic bottles. I used 70% ethylene glycol as a fixative medium. After 10 days, the containers were sealed with a screw cap and coded, stored in a cool box during collection and then at room temperature in the laboratory for further determination. In the laboratory, the samples were first poured into a larger Petri dish and then separated into groups using forceps and placed in a smaller glass dish for microscopic determination, and the data were entered into a digital database (Excel) and documented with photographs. Individuals were determined at the taxon level (e.g. Araneae, Hymenoptera, Diplopoda, Collembola, Carabidae spp.), not the species level.

The **pollinator** survey was carried out using a visual method based on Bihaly et al (2018), the main taxa observed were bees (Apidae), butterflies (Lepidoptera), songflies (Syrphidae) and other pollinators (Cetoniinae, Cantharidae andVespidea spp.). The category "other bees" included wild bees such as Megachile or Osmia species, while bumble bees and hare bees were listed in a separate category. First, abiotic factors affecting pollinators were listed, such as temperature, cloud coverage, and wind strength, followed by potential food sources, flowering crops and weeds. Then the survey was conducted for 30 minutes at a slow, walking pace along a defined route, covering the entire area to the end, excluding greenhouses. Pollinators were recorded while feeding on flowers during the survey. The survey was carried out on three consecutive days in May (21–23), July (16–18) and August (28–30) 2020. Pollinators were recorded during their active period, i.e.

after 8–9 a.m., before 6 p.m. (also depending on the date of recording, spring or summer).

The **predation activity** was measured according to the method of the QUESSA European research project (Holland et al. 2020). Pests were modelled with two types of bait, flesh fly larvae (used for fishing, standard quality, white colour), which I stapled on 10*10 cm styrofoam sheets with a pin (10 larvae per sheet), and *Ephestia kuehniella*-mealworm eggs (procured from Szentes-Bio Kft., it is used in greenhouse production as feed for natural pests for overwintering), I glued them on 4 corners of cardboard cards with glue spray (TESA 60020-00000-02). During field research, one Styrofoam plate with the larvae was placed on the soil surface, one brown cardboard card also on the soil surface, and one green cardboard card with mealworm eggs on the leaves of the plant 30 cm above the soil surface using a hand clipping tool at 6 points on the farms. The baits were exposed for 24 hours, then recollected the next day. I counted the number of missing and damaged larvae on the plates during collection, while cardboard cards were photographed. Later missing eggs were measured from the photograph by estimating and averaging the percentage of each of the four corners. Predation surveys were carried out between 7–10 July and 27–30 August.

Agrobiodiversity indicators were surveyed once, in July 2020. On a printed satellite image, the current crop plots were delineated and cultivated crops were recorded, similar to the research of Hirschfeld and Van Acker (2019) and Flores and Buot (2021). Data were digitized using QGIS 3.10.9 (A Coruñ), and agrobiodiversity maps of the farms were created and the crop and weed species list was recorded per farm in Excel. The **habitat** survey was carried out in June. I visited the farms and the areas adjacent to them and determined the main plant species in the areas. Based on these field observations and aerial photographs, the habitat patches of the farms and their surroundings were defined and delineated according to the Hungarian General National Habitat Classification System (Á-NÉR- 2011, Bölöni et al. 2011) and the naturalness of the habitat patches were also determined (based on Király et al. 2009).

To assess the **sustainability** of the farms, also to improve the interpretation of the field data, all farmers were **interviewed** after the field surveys, between February and April 2021. The **interview questionnaire** was based on the auditor questionnaire of the SMART Farm tool, the sustainability assessment tool used for my previous thesis work, but I revised and supplemented it. Thus, the original questionnaire survey became an interview thread with a more structured section, mainly to assess farm management practices and a semi-structured, more openended section to assess farmers' attitudes and perceptions. In the interview, I first asked for general information (establishment of the farm, certification, etc.) and then asked the farmers about their farming practices (crop production, soil cultivation, nutrient supply, water management, crop protection and yields). Also about materials used on the farm (waste management, energy use and inputs used) and questions related to sales and product quality. Finally, we talked about the working conditions of the staff, the farmer's social responsibility, community activities and farm management strategies. The main topics of the semi-structured part were the attitude towards ST, the economic dimension, the ecological orientation, the social dimension, the organisation of work, the management of employees and their future vision. After making an appointment with the farmers, I sent them the interview questionnaire and the data questionnaire. The interview took on average 1.5–2 hours. I recorded the interviews with a voice recorder and took notes during the interviews. The interviews were transcribed and used as a basis for further analysis.

2.2. Analyses

In the **data analyses**, I calculated pollinator taxonomic group numbers, earthworm species numbers and Shannonian diversity based on the prevalence-absence and abundance data of all taxonomic groups (families and species). For the residuals of the relationships between the different categorical (farm types) and numerical variables, normality was tested using the Shapiro-Wilk normality test. To determine significant differences ($p < 0.05$) between different farm types, TukeyHSD test for normally distributed residuals, while for residuals with non-normal distribution Kruskal-Dunn post hoc test was used. All calculations were performed in the R 3.5.1 program environment (R Core Team 2018) with the packages "PMCMR", "PMCMRplus" and "vegan". I also evaluated the **soil test data** qualitatively, i.e. whether the value was good, poor or moderate, according to the official soil test results guide (Szakál et al. 2006). For the **habitat** studies, I also qualitatively assessed the farm environment and farms in terms of habitat diversity based on the survey and field observations (biodiversity enhancing elements on the farm).

For the assessment of **farm sustainability**, I used a modified version of the SAFA framework. The assessment was based primarily on information from interviews, and the transcripts were subjected to a simple qualitative content analysis. The detailed analysis structure was based on a priori codes derived from the adapted version of SAFA (dimensions, themes, sub-themes) and farm types. The assessment of the environmental dimension was supplemented by the biophysical data from the field research. I used soil-related data (humus content, soil resistance, soil nutrient content, soil life) for the soil quality sub-theme and the results of biodiversity indicators (pollinators, earthworms, agro- and habitat diversity) for the biodiversity theme.

The **ecosystem services** (and biodiversity as an agroecosystem condition indicator) were assessed based on quantitative and also qualitative data. The connections and the impacts of the indicators on the individual ES are summarised in Table 1.

Table 1: Correlations in the assessment of the studied ESs: impact of biophysical indicators and farming practices on each of the studied ESs

The potential of studied ES	**Impact of biophysical indicators on the ESs**	**Impact of Farming practices on the ESs**
Decomposition potential is high	if decomposition is rapid, humus and nutrient content in the soil is high, soil resistance is low, abundance and diversity of decomposing organisms is high, and the crops grown have a high biomass	if soil tillage is reduced, crop rotation is complex, irrigation is provided continuously, during fertilizing organic matter is added to the soil, soil amendments (e.g. compost) are used, a pro-active attitude to soil life is adopted
Global climate regulation potentia is high	if soil resistance is low, humus and nutrient content are high, the decomposition (speed and quality) helps to retain organic matter and at the same time improve the nutrient supply capacity	if soil tillage is reduced, during fertilizing organic matter is added to the soil, soil amendments (e.g. compost) are used, crop rotation is complex, a pro-active attitude to soil life is adopted
Biological pest control potential is high	if predation is intense, the soil surface fauna abundance and diversity are high and habitat diversity is high	if there is no chemical plant protection, biological control is used, the crop rotation is complex and the farmer's attitude to biodiversity is proactive
Pollination potential is high	if the abundance and diversity of pollinators are high, the number of weed species and cultivated crops is high and habitat diversity is high	if there is no chemical plant protection, the crop rotation is complex and the farmer's attitude to biodiversity is proactive

Biodiversity (agroecosystem condition indicator) increases	if habitat diversity is high, the abundance and diversity of pollinators, nematodes, earthworms, soil surface fauna, weed species and cultivated crops are high	if there is no chemical plant protection, the tillage is reduced, the crop rotation is complex and the farmer's attitude to biodiversity is proactive

3. RESULTS AND DISCUSSION

3.1. Results of the field study

CONV soils had a significantly lower Arany-type **compactness** (37) compared to PERM (46) and ORG (44), i.e. they had a lower proportion of clay fraction. The depth of the humus layer was the largest in the PERM soils (51 cm, not significant). pH and lime content showed no significant difference between the soil types. The pH was shown to be neutral (7.05–7.23) in all three types. These soil characteristics are not the result of farming but of the inherent soil geographical features. The highest average humus content was measured in the PERM type (3.6 ± 1.65%), followed by ORG (2.9 ± 0.83%), while the lowest was in the CONV (2.1 ± 0.8%). There was no significant difference between PERM and ORG, but both had significantly higher values compared to CONV.

The **nitrite, nitrate** (KCl soluble N-NO^2+NO^3 (mg/kg)) content showed similar values in all three soil types: PERM (25.2±18.3), ORG (23.2±14.57), while the lowest values were in CONV (22±15) but there was no significant difference between them. The Al soluble **potassium** content (mg/kg) of the soils was similar in ORG (473±371.1) and CONV (486.8±349), with higher values in PERM (693.2±497.3) – however, no significant difference was found. The Al soluble **phosphorus** content (mg/kg) of the soils was lowest in ORG (582.3±491.7), followed by PERM (614.6±582.1), with the highest values in the CONV soil (917.3.3±670.2), which showed a significant difference.

A significant difference was found between the **Mg** content of ORG (353 mg) and CONV (251 mg) soils. The Mg content of PERM (324 mg) was between that of the two other soil types. For **S, Na, Cu, Mn and Zn**, no significant difference was found between farm types.

The average **soil moisture** content was the same for PERM and CONV (10.9%) and significantly higher for ORG (15.6%). The average **soil resistance** per depth level did not show any significant difference between the three types at any level, with the average at 31–40 cm level being slightly higher for ORG (1.9

compared to 1.6 MPa for the other two), and the average at 41–80 cm depth being the highest for CONV (1.8 MPa) and the lowest for PERM (1.5 MPa). The soil resistance profiles suggest that there may be more serious problems with compaction in the PERM, as I measured 2.5 MPa resistance in three farms. It is unfavourable for plants if soil resistance is above 2 MPa. Among ORG soils the resistance reached 2.5 MPa only in one farm, and it reached 2 Mpa in four other. Based on the resistance profiles, the CONV has the most favourable conditions, with only two farms reaching 2 MPa and all the rest showing values below the 2 MPa threshold, presumably due to intensive soil rotation, decades of cultivation and a more homogeneous character. In ORG, the results were due to tillage, organic fertilisation and compost use, while in the PERM, they were probably due to the minimisation of tillage and higher clay content.

Decomposition was the most intensive in CONV (22.45 % residual on average), while PERM and ORG were almost identical, with significantly lower decomposition (28.41 and 28.75 % residual biomass) for the whole period studied (May–September). However, if only the first stage (May–July) of the study is considered, decomposition was significantly higher in PERM and ORG than in CONV.

In May, **earthworm** abundance was significantly higher on PERM farms compared to both ORG and CONV, but no significant differences were found in September. The number of earthworm species was significantly higher as well on PERM farms in the May samples compared to ORG and CONV. Although Shannon diversity was highest in PERM and lowest in ORG, these were not significant differences. In September–March, the average number of earthworm species and Shannon diversity were the highest in PERM, but there were no significant differences between farming systems in either number of species or Shannon diversity. Although, in contrast to what previous studies showed (e.g. Dominguez et al. 2014), earthworms were not more abundant and diverse in ORG soil compared to the CONV, but they were significantly more abundant in the PERM, confirming the initial hypothesis. This could be the result of either the efforts of PERM farmers to minimize soil disturbance, which favors earthworms (e.g., Dekemati et al. 2019), or higher fresh organic matter content due to mulching and crop residue management. On the other hand, soil type might have also favoured earthworms, as PERM farm soils are more compacted and more clayey, while CONV farmers have more sandy soils.

In the spring samples, the highest number of **nematodes** was found in the CONV farm soils (non-significant), followed by ORG and PERM. While in the repeated sampling in September lower nematode numbers were recorded in all soil types, the highest number was found again in CONV farms. Numbers from PERM soils almost reached the CONV values, while they were significantly lower in ORG. At first glance, this result is different from the study by Ilieva-Makulec et al. (2016), who found higher nematode abundance in ORG soils. However, when we look behind the numbers, the results are consistent with the previous study, where samples were only taken in autumn and in the sandier soil type, which in my case was the case for CONV. Here again, spring soil cultivation may have resulted in the nematode abundance in CONV soils due to the nutrient release associated with rotation, although this is contradicted by the fact that the highest abundance was found on farm K3, where there was no intensive tillage with rotation.

For **Arachnidae, Collembola, Isopoda and Diplopoda**, we found a significantly higher average abundance on PERM farms compared to CONV at the May survey, with ORG values being higher than CONV but lower than PERM. The average abundance of Hymenoptera and Carabidae was highest in CONV – the former values being significantly different from ORG. No significant difference was recorded for Isopoda. In the September survey, the highest numbers of Arachnidae, Collembola, Isopoda, and Hymenoptera were recorded in ORG, but the difference from PERM and CONV was not significant. The average abundance of Carabidae was again highest in the CONV samples (with a value of 13 on average of the 30 samples), although the difference from ORG and PERM was smaller than in May. In spring, we found a much higher average abundance for almost all taxa. This may be due to seasonality (environmental factors), the life cycle of these organisms and presumably, the availability of food. For many taxa, the PERM samples showed the highest numbers in spring, while the ORG samples had the highest number of individuals in autumn. However, these are not statistically confirmed differences. Abundance of the **soil surface fauna** was higher in ORG compared to the CONV for most taxa – except Hymenoptera –, which is consistent with previous studies (e.g. Dominguez et al. 2014, Ortaç et al. 2015) and confirmed my initial hypothesis that it is highest in the PERM. The more favourable conditions for them may have been the result of the surplus organic matter available through the management of crop residues and application of compost, the less disturbed, often covered soil surface, and the absence of chemical pesticide treatments. The presence of weeds could also have had a positive effect on insect abundance, as shown e.g. by Smith et al. (2020).

No significant differences in **pollinator** abundance were found between the farm types in either the May or the July sampling, although the average abundance was highest on PERM farms and lowest on CONV. However, the total number of pollinators in August was significantly higher in PERM and ORG than in CONV farms. No significant differences were found in either pollinator taxonomic group numbers or Shannon diversity at any sampling time. The average Shannon diversity index was highest on PERM farms in May, while it was highest on ORG in July and August 2020. In both July and August, the average was lowest in PERM. The variation in abundance is consistent with previous studies that found ORG is more favourable for pollinators (Holzschuh et al. 2006, Kennedy et al. 2013). It also partially confirmed our hypothesis that PERM has the highest number of pollinators – as this was the case in August only. These results may have been driven by the higher abundance and diversity of weeds, which was also confirmed by Holzschuh et al. (2006): this constitutes the semi-natural habitats, and the landscape surrounding the farms (Kennedy et al. 2013). In addition, the presence of certain pollen-providing plant species, such as members of the Rosacea, Asteraceae, and Leguminosae families, are particularly attractive to pollinators, as found by the researchers during the QUESSA project. Similar observations were made during our sampling, especially for Cucurbids, herbs, and flowering weeds (Mészáros et al. 2021). The species composition of pollinators might have been strongly affected by the presence of bee hives (Apis mellifera- honeybee). Hives were installed in some farms (e.g. P3, P4, B4) and their presence was observed in high numbers during the sampling period, as confirmed by the results as well. However, I was unable to obtain consistent data from farmers, so this aspect is not included in the assessment. The data and methodology of pollinator sampling are described in more detail in Mészáros (2021).

There was no significant difference in the loss of Ephestia eggs placed on the soil surface during the July predation survey: the mean loss and standard deviation for ORG and CONV were very similar, while PERM had the highest mean with the lowest deviation. In the August sampling, there was no significant difference in the loss of either Calliphora or Ephestia eggs placed on the surface. In July, Calliphora larvae loss was significantly higher in CONV compared to ORG – while PERM values were in between. In the case of cardboard cards laid on the soil surface, Ephestia egg loss in both July and August was significantly higher in PERM than in CONV, while ORG results were higher than CONV but lower than PERM. **Predation activity** could have been influenced by several factors in the sampling locations. For instance, one reason for the higher larvae loss in CONV may be the lower overall abundance of prey animals for predators in these farms. The type of used bait may have also influenced the results (McHugh et al. 2020), as well as the method of preparing and setting the traps (Ward 2001, Winder et al. 2001). In addition, the quality of habitats in the farm and near the farm may have been a significant factor, especially in terms of the semi-natural habitat patches with woody vegetation (Bartual et al. 2019, Holland et al. 2017, 2020) and the presence of weeds (Smith et al. 2020). High predation rates of Ephestia eggs in soil surface samples indicated that, regardless of farm management type, natural predators of pests are active in horticultural agroecosystems. Based on the Ephestia egg samples and compared to spring, their activity somewhat decreased in autumn, while in the case of Calliphora larvae loss, there was less seasonal/ temporal variation.

On average, PERM had the highest **number of crops** grown (17.8), followed by ORG (13.8) and CONV farms (12.2). These were not statistically verified differences. The highest number of **weed species** was recorded in ORG: 16 species on average and 80 species in total, with O3 farm having the highest individual number of species (24). This was followed by PERM (average: 11, total: 55) and CONV farms (average 7.8, total 39). ORG had a significantly higher number of weed species compared to CONV. PERM results were higher than CONV and lower than ORG and did not significantly differ from either. The most frequent **habitat type** on all farms was T1, which refers to spring or autumn sown annual arable crops or their harvested sites, regularly cultivated fields (Bölöni et al. 2011). The number of habitat types within a farm was highest in PERM (mean 4.4), followed by ORG (mean 4), and lowest in CONV (mean 3.2), but no significant differences were found between the three types. Overall, the number of habitat types within farms was not high, regardless of farm type, which is mainly due to their size: these farmers manage small-sized farms and thus try to fully exploit the entire area of the farms. Furthermore, the farms are mostly located in or near populated areas due to infrastructure needs and other reasons. This is also the reason for the lack of more natural habitats in the farms' immediate surroundings, in addition to the generally less natural and highly homogeneous habitats of the national agricultural landscape. This is also highlighted by the qualitative assessment of the farm environment, as out of the 15 farms surveyed, there were 5 with low scores, 4 with medium, and only 6 achieved high scores. My qualitative assessment based on the integration of biodiversity-enhancing elements showed that the majority of the PERM farms were rated high in naturalness (3 out of 5), while the rest achieved medium scores. At the same time, only two of the ORG farms and only one of the CONV farms were rated high, and the rest were rated low. I therefore suppose that PERM farms have done the most to increase habitat diversity and biodiversity, while CONV farms have the greatest deficiency in this respect.

3.2. Summary of sustainability assessment

In the **good governance** dimension, ethical farm management and a holistic approach were the most prominent in PERM farms: they put these into practice by following an alternative farming model, which includes elements such as community farming and self-sufficiency. Otherwise, they met the relevant objectives of the SAFA dimension to the highest degree. In other aspects, however, namely, in strategic management, ORG farms performed the best. They also introduced most innovations, thus developing a complex farming model, including a Community Supported Agriculture scheme, marketing, organic certification, professional production tools, etc. In contrast, the CONV farms were the least in line with the SAFA objectives, as they were characterised by the use of out-of-date technology, the lack of professional agricultural background/ education, and therefore the lack of innovation. Although this was offset by the practical knowledge collected over several generations, they still implemented a simplistic, outdated farm model (Table 2.).

Table 2. Keyword summary of the four dimensions of SAFA for the three farming systems studied (PERM, ORG, CONV).

SAFA dimensions/ farming systems	**PERM**	**ORG**	**CONV**
Good governance	Ideals, holistic approach, alternative farm models	Professionalism, strategic management, innovation, complex farm model	Outdated technology, minimal innovation, lack of agronomic education generational experience
Environmental integrity	Biodiversity focus, minimise soil disturbance, reduce dependence on external inputs	Protecting the environment, non-pollution principle, inclusion of external inputs	Synthetic fertiliser and pesticide use, external input dependency
Economic resilience	Prioritizing ethical principles above economic considerations, services as additional income sources	Viable, prosperous, viable economic scale	Limited market position, vulnerability
Social integrity	Focus on positive social impacts, social innovation	Knowledge transfer, employees	Minimal, spontaneous, lack of cooperation

In the **environmental** dimension, PERM farms performed the best. According to the interview responses, this is where environmental considerations in farming were most relevant, and this was largely confirmed by the field study as well. The ORG farms were also closely aligned with the SAFA objectives in many aspects, but they were characterised by more compromises in terms of trade-offs between production efficiency and other aspects (e.g. more external input use, mechanisation). For the CONV farms, the environmental impacts were considered less or not at all due to the use of synthetic inputs and the production-oriented farm model, and this was mostly confirmed by the field studies. In the **economic resilience** dimension, the best-performing farms were the ORG farms, which were the least vulnerable to various risks; the CONV farmers were more vulnerable in some respects, but they still had a more stable background than the PERM farmers: consequently, this latter performed the worst.

In the **social integrity** dimension, in terms of farmers' well-being, ORG farms performed the best, as they had a higher degree of production and financial stability due to professional management and sufficiently high production volumes. Furthermore, these farms have employees, which also contributes to several positive social impacts. PERM farmers were similar to ORG farmers in some aspects, although, due to their different approaches and perspectives, PERM farmers assessed differently their satisfaction with farming and their standard of living. PERM farms performed the best in terms of participation and social innovation. PERM and ORG farms can be seen as the catalyst of the social debate and professional networking around sustainable agriculture in Hungary, and, consequently, their social impact has been significant. In contrast, the CONV farms' contribution to this has been minimal, sporadic, or completely absent, e.g. when it comes to social innovation.

3.3. Evaluation of ecosystem services

Decomposition was most intensive in the CONV farms over the full study period, suggesting that the potential is greatest here, although there were no large differences between the farm types. At the same time, the humus content was the highest in the PERM farms, implying that organic matter is more retained here, whereas they decompose more rapidly in the soil of the CONV farms. The farming practices are the most favourable in PERM farming, which also positively affects decomposition. In addition to organic manure, many ORG and PERM farmers also apply compost as a soil amendment during fertilizing, and in most PERM farms, crop residues are also left in place. The interviews show that the complexity of crop rotation, that is, the better utilisation of the growing season by including precrops and sequential cropping in the ORG and PERM farms, results in more biomass than in the CONV farms. In CONV farms, there is no complex crop rotation: at most, they adjust the rotation to various conditions. Although field measurements show that CONV has the highest potential for decomposition ES, considering the amount of humus content and other variables, I argue that the **PERM is the most favourable**

for the decomposition ES, as the humus content increases even with continuous biomass removal (crops etc.).

The total organic matter content was significantly higher in PERM and ORG compared to CONV, so this is where the most carbon was stored in the soil at the time of sampling, while decomposition was most intensive in CONV. Soil nutrient content and soil resistance also influence humus formation: the former was the highest in PERM and CONV soils, while the latter was the most optimal in CONV. Farming practices are the most favourable on PERM farms: they try to minimize tillage, leave crop residues *in situ* or return them composted, and the farmers' proactive attitude towards soil life has a positive impact on their farming practices. Soil amendments are used mainly on the ORG farms, and also on some PERM and CONV farms, with compost being used in high proportions on ORG and some PERM farms. Organic fertilisers are used on all farms. Overall, the highest carbon inputs to soil are found on PERM farms, followed by ORG and finally by CONV farms. As described above, the complex crop rotation also results in higher crop cover duration and biomass production in PERM and ORG compared to CONV farms. Taking all this into account, I argue that **the ES potential of climate regulation is the highest in PERM, followed by ORG and smallest in CONV.**

There were significant differences in the **predation** surveys: for Calliphora larvae, the highest losses were observed on CONV farms, while for Ephestia eggs placed on the soil surface, the losses were significantly higher on PERM farms than on other farm types at both sampling times. The soil surface fauna surveys showed that the number of Arachnidae and Diplopoda individuals, which are potential predators of the released pest models, was significantly higher in the PERM type during the May sampling. The qualitative assessment of the habitat survey did not show large differences in the farm environment – generally, all farms had a less-than-optimal environment in terms of the quality of their surrounding habitats. At the same time, when taking into account biodiversity-enhancing elements as well, the habitat diversity within the farms was highest in PERM and lowest in CONV farms. This is an important factor for the pest's natural enemies, as semi-natural habitats provide their habitat and feeding grounds. Farming practices (crop protection, biological control, crop rotation) and farmer awareness and approach are more favourable in PERM farms compared to ORG and CONV ones. **Based on all the data, I hypothesise that conditions are more favourable in PERM farms for organisms that provide pest control as an ES, thus the ES provision is also higher here**.

As for **pollinator** abundance, I observed a significant difference in August in favour of PERM farms compared to CONV (ORG results were lower than PERM but higher than CONV). The field survey partly supports the idea that PERM has the highest abundance of pollinators, but the results are not consistent with the pollinators' diversity. The number of weed species was significantly higher in ORG farms compared to the CONV, while the number of cultivated crops and the plot density were the highest in the PERM farms - although the difference in this case was not significant. Overall, this suggests that agrobiodiversity was more favourable for pollinators in the PERM and ORG farms than in CONV. This is also supported by the qualitative habitat diversity assessment for the reasons detailed above. Furthermore, it is complemented by farming practices: PERM (and ORG) farms maintain a complex crop rotation compared to CONV farms. In addition, they do not use synthetic pesticides, which could be particularly harmful to pollinators. CONV farmers claim to use bee-friendly plant protection technology. Finally, the biodiversity approach of farmers also confirms that pollinators play a prominent role on PERM farms. For instance, farmers insert flowers into crop rotations for the pollinators' benefit. **All in all, I argue that the pollination potential is the highest on PERM farms.**

As mentioned above, there was no significant difference in pollinator diversity across farm types, but pollinators were significantly more abundant in PERM farms than in CONV in August. Earthworm diversity was the highest in the PERM farms in May. For some taxonomic groups (Arachnidae, Collembola, Isopoda), the abundance was significantly higher in the PERM farms compared to the ORG or CONV farms when the soil surface fauna was surveyed in May. Weed species abundance was highest (significantly) in ORG, followed by PERM, and lowest in CONV. When it comes to habitat diversity, only the qualitative analysis could show a difference between the farm types, which also took into account the biodiversity-enhancing elements in the farm. It showed that PERM farms aim to do the most to improve habitat diversity. At the level of farming practices (plant protection, crop rotation, biological control), PERM farms are also more favourable. This is supported by the farmers' approach to biodiversity, as PERM farmers proactively build on biodiversity, while CONV farmers are more neutral. In summary, biodiversity as an agroecosystem condition indicator is the most favourable in PERM, followed by ORG and CONV. At the farm level, this has not yet been investigated in studies with an ES focus, but it has been shown in more extensive biodiversity studies (e.g. Bengtsson et al. 2005). This significantly contributes to and justifies the higher potential of the studied ESs in the PERM and the ORG farms. The results of the ecosystem services assessment are shown in Figure 3.

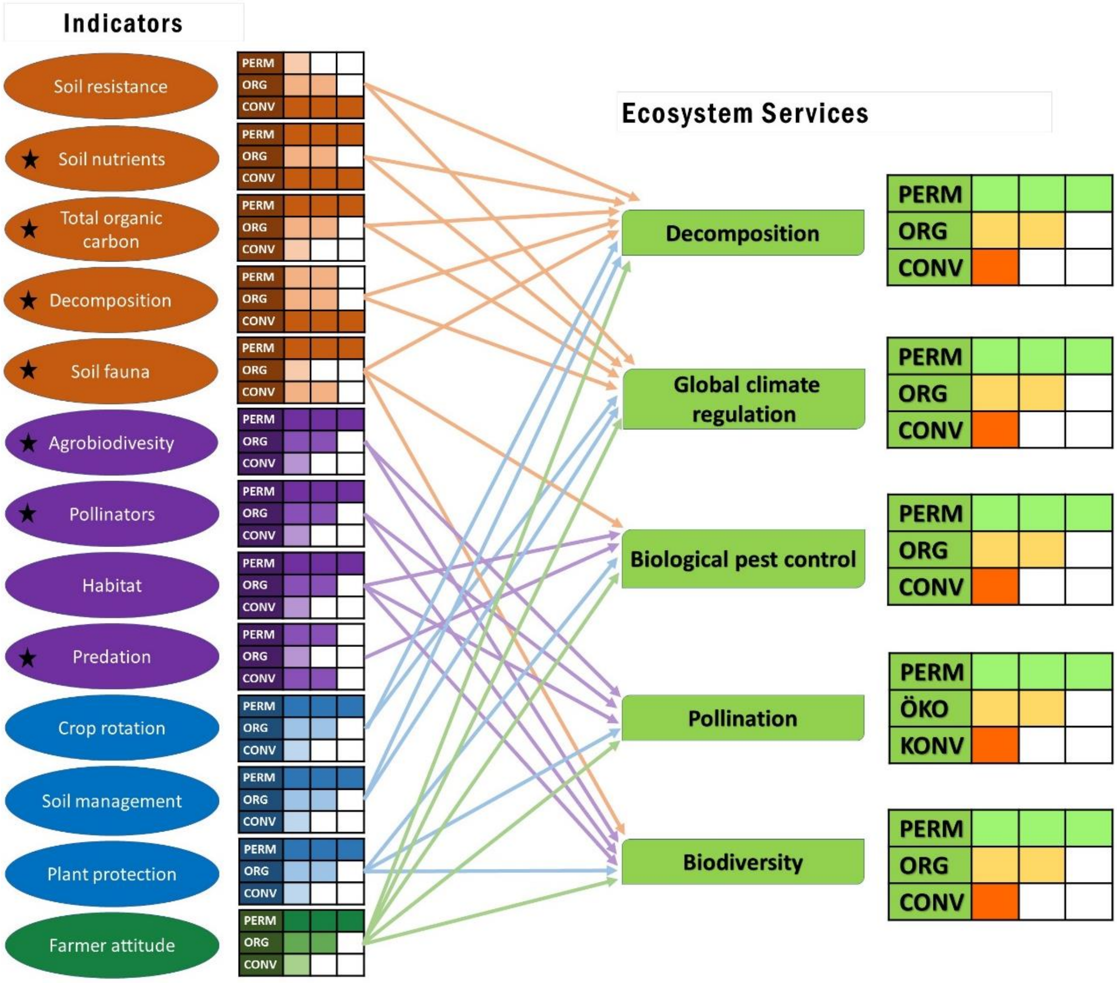

Figure 3: Results of the assessment of ecosystem services and agroecosystem condition (biodiversity) indicator. Arrows show the positive impact of the indicator on the relevant services. Tables show the results of the three farm types in terms of positive impact. On the left, indicators related to soil are marked in brown, biodiversity in purple, qualitative farming practices in blue, and farmer attitudes in green. Indicators, where statistically proven difference was found between farm types, are marked with a black asterisk.

4. CONCLUSIONS AND RECOMMENDATIONS

4.1. Conclusions

I have explored the **connections between ES and STA** at the framework level, in particular in the environmental dimension, and I have identified several **overlaps** between the STA themes and the relevant ESs: atmosphere (global climate regulation ES), water (water cycle ES), soil (decomposition, nutrient cycle ES) and biodiversity (agroecosystem condition indicator). In the methodological description, I have shown in detail that the used natural science biophysical parameters and social science indicators can be applied to assess both the relevant ES and STA themes. For example, soil physical and chemical parameters affect the soil theme and the decomposition and climate regulation ESs, while soil fauna also affects biodiversity in addition to soil, in parallel to the decomposition and biological pest control ESs, and pollinator abundance affects the biodiversity theme, in parallel to the pollination ES. Through the results of the case study, the practical application of the methods is also demonstrated. The **advantages of aligning the two concepts** (STA and ES) are: better comparability of research; avoiding the misuse of the terms in scientific and professional spheres; synergies and trade-offs between the concepts (which concept how to use in specific contexts); a common professional platform and better transition possibilities between research groups and disciplines; and finally, the possibility to unite efforts towards a shared goal: more holistic policy planning to engage with more stakeholders. Based on the research I have carried out, I have identified several **sustainability issues** (**trade-offs** between economic efficiency and ecological considerations) for small-scale horticulture: some of these are agronomic, i.e. related to the production technology, such as soil management, fertilizing or irrigation, while others are more strategic, such as marketing and professional networking, and finally social, such as social responsibility, succession.

4.2. Recommendations

The set of field study methods I have designed is potentially suitable as a complex assessment model for the analysis of the ES and STA at the farm-level. I have formulated several suggestions for further development of the indicators and methods used, such as: i) the addition of qualitative analysis to the humus content measurement; ii) the measurement of decomposition in an annual cycle; iii) a farm-gate carbon balance; iv) the development of a standardised quantitative evaluation method for soil resistance; v) more detailed determination (species) of different taxonomic groups and supplemented by soil microbiome analyses. The methodological framework should be further developed to allow a consistent method for the assessment of the ES at all levels of the cascade system at the farm level. The interview questionnaire for assessing STA should be extended to provide more directly integrable data and the interview method should be complemented with other social science methods (e.g. focus group discussion). In addition to the interview, I tried to obtain numerical data from the farmers using a spreadsheet (input use, financial information). However, the resulting data series were not consistent, thus they were consequently not included in this study, although they could have provided additional possibilities for evaluation. To better analyse the collected data, it would be useful to use complex statistical models and tests that could handle both quantitative and qualitative data together and could statistically verify the trends in the ESs and the correlations between the data measured in the field and the data from the farmer interviews. My main **recommendations for professionals in practice** are the following: i) to develop an ecological approach to weed management that would take into account the positive impact of weeds on ESs; ii) to increase the use of compost as a soil amendment material; iii) and finally, to communicate the ecological benefits of farming to consumers more actively. For **policymakers**, I suggest that the ES and STA concepts should be jointly considered during the implementation of the relevant policy (such as strategies) based on the identified interconnections. This would greatly contribute to the integration of the different policies that have been in focus recently. Furthermore, since permaculture farms have shown further promising results following my previous research, it is worth considering promoting its dissemination in agriculture through farmer and advisor training and support to relevant professional organisations. It would also be important to boost support for the small-scale horticulture sector to maintain the rural population, and enhance food sovereignty and diversified agriculture, as these (mostly) family-run farms are much more than production units: they are complex systems with diverse social, ecological and economic functions. It is also recommended to increase farmers' ecological knowledge (biodiversity and ES-focused training, knowledge transfer on functional biodiversity) and to create an advisory scheme that focuses directly on farm-gate biodiversity support. Finally, linking agri-environmental subsidy schemes to ESs would make it more feasible to monitor the impacts e.g. performance-based subsidies and easier to communicate to the wider society. Carrying out similarly complex analyses in other sectors (e.g. livestock, grassland, orchard) would be a relevant **research** goal. Moreover, it would be gap-filling for practical applications as well as for policies, if absolute values/scales for the studied indicators were given for the agricultural context. That would facilitate a standardised evaluation and help farmers benchmark their results (e.g. how many earthworms are optimal?). It would also be worthwhile to create a national STA indicator system that would be accessible and user-friendly for farmers. I participated in a project (Agritoolkit) in parallel to my PhD research for this purpose, which could be extended with an ES module.

5. NEW SCIENTIFIC RESULTS

1. I was the first to **compare** the **concepts of sustainability and ecosystem services** and propose a **common understanding** of these concepts for **agriculture**.

2. I found that **harmonising** and using the **two concepts** together could have multiple **benefits for practice, research and policy** (better comparability of research; more professionally sound application; more effective joint efforts).

3. This study is also the first to develop and empirically test a **methodological framework** for **measuring** environmental **sustainability** and the concomitant regulatory **ecosystem services** at the **farm level** in the small-scale horticulture sector. The applied methods were evaluated and suggestions for improvements in their future use were formulated.

4. New scientific results ($p<0.005$) from the field survey of small-scale permaculture ($n=5$), organic ($n=5$) and conventional ($n=5$) farms in 2020:

- I found that permaculture and organic farm soils have higher humus content and lower phosphorus content compared to conventional ones,
- I found that the magnesium content of organic farm soils is higher than that of conventional soils,
- I found that the decomposition rate is higher in permaculture and organic farms in July, but lower in September compared to conventional farms,
- I found that earthworm abundance and species abundance were higher on permaculture farms in May compared to organic and conventional farms,
- I found that nematode numbers were higher in September on permaculture and conventional farms compared to organic farms,
- I found that the abundance of *Arachnidae* and *Collembola* individuals is higher in permaculture farms in May compared to conventional farms,
- I found that the abundance of *Diplopoda* individuals is higher in May on permaculture farms compared to organic farms,
- I found that the abundance of *Hymenoptera* individuals was higher in May on permaculture and conventional farms compared to organic farms,
- I found that the total number of pollinators was higher in August on permaculture farms compared to conventional farms,

- I found that *Calliphora* larvae losses are higher in July on conventional farms compared to organic farms,
- I found that surface losses of *Ephestia* eggs were higher in July and August on permaculture and organic farms compared to conventional farms,
- I found that the number of weed species is higher on organic farms compared to conventional farms.

  Permaculture and organic farming are associated with significant positive environmental impacts compared to conventional farming for most soil and biodiversity parameters across the farms, period and indicators studied.

5. I was the first to investigate the **ecosystem service potential** of small-scale permaculture, organic and conventional horticulture at the farm level. I found that, based on the applied natural and social science indicators, **the potential for decomposition, global climate regulation, pollination and biological pest control as ecosystem services is highest in permaculture farms**, followed by **organic** farms and **lowest in conventional**. Overall **biodiversity** (wildlife and habitat maintenance and agrobiodiversity) as an **agroecosystem condition indicator** is **most favourable in permaculture farms and least favourable in conventional farms.**

6. **I was the first to adapt the SAFA framework to Hungarian, small-scale horticultural farms and assess the four dimensions of sustainability by using biophysical measurements to investigate some subthemes in environmental sustainability.** I found that in the good governance dimension, permaculture farming performs best in terms of ethical farm management, while organic farming performs best in terms of professional management. In the environmental dimension, the permaculture farming system performs best, with conventional performing worst. In the economic dimension, the organic farming system performs best, while permaculture performs worst. In the social dimension, organic farming performs best in terms of farmer well-being, while permaculture in terms of social innovation and participation, conventional farming performs worse than both organic and permaculture.

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7. LIST OF PUBLICATIONS

7.1. Journal articles:

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Landert, J., Pfeifer, C., ...**Szilágyi A.**, ...Miller, D. (2020): Assessing agro-ecological practices using a combination of three sustainability assessment tools. Landbauforschung (Journal of Sustainable and Organic Agricultural Systems) 70 (2): 129-144 https://doi.org/10.3220/LBF1612794225000 (**Q4**, **IF= 0,25)**

Mészáros F. A., **Szilágyi A.**, Kun, R., Sárospataki, M. (2021): Megporzó közösségek vizsgálata permakultúrás, ökológiai és konvencionális gazdaságokban a Szentendrei-szigeten. Tájökológiai Lapok, 19 (2): 133–149. https://doi.org/10.56617/tl.3435 **(Q4)**

Centeri, C., Saláta, D., **Szilágyi, A.**, Orosz, G., Czóbel, S., Grónás, V., Gyulai, F., Kovács, E., Pető, Á., Skutai, J., Biró, Z., Malatinszky, Á. (2021): Selected Good Practices in the Hungarian Agricultural Heritage. Sustainability, 13, 6676. https://doi.org/10.3390/su13126676 **(Q1, IF: 3,889)**

Szilágyi, A., Plachi, E., Nagy, P., Simon, B., Centeri, Cs. (2021): Assessing earthworm populations in some Hungarian horticultural farms: comparison of conventional, organic and permaculture farming. Biology and Life Sciences Forum, 2(1): 11, https://doi.org/10.3390/BDEE2021-09416

Szilágyi, A., Mészáros, F., Kun, R., Sárospataki, M. (2021): Pollinator Communities in Some Selected Hungarian Conventional, Organic and Permaculture Horticultures. Biology and Life Sciences Forum, 2(1):13. https://doi.org/10.3390/BDEE2021-09492

Nel, L., Boeni, A.F., Prohászka, V., **Szilágyi, A.**, Kovács, E., Pásztor, L., Centeri, C. (2022): InVEST soil carbon stock modelling as an ecosystem service in agricultural landscapes. Sustainability 14(9808):1-19. https://doi.org/10.3390/su14169808. (**Q1, IF: 3.251**)

7.2. Conference full papers:

Nel, L., **Szilágyi, A.** (2018): Selection of indicators for assessment of soil-related agricultural ecosystem services and sustainable management. 25th International Poster Day and Institute of Hydrology Open Day, 7 November 2018, Bratislava, Slovakia. 103–118 pp. ISBN 978-80-89139-42-2

Szilágyi, A., Kolár, A., Seres, A., Nagy, P., Balogh, J. (2019): Decomposition rates and soil organic matter content of conventional, organic and permaculture farms on the Szentendre Island, Hungary: an explorative case study. 26th International Poster Day and Institute of Hydrology Open Day, 6 November 2019, Bratislava, Slovakia. 222–231 pp. ISBN 978-80-89139-44-6