



Quantification of ecological services for sustainable agriculture

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Collaborative Project

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Report on spatial explicit heat maps for multiple ES at farm and landscape level



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Executive summary

Agriculture relies on multiple ecosystem services that are often associated with semi-natural habitats. Here we (i) analyse the spatial distribution of five ecosystem services (soil erosion prevention, conservation value for biodiversity, carbon sequestration, landscape aesthetic value, and biocontrol),

(ii) explore synergies and trade-offs among these ecosystem services, and (iii) identify landscape configurations that support multiple ecosystem services. Evidence-based indicators were derived for the five ecosystem services and these were applied to landscape sectors in Germany and Hungary to generate heat maps for ecosystem services. These heat maps indicated that ES provision levels can differ markedly between and within landscapes and were strongly associated with semi-natural habitats. In arable fields soil organic matter can be increased by application of green manures, which can increase carbon sequestration, and also improve soil fertility, soil structure, water infiltration and water holding capacity. Hence, the attained ecosystem service level depends on characteristics of the landscape (e.g. proportion of semi-natural habitats) and management (e.g. application of green manure). When exploring trade-offs and synergies of alternative landscape designs trade-offs were observed between aesthetic and conservation value, whereas synergies were observed between aesthetic value and carbon sequestration (in terms of soil organic matter), the prevention of soil erosion and aesthetic value, and biocontrol and carbon sequestration. The exploration of alternative landscape configurations for multiple ecosystem services indicated that the configuration of the Hungarian landscape sector was more favourable for supporting multiple ES than the German landscape sector. Collaboration between actors offers scope for the redesign of agricultural landscapes that better support multiple ecosystem services.

Main conclusions for stakeholders

Agriculture relies on multiple ecosystem services that are often associated with semi-natural habitats. In this study, we investigated how the presence woody and herbaceous semi-natural habitats influenced the prevention of soil erosion, conservation value for biodiversity, carbon sequestration, landscape aesthetics, and biocontrol. For this purpose we developed maps of the spatial distribution of these five ecosystem services for landscapes in Germany and Hungary. The maps indicated that ecosystem service provision levels can differ markedly between and within landscapes and are strongly associated with semi-natural habitats. For instance, woody and herbaceous semi-natural habitats sequestered carbon in the soil, supported populations of natural enemies that can provide pest suppression services in crops, played an important role in the conservation of spiders, prevented soil erosion, and also contributed to the aesthetic value of the landscapes. Soil organic matter in arable fields can be increased by adding green manures, for instance by growing a cover crop in winter, which can not only increase carbon sequestration, but also improve soil fertility, soil structure, water infiltration and water holding capacity. Hence, the attained ecosystem service levels depend on characteristics of the landscape (e.g. proportion of semi-natural habitats) and management (e.g. application of green manure). The analysis of multiple ecosystem services in the German and Hungarian landscape revealed that the current configuration/management of the Hungarian landscape was quite favourable, while there was much room for strengthening ecosystem services in the German

landscape. Collaboration between actors offers scope for the redesign of agricultural landscapes that better support multiple ecosystem services.

Main conclusions for policymakers

Agriculture relies on multiple supporting ecosystem services that are often associated with semi-natural habitats. However, trade-offs may arise between supporting ecosystem services, or between ecosystem services and agricultural production. Here we investigated the spatial distribution of five ecosystem services (soil erosion prevention, conservation value for biodiversity, carbon sequestration, landscape aesthetic value, and biocontrol) in a German and Hungarian case study, and assessed the interactions among the ecosystem services. Heat maps for the five ecosystem services indicated that provisioning levels can differ markedly between and within landscapes and were strongly associated with semi-natural habitats. In arable fields soil organic matter can be increased by application of green manures, which can increase carbon sequestration, and also improve soil fertility, soil structure, water infiltration and water holding capacity. Hence, the attained ecosystem service level depends on characteristics of the landscape (e.g. proportion of semi-natural habitats) and management (e.g. application of green manure). The analysis of multiple ecosystem services in a German and Hungarian case study revealed that the current configuration/management of the Hungarian landscape was quite favourable, while there was much room for strengthening ecosystem services in the German landscape. When exploring trade-offs and synergies of alternative landscape designs trade-offs were observed between aesthetic and conservation value, whereas synergies were observed between aesthetic value and carbon sequestration (in terms of soil organic matter), the prevention of soil erosion and aesthetic value, and biocontrol and carbon sequestration. While some ecosystem services can be managed at the field and farm level (e.g. carbon sequestration by application of green manure), many ecosystem services operate at spatial scales exceeding the farm scale (e.g. aesthetic value, biodiversity conservation and biocontrol which depends on mobile natural enemies of pests). Therefore, there is need to these manage ecosystem services at the landscape scale, which requires collaboration between actors in agricultural landscapes. Policy instruments should accommodate efforts of actors that support ecosystem services that benefit the broader public.

1. Introduction

In this deliverable we report on the development of spatially explicit “heat maps” for multiple ecosystem services at farm and landscape level. Key ecosystem services (ES) other than biocontrol or pollination (‘other’ ecosystem services, as defined in QuESSA) were identified in interaction with the local stakeholders in case study locations. In an interactive approach first the ecosystem services other than pest suppression or pollination from each of the case study teams were elicited, and then it was decided on which indicators and methods would be appropriate to quantify these ecosystem services. During the QuESSA meeting in Gödölö (Hungary, 25th – 26th November 2013), a session was organized in which other ecosystem services were listed and prioritized per case study. Based on

priority and common interest across case studies, indicators were prototyped and discussed during the QuESSA meeting in Landau (Germany, 14th – 17th January 2014). The approach served to achieve contextualization and identify potential for addressing other ESs across the case studies. At the QuESSA meeting in Tartu (Estonia, 2-4 February 2016) four other ESs were identified for further analysis: (i) soil erosion prevention, (ii) conservation value, (iii) soil organic carbon, and (iv) landscape aesthetic value. Biological control was later added to the analysis as a fifth ecosystem service. Here we present a description of the indicators for five ecosystem services (four ‘other’ ES and biological control), heat maps for the spatial distribution of these ESs, and the result of a multi-objective optimization analysis highlighting synergies and trade-offs between these ESs.

2. Material and methods

2.1 Conceptual framework

The purpose of this study is to explore trade-offs and synergies between multiple ESs associated with semi-natural habitats (SNH) in agricultural landscapes, and to identify landscape configurations that better capitalize on these ESs. In QuESSA, landscape sectors were defined as focal fields and the landscape within a 1 km radius around it (Fig. 1). Focal fields were selected to represent distinct proportions of semi-natural habitat (SNH) in the surrounding landscape sectors. Landscape sectors were digitized and all landscape elements wider than 3 m were mapped. Here we will illustrate the procedure for landscape sectors in Germany and Hungary (Fig. 1). We followed a 3-step procedure. First, generic indicators were developed for the five ESs, which allowed the assessment of the provisioning level of these ESs for any given landscape. Second, the spatial distribution of each of the five ESs in the current landscape configuration were derived using the Landscape IMAGES framework. Third, trade-offs and synergies between the five ESs associated with SNHs were explored by simulating ES provisioning levels of a large number of alternative landscape configurations in Landscape IMAGES. Landscapes with a satisfactory level of provision for multiple ES were identified, and can be used to inform landscape management for multiple ES.

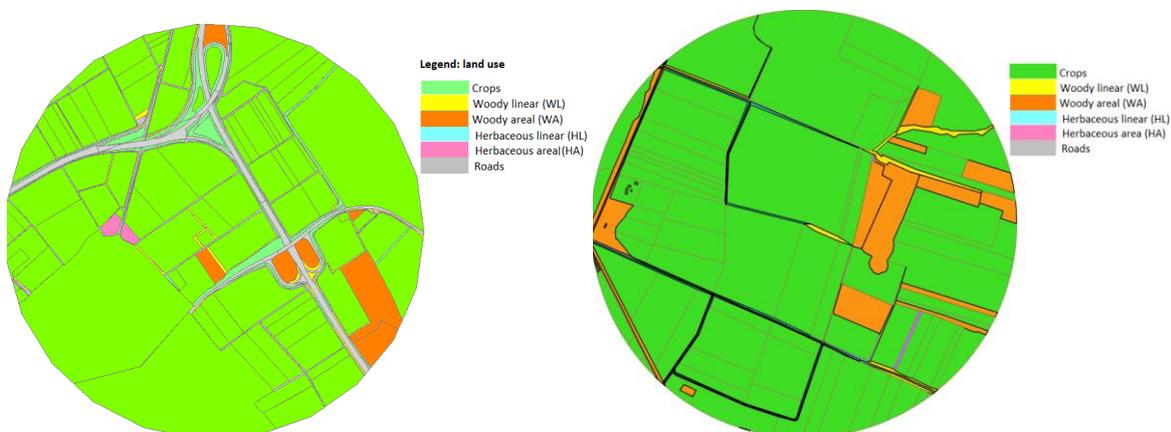


Fig. 1. Example of a landscape sector of the German (left) and Hungarian case study (right).

2.2 ES indicators

Indicators for the ‘other’ ESs (soil erosion prevention, conservation value, soil organic carbon, and landscape aesthetic value) were developed and underpinned by literature review, analysis of local and regional data, and the use and development of models.

2.2.1 Soil erosion prevention

Soil erosion is modelled using the Revised Universal Soil Loss Equation (RUSLE; Renard et al., 1997), which is applicable for European conditions (Gobin et al., 2004). This empirically-derived equation estimates the amount of sediment load out of a spatially defined landscape unit (equation 1):

$$E = R * K * L * S * C * P \quad (1)$$

where E is the average annual soil loss per unit area ($\text{t ha}^{-1} \text{ year}^{-1}$); R is the rainfall erosivity factor ($\text{MJ mm ha}^{-1} \text{ h}^{-1} \text{ year}^{-1}$); K is the soil erodibility factor ($\text{t ha h MJ}^{-1} \text{ mm}^{-1} \text{ ha}^{-1}$), which represents the soil loss rate per erosion index unit for a specific soil. The K factor integrates the effect of rainfall, runoff and soil characteristics such as texture, structure, organic matter content and soil permeability on soil loss; LS is the combination of the slope length (L) and slope steepness (S) (unit less); C is the cover and management factor which estimates the soil loss ratio. The C factor integrates the effects of crop characteristics, soil cover, and soil disturbing activities on erosion and corresponds to the ratio of soil loss from an area with specified cover and management to soil loss from an identical area in tilled continuous fallow. P is the support practice factor, i.e. the ratio of soil loss with a support practice such as contouring or terracing, and soil loss with straight-row farming up and down the slope. The RUSLE parameters were derived from land-cover maps, soil maps (European Soil Database; (Panagos, 2006)), digital elevation models (DEM), slope and length (computed from DEM), rainfall intensity (Panagos et al., 2015), and management and crop cover factors were derived from case study expert opinion.

2.2.2 Biodiversity conservation

Biodiversity conservation was quantified using an indicator denoted as conservation value, which estimates the number of species in relation to the area under SNH. The indicator was formulated based on pitfall trap data (for spiders) in the four types of semi-natural habitats (woody linear, woody areal, herbaceous linear and herbaceous areal) in a Germany landscape. These spider species data from the German case study were used to construct species accumulation curves for each semi-natural habitat type using the Vegan package in R (Oksanen et al., 2007) (Fig. 2). As the curves were quite similar for the two woody and the two herbaceous habitat types, the data of linear and areal woody habitats were pooled into “woody habitats”, and data for linear and areal herbaceous habitats were pooled into “herbaceous habitats”. Species accumulation curves were then constructed for woody and herbaceous habitat types (Fig. 3 and 4). Samples from the linear and areal elements were considered as independent observations (i.e. data were not pooled), giving 2 elements per landscape site for woody and herbaceous habitats, respectively. Lomolino curves (Lomolino, 2000) were fitted using equation (2):

$$S = \frac{S_{max}}{1 + slope \log\left(\frac{A_{50}}{Area}\right)} \quad (2)$$

where S represents species richness; S_{max} is the asymptote (maximum species richness); $slope$ is the slope at the inflection point of the curve; A_{50} is the number of sites where 50% of the maximum species richness is obtained and $Area$ is the sampled area (Lomolino, 2000). The curves provided an excellent fit of the experimental data (Figs 3). The estimates of the parameters indicate that both woody and herbaceous habitats have similar maximum species richness (S_{max}), but that the slope of the curve for herbaceous habitats is flatter than for the woody habitats (Table 1).

To account for double counts of spider species that occur both in woody and herbaceous habitats the fraction unique spider species in woody and herbaceous habitats was calculated for the pooled spider species in woody and herbaceous habitats across all landscapes. Woody and herbaceous habitats harboured a fraction of 0.46 and 0.31 unique spider species, respectively. The estimated spider species richness (thus accounting for double counts) in a landscape sector was calculated using Equation 3:

$$S = \max \begin{cases} S_W + S_H \cdot 0.31 \\ S_H + S_W \cdot 0.46 \end{cases} \quad (3)$$

where S is the (gamma) species richness at the landscape scale, S_W is the estimated species richness in woody habitats, and S_H is the estimated species richness in herbaceous habitats. Equation 3 gave a satisfactory description of the gamma species richness S based on the species richness of woody and herbaceous habitats (i.e. S_W and S_H ; Fig. 4). We applied this species-area relationship based on German pitfall data to the German and Hungarian landscape sectors.

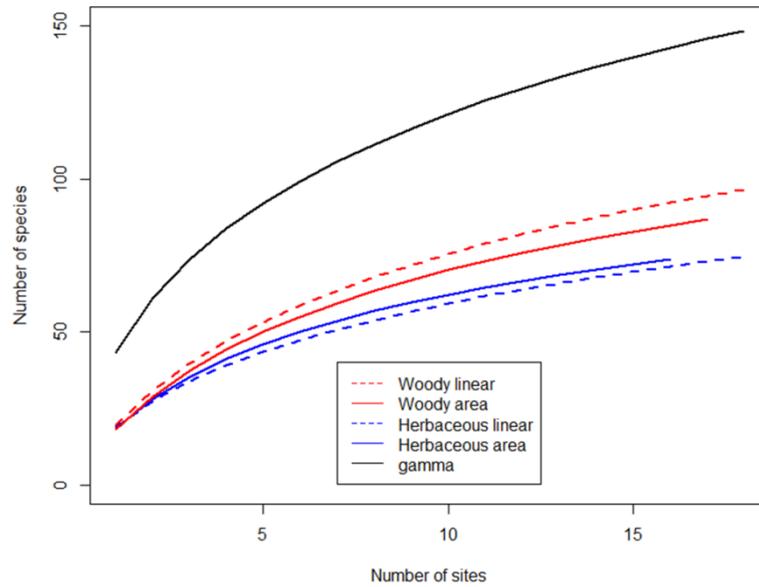


Fig. 2. Species accumulation curves for four types of semi-natural habitats (woody linear, woody areal, herbaceous linear and herbaceous areal) in 18 landscape sectors in the Landau region, Germany. The total (γ) species richness is indicated in black.

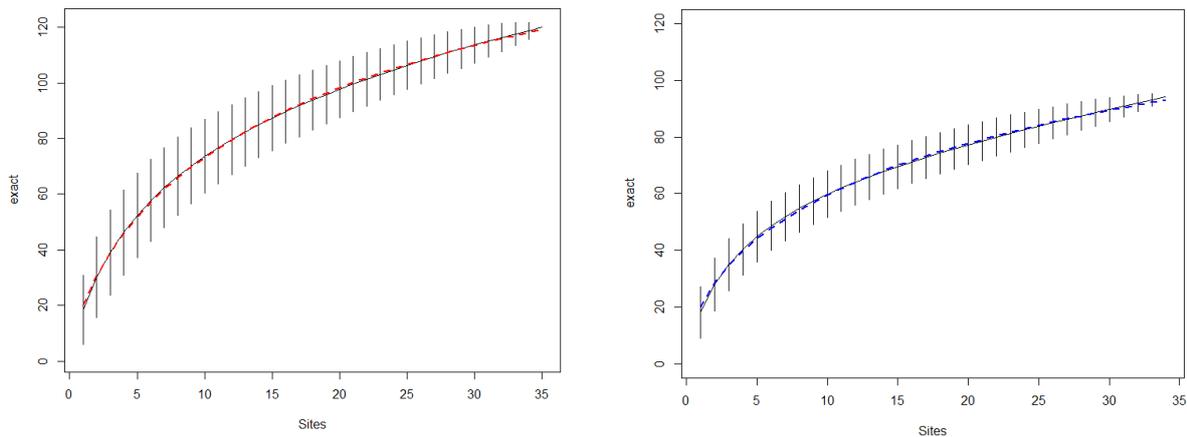


Fig. 3. Species accumulation curves for woody (left) and herbaceous (right) semi-natural habitats in 18 landscape sectors in the Landau region, Germany. Each landscape sector contains two elements for each habitat type, giving a total of 36 sites. Fitted Lomolino curves are indicated with dashed lines.

Table 1. Overview of parameter estimates of the fitted Lomolino curves for woody and herbaceous semi-natural habitats. S_{max} is the asymptote (maximum species richness), $slope$ is the slope at the inflection point of the curve, and A_{50} is the number of sites where 50% of the maximum species richness is obtained.

	Woody	Herbaceous
S_{max}	214.7	209.9
$slope$	2.02	1.77
A_{50}	25.5	50.5

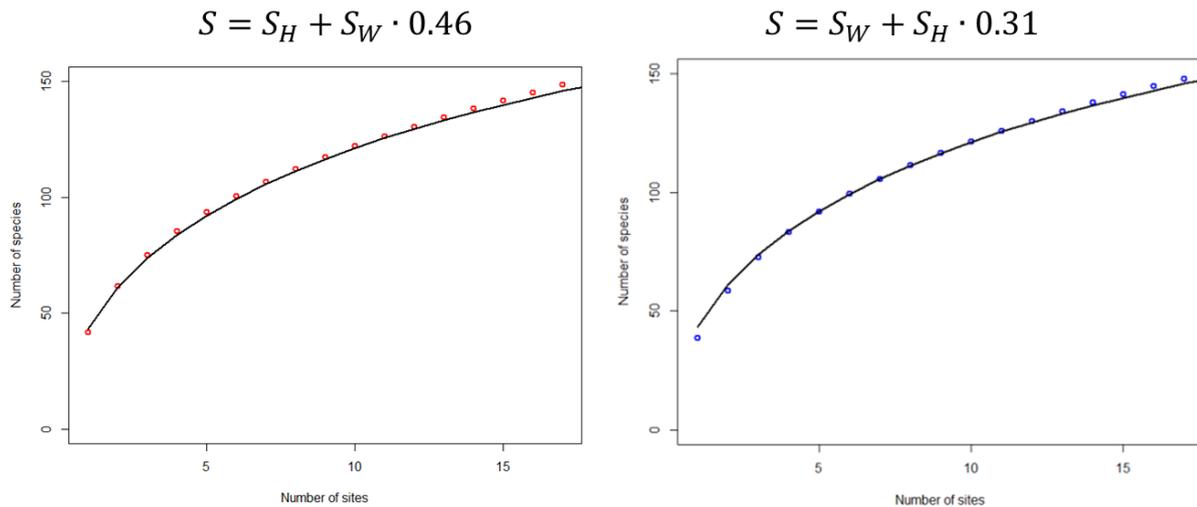


Fig. 4. Observed gamma species richness (solid line) and predicted gamma species richness using the two formulas of Equation 3 (points).

2.2.3 Carbon sequestration

Carbon sequestered in the soil resides in the soil organic matter pool. Soil organic matter consists of approximately 58% carbon (Schulte, 1995), and is positively associated with soil fertility, soil structure, water infiltration and water holding capacity. Land cover and rotation systems can affect soil organic content. The carbon sequestration indicator is a relative measure of the amount of soil carbon at the landscape scale. That is, the indicator shows the potential change in soil carbon resulting from changes in land-use as compared to the initial situation. We used different approaches to evaluate the effect of changes in areas of SNH (woody and herbaceous habitat) and green manure.

Soil carbon levels were measured in woody and herbaceous habitats. Since these habitats are permanent and relatively undisturbed, we assumed that the soil carbon levels reached equilibrium. In the case that no measurements were available in case study sites, estimates of equilibrium levels were derived from literature. For instance, Poeplau and Don (2013) reported changes in soil carbon under different types of land-use in Europe.

For green manure applications, the indicator accounted for the addition of soil organic matter by the crop residues. We compared a situation where (i) the focal field was left fallow in between crops, and (ii) a cover crop was grown in between crops. The SOM added by the green manure crop was calculated for individual case study areas using the NDICEA model (van der Burgt et al., 2006). Using input data on soil texture, climatic data on temperature and rainfall, fertilizer/organic manure application, cropping sequence, and atmospheric deposition of NPK, the model was used to calculate organic matter content dynamics over the course of a cropping system. The final level of SOM was then compared to SOM at the end of the same crop sequence that now included a maximum number of times green manures. The contribution of green manure to carbon sequestration was then defined as the change in carbon sequestration when current typical cropping systems would be replaced by

cropping systems that included green manures at landscape scale. Datasets used for this analysis included values of measured values of SOM from SNH and focal fields. The total effect of establishment or removal of SNH and application of green manure at the landscape level was obtained by area-weighted summation of changes in soil organic carbon across polygons (in terms of tone of carbon per hectare (ton C/ha)).

2.2.4. Landscape aesthetics

Indicators for landscape aesthetics were formulated based on generalized geographic attributes for landscape aesthetics in the Netherlands (De Vries et al. 2007; Lankhorst et al. 2011). Based on this conceptual framework, three ‘positive’ and two ‘negative’ geographic information systems (GIS)-based factors affecting landscape aesthetics were defined. The three positive attributes were naturalness (distance from natural elements such as forest, water, ditches), historical distinctiveness (unique local heritages), and relief (elevation). The two negative attributes were urbanity (distance from urban areas: the closer to urban areas the less attractive) and skyline disturbance (visibility distance). The landscape aesthetics indicator was calculated by summation of values of all the ‘negative’ factors (urbanity and skyline disturbance) subtracted from the sum of values of all the ‘positive’ (naturalness, relief and historical distinctiveness) factors given by equation (4):

$$A = \sum_{i=1}^j \left(\sum_{i=1}^m (F_p) - \sum_{i=1}^k (F_q) \right) \quad (4)$$

where A is the landscape attractiveness (unit less); j is the number of landscape elements/polygons, m is number of ‘positive’ factors, k is number of ‘negative’ factors, F_p = ‘positive’ factors, F_q = ‘negative’ factors. Data were gathered from case studies and global GIS based data sources¹.

2.2.5 Biocontrol

Semi-natural habitats often provide floral resources for natural enemies that can suppress pest populations in crops. Therefore, we assumed that SNH are source habitats for natural enemies, and the crop area within the foraging distance of natural enemies from SNH can count on biocontrol services. For this study we assumed that the foraging distance of natural enemies was 150 m, a value that may be considered high for carabids (e.g. Allema et al., 2015) and low for spiders (e.g. Schmidt et al., 2008). The potential natural pest control of a target field in a landscape is thus given by the ratio of area in the influence zone of SNH (150 m here) and the total area of the field (equation 5):

$$B = \frac{\sum_{i=1}^m \sum_{j=1}^n (P_{ij})}{A_i} \quad (5)$$

¹ <https://earthengine.google.com/>

where B is the biocontrol potential; i is the target polygon ID, m is the total number of polygons; j is the neighbouring SNH polygon of the target polygon; n is the number of neighbouring SNH polygons; and P_{ij} is the target polygon i with neighbouring SNH polygon j .

Biocontrol values of polygons are scaled up to the landscape level by summing the biocontrol potential of all polygons with potential resource for biocontrol in the landscape. Inputs for modelling biocontrol included GIS maps of the SNHs and other land-uses in the study areas.

2.3 Landscape IMAGES

Trade-offs and synergies between various ES indicators were analyzed using evolutionary algorithms implemented in the Landscape IMAGES (LI) modeling framework (Groot et al., 2007). The framework consists of two main parts (i) the system domain which constitutes the generic framework that incorporates database, GIS libraries, and an optimization algorithm, and (ii) the application domain that is designed to enable implementation of modelling routines and decision rules to address landscape optimization objectives (Fig. 5). Each structural element in an agricultural landscape (fields, borders, roads, rivers, semi-natural habitats, etc.) is represented by a GIS polygon, line or point element. Characteristic data about each shape file element is loaded as an internal attribute table of the shape file. Data about alternative properties (e.g. vegetation type, land-use) and management of the landscape elements are stored in MS-Access/SQLite database tables.

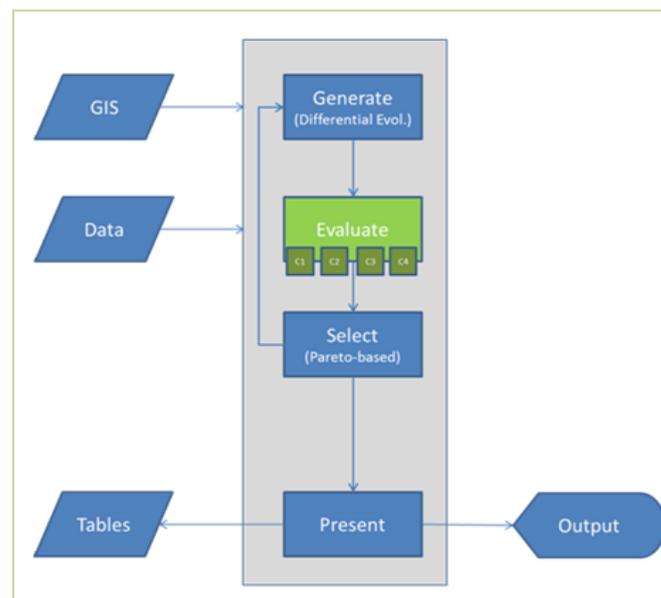


Fig. 5. Schematic representation of the Landscape IMAGES framework. 'GIS' represents one or more shape files containing layers with landscape elements and 'Data' represents MS-Access/SQLite database tables storing properties of landscape elements. 'Generate', 'Evaluate' and 'Select' represent procedures in the heuristic generation of landscape designs, computation/evaluation and ranking of potential solutions, respectively. 'Present' represents the visualization of solutions using the Pareto-ranking method. The layout of resulting landscapes can be saved as database tables ('Tables') or shown in the graphical user interface ('Output'). The 'Evaluate' procedure comprises a flexible collection of components relevant to the application domain, here indicated as C1-C4, which quantify indicators of ecosystem service performance.

We used Landscape IMAGES to (i) generate a wide diversity of landscape arrangements by randomly allocating land use types (including SNH and with their associated ES) to polygons, (ii) calculate the ES provision level for the five ESs for each landscape, (iii) plot the landscape performances in multidimensional space, and (iv) identify landscapes with various favorable performances using a Pareto-ranking method. The outputs of Landscape IMAGES include spatial heat maps for ES for individual ES, and bi-plots of ESs that indicate trade-offs or synergies.

Pareto-optimality represents a powerful criterion to combine objectives without a priori weighing. The Pareto-optimal solution set is a collection of alternatives that cannot be improved for one of the objectives without compromising any of the other objectives involved (Fig. 6a). Put differently, the alternatives in the Pareto-optimal set are not ‘dominated’ by solutions that perform better for all the objectives (Fig. 6b). In a set of alternatives comprising both optimal and non-optimal solutions, the dominance concept can be used to rank the alternatives in terms of Pareto-optimality in different ways (Coello Coello, Lamont, & Van Veldhuizen 2007). For example, after removal of the non-dominated alternatives (rank 1) from the set, a new collection of non-dominated alternatives can be identified that will receive rank 2 (Fig. 6b). This can be repeated until all alternatives have been ranked (Goldberg 1989). In this way, the initial n-dimensional optimization problem is reduced to a one-dimensional problem without a priori weighing.

At the operational level, the ES indicators were first implemented in the Landscape IMAGES framework for trade-off/synergy analysis. Then, landscape objectives were specified for each ES indicator and alternative landscape configurations were explored (simulated) for 1000 time-steps. The genetic algorithm (optimizer) generated multiple landscape configurations, each represented by a dot. Each polygon (SNH or field) was assessed for its capacity to provide ES. The cumulative landscape ES value for each indicator and landscape configuration was then compared with indicator values from other landscape configurations. For this study the objective was to maximize aesthetic value, conservation value, and soil organic matter and biocontrol ecosystem services and to minimize erosion (thus maximize erosion prevention ES). Trade-offs arise when a particular ES cannot attain more desirable values without compromising other ESs. Synergy between ESs occurs when two or more ESs achieve more desirable values simultaneously.

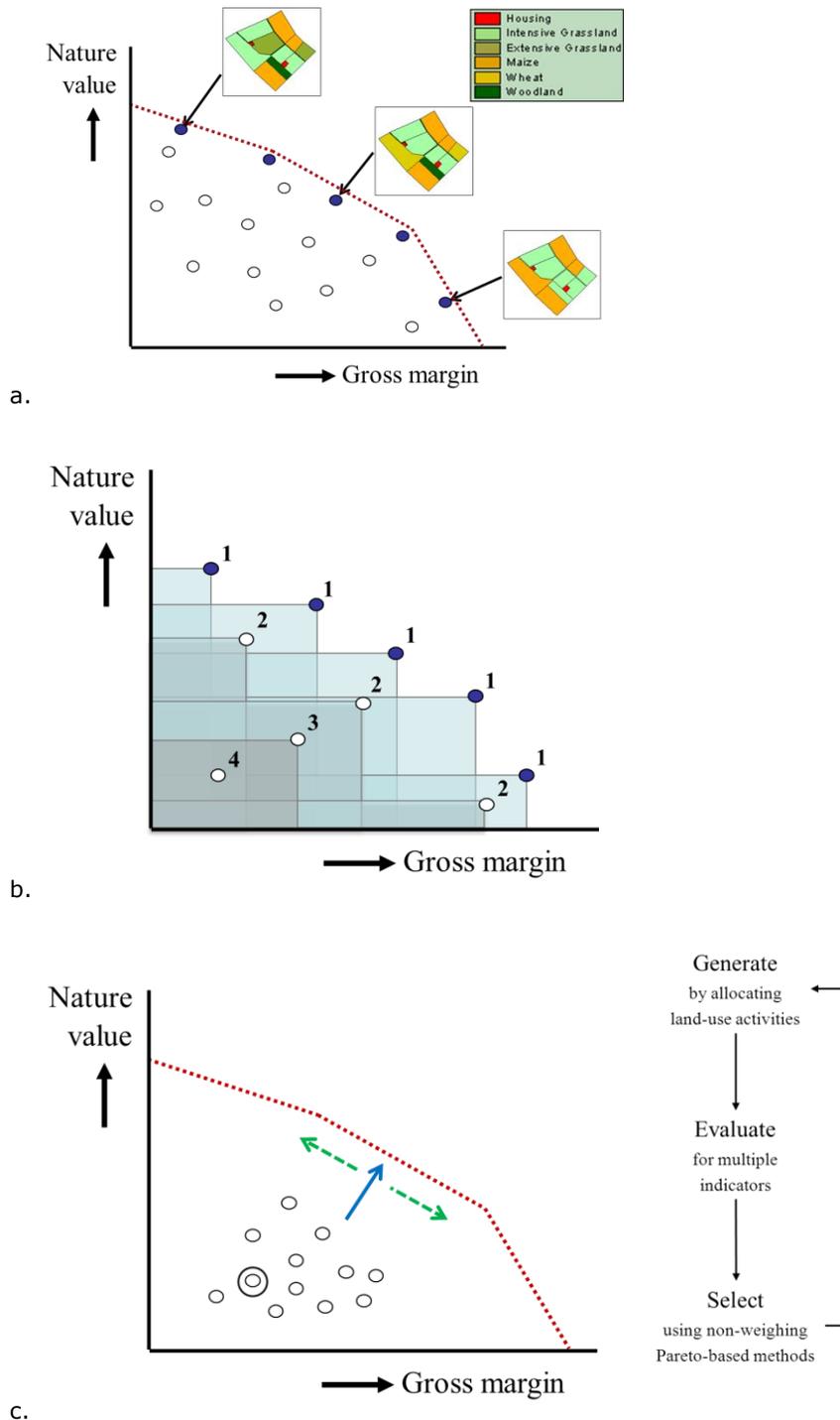


Fig. 6. (a) Stylized illustration of a trade-off between farm gross margin and nature value in an agroecosystem, and associated landscape maps for three alternatives. The closed symbols represent landscape alternatives belonging to the Pareto-optimal set (i.e. having rank 1). The ranking scheme is demonstrated in (b), where the shaded areas indicate the region of the solution space that is dominated by the solution located at the top-right corner: the solution outperforms all other solutions within the shaded area for each objective (for further explanation see text). (c) Conceptual outline of the optimization process employing the iterative steps of generating, evaluating and selecting (right side) and in the graph the pressures exerted by the optimization algorithm through Pareto ranking (solid arrow, blue) and the search for less crowded areas (dashed arrows, green) are indicated. The encircled solution may represent the original situation. The dotted line in (a) and (c) indicates the Pareto frontier, which is approached by the evolutionary optimization algorithm (Source: Groot and Rossing, 2011).

3. Results and discussion

3.1 Visualization using heat maps

The spatial distributions of landscape aesthetic value, soil organic matter, and soil erosion for the current landscape configurations in the landscape sectors in Germany and Hungary are shown in Fig. 7. These heat maps indicate that ES provision levels can differ markedly between and within landscapes.

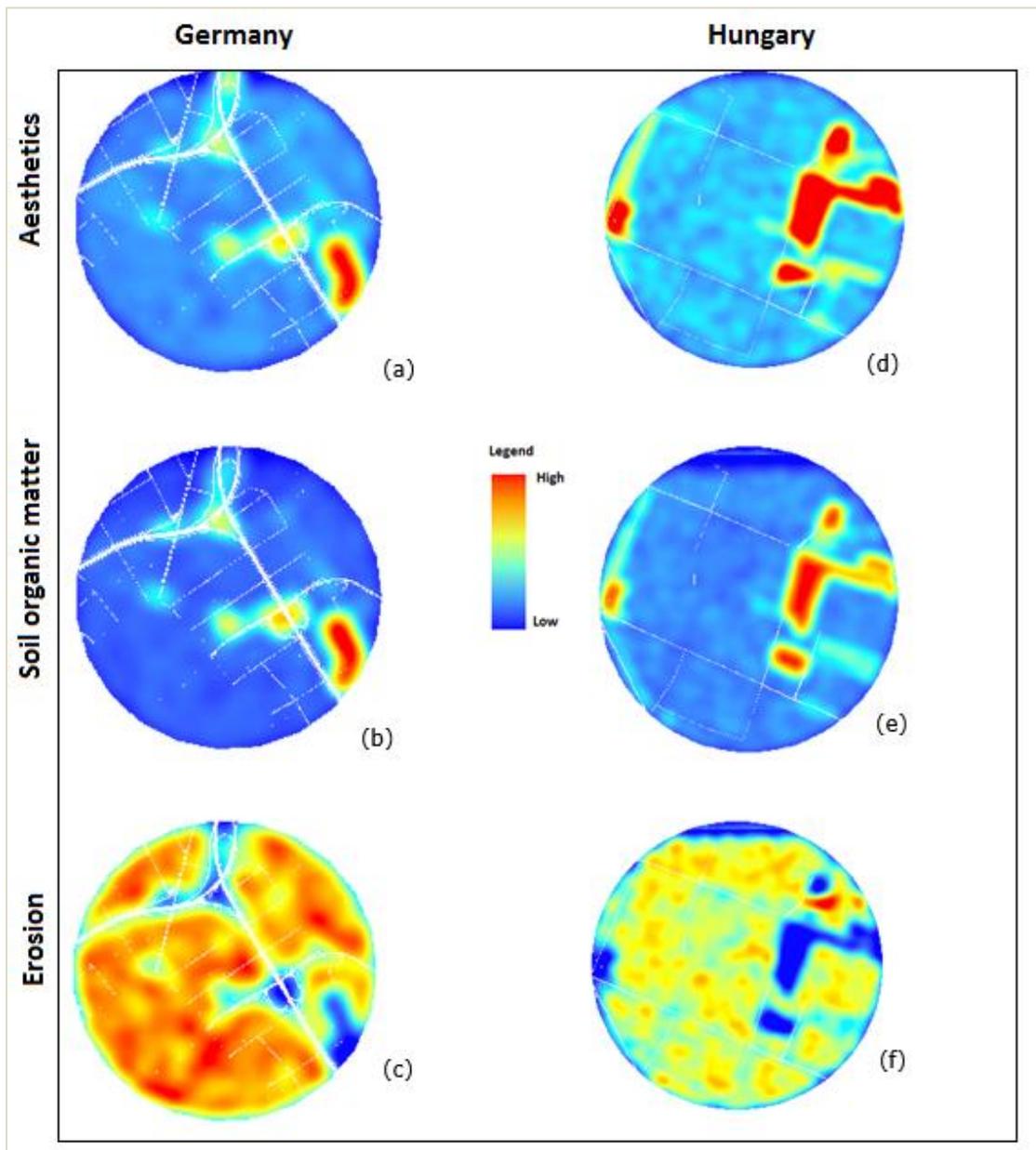


Fig. 7. Heatmap visualization of the spatial distribution of various ES indicators in the current landscape configurations of Germany (left) and Hungary (right). The scale ranges from low indicator values (blue) through green, yellow and orange to red (high indicator values). The ES indicators include aesthetic value (a and d), soil organic matter (b and e) and soil erosion (c and f). Urban areas and road networks are discarded from the analysis (white areas). Also note that soil erosion risk, and not soil erosion prevention ES, is mapped in c and d (high soil erosion risk implies low soil erosion prevention ES).

In the Germany landscape sector the landscape aesthetic value is generally low, except for areas with SNH that have a high aesthetic value (Fig. 7a). The same pattern is observed for soil organic matter with low organic matter levels in arable fields and high organic matter levels in SNH (Fig. 7b). Soil erosion shows a contrasting trend with high risk of soil erosion in arable fields and low risk in SNH (Fig. 7c). These results indicate that (i) SNH plays a crucial role in supporting these ES, and (ii) that a synergy arises between aesthetic value, soil organic matter and prevention of soil erosion. Hence, increasing the proportion of SNH would improve the aesthetic value of the landscape, increase the soil organic matter at the landscape scale, and reduce the risk of soil erosion.

The landscape aesthetic value and soil organic matter in the Hungarian landscape sector was slightly higher than in the German landscape sector (Fig. 7d and 7e). Furthermore, the risk of soil erosion was lower in the Hungarian than in the German landscape sector (Fig. 7f). This can be explained by smaller slopes and shorter slope lengths. The analysis of the Hungarian landscape sector confirms the positive contribution of SNH to landscape aesthetics, soil organic matter and erosion risk mitigation, and highlights the synergy between these ES.

3.2 ES analysis

Analysis of interactions between the various ESs revealed different patterns (Fig. 8). For the German landscape sector, a trade-off occurred between aesthetic and conservation value (Fig. 8a), whereas synergies were observed between aesthetic value and soil organic matter (Fig. 8b), aesthetic value and erosion prevention (Fig. 8c), and biocontrol and soil organic matter ESs (Fig. 8d).

The analysis shows that there are many alternative landscape configurations possible that have higher aesthetic values, conservation values, soil organic matter and biocontrol than the current landscape configuration (Fig. 8a, b, c and d). However, increasing aesthetic and conservation value simultaneously, for example, is only possible until a certain point. Once the Pareto optimal front is reached (upper right points), increasing one ES is only possible when reducing the other. In contrast, for synergistic relationships, increasing one ES can go hand in hand with increasing the other (Fig. 8b and 8d). The underlying reason for this synergy is the positive association of biocontrol and soil organic matter with SNH.

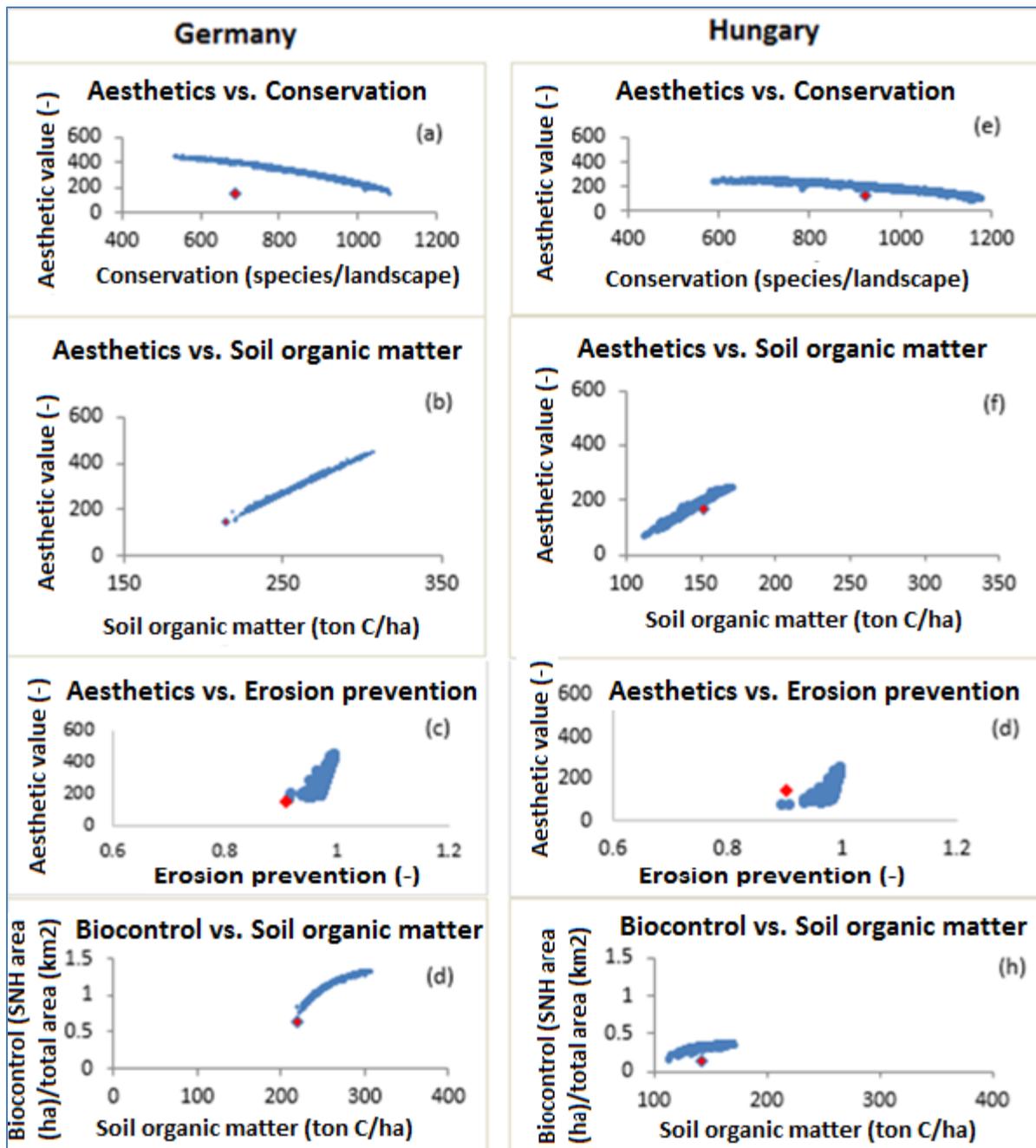


Fig. 8. Relationships between ES for a wide variety of landscape configuration based on the German (left) and the Hungarian landscape sectors (right panel). The red dot shows the ES level of the current landscape configuration, while blue dots show ES levels for alternative landscape configurations.

Analysis of the Hungarian landscape sector reveals similar patterns as the German sector (Fig. 8, e, f, g and h). That is, aesthetic value shows a trade-off with conservation value (Fig. 8e) but a synergistic relationship with erosion prevention (8g) and soil organic matter (Fig. 8f). Biocontrol and soil organic matter show a synergistic relationship (Fig. 8h).

Although the directions of the relationship between the various ES in the two landscape sectors are similar, there are also notable differences. For example, the position of the current landscape configuration (represented by the 'red diamonds' in Fig. 8) and the shape of the data clouds are

different in the German and Hungarian sector. In general, the current configuration of the Hungarian landscape sector seems to be more favourable for supporting multiple ES than the current German landscape sector.

The analysis allows the evaluation of the spatial distribution of multiple ES in agricultural landscapes and the identification of landscape configurations that support multiple ES. While our approach to modeling ES in two landscape sectors in different case study areas was successful, the potential for upscaling to the regional, national and EU level will be limited due to data availability constraints. For instance, because the QuESSA project had a strong focus on biocontrol and pollination, data availability of the ‘other’ ES from the case studies was limited. Bringing together data on agricultural attributes of the different polygons would have enabled elucidation of production and productivity-related trade-offs with the currently used indicators. Such analyses are urgent, but require analyses beyond those possible in biocontrol and pollination dominated research. The analysis nevertheless showed that landscape-level analyses of multiple ES indicators simultaneously result in trade-off and synergy patterns that differ considerably between landscapes. Moreover, it showed in addition to ‘hotspots’ and ‘coldspots’ for ES, current landscapes can have different development potential, in terms of their distance to trade-off frontiers. Such insights enable landscape-level discussions among stakeholders about how to benefit from options to enhance ES provisioning by changing land use.

4. Conclusion

In this study, we developed a novel approach for quantification and evaluation of ecosystem services in a spatially explicit manner. Our main findings are that (i) SNH plays a crucial role in supporting aesthetic value, carbon sequestration (in terms of soil organic matter) and prevention of soil erosion, and (ii) that synergies arise between these ES. These findings held for both the German and Hungarian landscape sectors that differed in composition and spatial configuration of landscape elements. While there was a high potential for increasing ES in the German landscape sector, the ES provision levels in the Hungarian landscape in some cases approached the calculated maximum levels.

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