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Research Article

As green infrastructure, linear semi-natural habitats boost regulating ecosystem services supply in agriculturally-dominated landscapes

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Abstract

Semi-natural linear landscape elements, such as hedgerows, are vital structures within agricultural landscapes that have an impact on ecosystem processes and support biodiversity. However, they are typically omitted from green infrastructure planning, which could lead to significant undervaluing of landscapes and their multifunctionality in terms of ecosystem service supply. Using the InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) model suite, we tested the effects of additionally including semi-natural linear landscape elements on the model outcomes for crop pollination, nutrient regulation, erosion regulation and water flow regulation ecosystem services supply. The results showed that linear semi-natural landscape elements contribute positively to the landscape's multifunctionality. Small changes have been identified for water flow regulation, whereas, considering both spatial extent and magnitude of the changes, the greatest changes have been found with respect to the supply of pollination and nutrient regulation. Direct proximity of the linear elements had the greatest effect on ecosystem service supply, in particular with regard to pollination. Based on our results, a more pronounced consideration of semi-natural linear landscape elements as an important element of green infrastructure is advisable.

Keywords

hedgerow, ecosystem service model, InVEST, scenarios, agroecosystems, GI

Introduction

Agricultural landscapes are dominated by cultivated areas that are typically interspersed with resource-rich, semi-natural elements, such as fallow fields, field margins, hedgerows or woodlands (Bennett et al. 2006). As intensification has increased through the second half of the 20th century in many parts of the world, agricultural landscapes have often been associated with drastic structural changes and declining biodiversity (Robinson and Sutherland 2002). Supporting biodiversity within agricultural landscapes, however, is key for the long-term supply of multiple ecosystems services and, thus, for sustainable agriculture (Bommarco et al. 2013). As such, there is a necessity to restore biodiversity and ecosystem processes across landscapes in order to harness the multiple societal, environmental and economic benefits ecosystem services provide (Bommarco et al. 2013). One such way is the development and restoration of so-called Green Infrastructure (GI), which is now highlighted in European planning and decision-making and has become a key focus in reaching EU environmental policy goals (European Commission 2013a, European Environment Agency 2017). Green Infrastructure is the interconnected network of natural and semi-natural elements which intersperse the wider landscape, as well as man-made connecting elements, such as ecoducts (Naumann et al. 2011, European Commission 2013a, CEEweb for Biodiversity 2017, EEA 2017). As a strategically planned network of high quality natural and semi-natural areas, it is designed and managed to supply a broad set of ecosystem service bundles and to protect biodiversity (European Commission 2013b). Removal of pollutants from air and water, pollination enhancement, protection against soil erosion and rainwater retention can be found amongst the environmental benefits to be provided by GI (European Commission 2013b, BfN 2017). As part of GI, the integration of green corridors and buffer zones facilitates species movement, allowing for the establishment of resilient ecological networks even in fragmented environments (Cannas et al. 2018, Molné et al. 2023).

At a national scale, smaller scale Linear Semi-natural landscape Elements (LSE), such as hedgerows, rows of trees, field copses and riparian vegetation, are not typically included in the official national GI network (BfN 2017). It has been well documented, however, that such LSE increase the heterogeneity and structural diversity of the landscape, are associated with high internal diversity of both flora and fauna and enhance connectivity of otherwise isolated patches (LLUR 2008, Ponisio et al. 2015, BfN 2019), thereby being aligned with the EU GI aims and objectives outlined above (European Commission 2013b). Bartesaghi Koc et al. (2016) have advocated the need to create a typology that accommodates diverse contexts, locations and research objectives, embracing a multi-scale and multi-purpose approach enabling the consideration of smaller scale elements into GI.

LSE have been described as resembling two forest edges standing back to back, characterised by forest species boarded by ecotones on either side (LLUR 2008). The value of these elements can be related to availability of resources at their boundaries such as berries and flowers, as well as internal characteristics such as structural complexity, height, width and woody biomass (Graham et al. 2018). As such, they have the potential to support a rich fauna of invertebrates, birds, mammals and reptiles, which supply not only services to agriculture, but also cultural services to society (Burel 1996, Fuller et al. 2001, Gelling et al. 2007, LLUR 2008, Perennes et al. 2020). Nectar and nesting sites can support pollinators, while shelter, refuge and alternative prey/hosts can support biological control agents and facilitate the supply of their services to the agricultural crops (Jobin et al. 2001, Krewenka et al. 2011).

In adjacent fields, the presence of LSE can alter microclimate characteristics (Forman and Baudry 1984, LLUR 2008, BfN 2019), which may impact agricultural crop production (Cleugh 1998). LSE have been proven to reduce wind speed and evaporation, which increases both soil and atmospheric moisture, as well as day temperatures, whilst decreasing night temperatures (Forman and Baudry 1984, BfN 2019). These microclimate effects directly help to mitigate soil desiccation, soil erosion and nutrient runoff (Forman and Baudry 1984, Bird et al. 1992, Röser 1995, Burel 1996, BfN 2019). In this context, also the landscape elements' spatial distribution with respect to the topography, especially the slope inclination, are of particular relevance (Forman and Baudry 1984). When LSE such as hedgerows are planted perpendicular to a sloped inclination, they have the potential to decrease the effective length*[1] of the sloped area with regard to erosion. As combination of the described effects of the linear semi-natural landscape elements, the area's water flow is adapted while the potentials for erosion and nutrient runoff are decreased (Müller 1990, Deutscher Verband für Landschaftspflege e.V. 2006, Schindewolf 2012). Thus, soil degradation is prevented or at least decreased which, in turn, positively affects the agricultural field's soil fertility.

The above-described biotic and abiotic characteristics of LSE, therefore, have the potential to significantly impact the supply of ecosystem services such as pollination, nutrient regulation, water flow regulation and erosion regulation (Klein et al. 2006, Zhang et al. 2007, Power 2010, Wiggering et al. 2016, see Table 1). The functioning of such regulating services is fundamental within the agro-environment if cropping systems are to be maximised whilst simultaneously decreasing inputs, such as plant protection products and fertilisers and supporting biodiversity (Power 2010, Wiggering et al. 2016, Bergez et al. 2022, Müller and Lange 2022). All four of these ecosystem services and the functions that are the base behind their supply are strongly impacted by too intensive agricultural production.

Conventional agricultural practices lead to altered nutrient cycles, with nutrient in- and outputs being out of balance (Vitousek et al. 1997, Chapin et al. 2011). Consequently, these areas evolve to be featured by either nutrient deficiency or surplus. The capacity of nutrient-deficient ecosystems to grow crops diminishes with time. High nutrient surpluses, on the other hand, lead to nutrient losses from the agricultural areas threatening the environment, for example, through the enrichment of nutrients in ground- and surface water (Welte and Timmermann 1985, Sutton et al. 2013, Dominati 2013, Jónsson and Davíðsdóttir 2016, Jónsson et al. 2017). Besides, the temporary character of the agricultural plant cover and conventional tilling practices increase soil erosion and surface runoff, thus affecting the ecosystem services water flow regulation and erosion regulation. Erosion degrades soil quality and thereby reduces the fundamental natural base for agricultural production (Steinhoff-Knopp and Burkhard 2018, Rendon et al. 2022). Increased surface runoff leads to reduced groundwater recharge and increases the risk for flooding (Müller et al. 2020, FAO 2023). The spatial and temporal homogenisation of modern agricultural landscapes is accompanied by the loss of diverse resources such as food, nesting or overwintering habitats and has negative impacts on biodiversity and, thereby, the occurrence and activity of pollinators and related pollination ecosystem services. Further negative impacts arise from the application of pesticides. To counteract these effects, agricultural practices need to be adapted and land management measures need to be taken aiming to increase the supply of the ecosystem services that were considered in this study (Table 1).

Table 1.

Definition of the considered ecosystem services.

Pollination	Pollination relates to the transfer of pollen between flower parts and even more between flowers (Zulian et al. 2014, Müller et al. 2020). In this context, pollination by animals, in particular insects, plays a fundamental role (Gallai et al. 2009, Zulian et al. 2014, Müller et al. 2020). According to Williams (1994), more than 80% of the crop species cultivated in Europe rely on pollination by insects. Klein et al. (2006) discovered that, globally, around 75% of all crop species that are significant for the production of food are dependent on pollination by animals.
Nutrient regulation	Nutrient regulation has been described as the ability and magnitude of an ecosystem to recycle nutrients (Burkhard et al. 2014, Bicking et al. 2020). It is referred to as the capacity of an ecosystem to filter, absorb, recycle and retain nutrients (Dominati 2013, Jónsson and Davíðsdóttir 2016, Jónsson et al. 2017, Müller et al. 2020). In that sense, the ecosystem service supports a functioning and sustainable cycling of nutrients (Tivy 1987).
Water-flow regulation	Water-flow regulation is a very important regulating ecosystem service that is influenced by landscape configuration and the corresponding land-cover structure (FAO 2023). Water-flow regulation refers to water flow in general, as well as groundwater recharge (Müller et al. 2020). In that sense, water storage and buffer, natural drainage and irrigation are highly relevant aspects.
Erosion regulation	The ecosystem service erosion regulation refers to reduced soil loss from the ecosystem (Steinhoff-Knopp and Burkhard 2018, Haines-Young and Potschin 2018). Müller et al. (2020) define erosion regulation as soil retention and the capacity to prevent and mitigate soil erosion and landslides. Thus, in that sense, the ecosystem service refers to the mitigated structural impact (Fu et al. 2011, Guerra et al. 2014, Steinhoff-Knopp and Burkhard 2018), the erosion that would potentially occur given the absence of vegetation. In particular, site-specific characteristics such as topography, rainfall erosivity and soil erodibility influence potential soil loss (Fu et al. 2011, Guerra et al. 2014, Steinhoff-Knopp and Burkhard 2018).

In order to optimise the supply of these four regulating ecosystem services, evidence-based approaches are required to inform landscape management and to optimise the implementation of GI measures. Here, we assessed the relevance of LSE as a potentially integral and previously overlooked, part of GI. The objective of the study was to assess the influence of LSE on the simultaneous supply of four ecosystem services in an agriculturally-dominated landscape. More precisely, by applying the InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) model suite, we tested the changes in ecosystem service supply when semi-natural linear landscape elements were included in the landscape assessment. We hypothesised that, based upon our InVEST model test:

1. including or excluding linear semi-natural landscape elements changes the landscape's modelled ecosystem service supply and that
2. the extent of these changes depends on the particular ecosystem service considered.

In the following Section (Materials and methods), the study area, as well as the modelling and analysis approach of the four ecosystem services, are briefly outlined. In the subsequent Sections, the results are presented and discussed, respectively. Eventually, the Conclusions are drawn concerning the hypotheses outlined above.

Materials and methods

Study area

The study area, the Bornhöved Lakes District, is located in the federal state of Schleswig-Holstein in northern Germany, approximately 30 km south of the City of Kiel. With a spatial extent of around 147 km², it includes the municipalities of Belau, Bornhöved, Gönnebek, Kalübbe, Rendwühren, Ruhwinkel, Schmalensee, Stolpe, Tarbek, Trappenkamp and Wankendorf. The local climate is maritime and humid, with an annual precipitation of approximately 823 mm and an approximate mean temperature of 8.9°C (Deutscher Wetterdienst 2017). The landscape of the federal state of Schleswig-Holstein is strongly influenced by the Pleistocene and, in particular, the Saalian and the Weichselian glaciation periods (Schott 1956). The landscape can be divided into three main regions: Marsch, Geest and Hügelland (Stewig 1982, Bähr and Kortum 1987). The latter two are found in the study area (Fig. 1), with the northern part of the study area belonging to the Hügelland (engl.: Uplands) and the central and southern parts belonging to the Geest. The study area includes six glacially-formed lakes, which are surrounded by forests embedded in an agriculturally-dominated area. The northern parts of the study area, as well as the area in proximity of the lakes, are featured by a more hilly relief compared to the surrounding, flatter landscape (see Suppl. material 2). The abundance of linear semi-natural landscape elements (LSE) increases from the northwest to the southeast of the study area (Fig. 1). The study area was selected as the Bornhöved Lakes District as it is considered as a representative landscape for northern Germany (Fränzle et al. 2008, Fohrer and Schmalz 2012), with extended networks of LSE. Furthermore, this area has been included as a case study site in the BiodivERsA project IMAGINE and has a long history of ecosystem research (Müller et al. 2006, Fränzle et al. 2008, Kandziora et al. 2013, Bicking et al. 2018, Perennes et al. 2020, Perennes et al. 2021). The study area belongs to four different watersheds, which correspond to the rivers Schwentine (with 63%), Eider (with 3.7%), Trave (with 4.2%) and Elbe (with 28.6%).

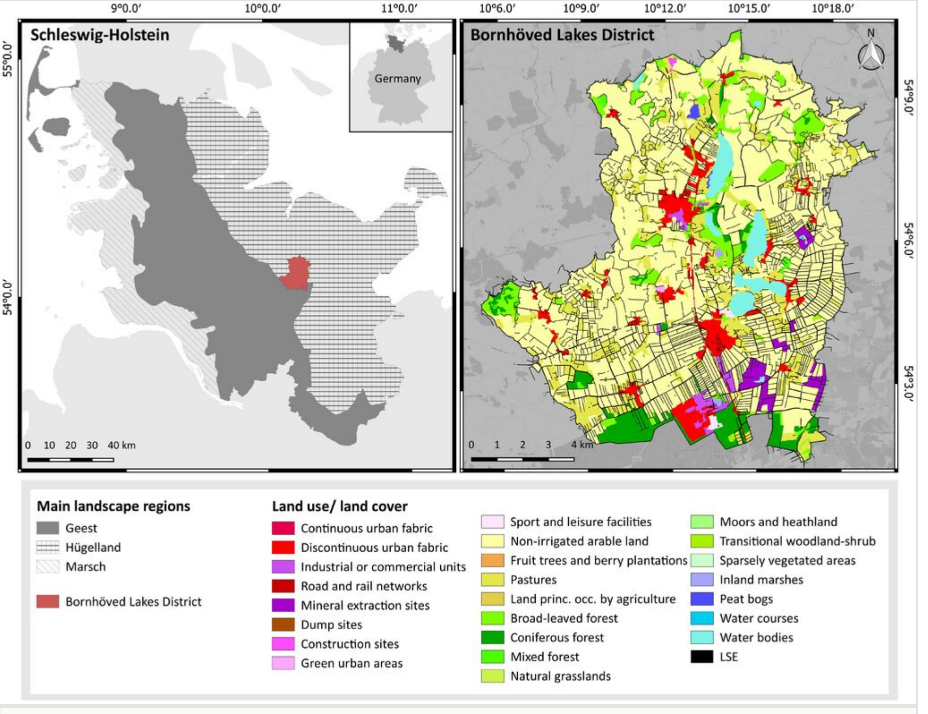

Figure 1.

Location and extent of the Bornhöved Lakes District with land-use/land-cover types (LLUR 2019, Natural Earth 2020, OpenStreetMap contributors 2020).

Ecosystem services modelling

The four ecosystem services were modelled with the open-source software InVEST (Integrated Valuation of Ecosystem Services and Trade-offs) geospatial model suite (version 3.12.0). The various InVEST models can be used to map and quantify individual ecosystem services and, thereby, identify the direction and magnitude of change in ecosystem service supply (Sharp et al. 2020) caused by ecosystem alterations, such as the inclusion of LSE. For each of the four ecosystem services:

- pollination services,
- nutrient regulation,
- water flow regulation and
- erosion regulation (for definitions, see Table 1),

the corresponding InVEST models were selected:

- ‘Pollinator Abundance: Crop Pollination’ (CP);
- ‘Nutrient Delivery Ratio’ (NDR);
- ‘Seasonal Water Yield’ (SWY); and
- ‘Sediment Delivery Ratio’ (SDR).

Each InVEST model requires spatial input data which were generated using the open-source software QGIS 3.6.3. Two landscape scenarios were simulated: A) landscapes without LSE (herein, scenario A) and B) the actual landscapes with LSE (herein, scenario B). The 2018 CORINE Land-Cover dataset (GeoBasis-DE / BKG 2020) was used as baseline input data for both scenarios. Additionally, the VEG04-Vegetationsmerkmal (GeoBasis-DE / BKG 2020) dataset, which comprises, inter alia, officially mapped LSE, such as hedgerows, wooded strips, isolated trees, trees in line and groups and field copses, was then overlaid to map landscapes with LSE. For means of simplification, within the study, no differentiation has been made into different LSE element types, such as hedgerows, wooded strips, isolated trees or field copses. Furthermore, due to limited data availability, non-irrigated arable lands have not been differentiated into specific crop types. Mapped LSE covered approximately 5% of the total study region. Whereas, in the landscape of scenario A, these 5% were predominantly allocated to the ‘non-irrigated arable land’ (68%) and ‘pastures’ (19%) Land-Use/Land-Cover (LULC) types from the CORINE classifications (GeoBasis-DE / BKG 2020) (Fig. 2).

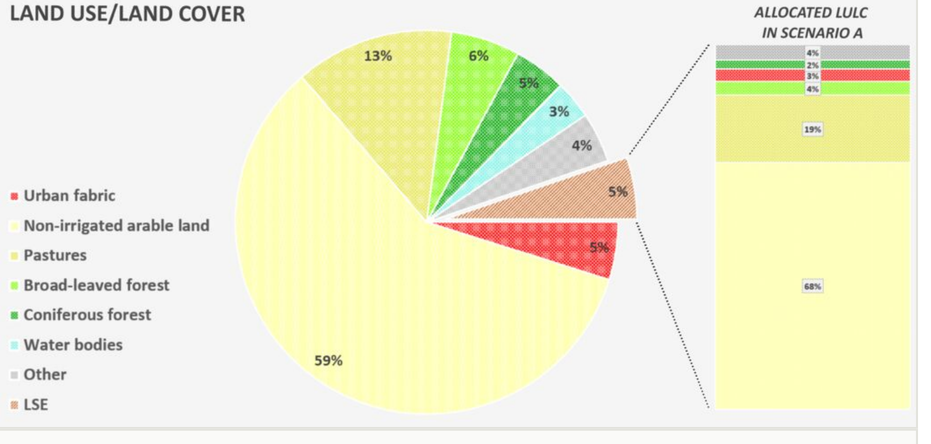

Figure 2.

Distribution of Land-Use/Land-Cover (LULC) classes in the study area in scenario B (pie) and scenario A (pie + bar), i.e. the bar plot presents the allocation of LULC classes in the model runs excluding LSE in the 5% of the area that is covered with LSE in the model runs including LSE (GeoBasis-DE / BKG 2020).

In addition to the LULC data, the ecosystem service-specific InVEST models require so-called “biophysical tables” as input datasets (Table 2). The biophysical tables follow the same general structure for each service-specific InVEST model, but comprise different information, adjusted according to the respective model. In each of these tables, for each LULC class, model-specific information is recorded, based upon field surveys, literature and expert assessments (Table 2). For example, for the pollinator abundance model, the availability of nesting sites and the availability of floral resources were defined for each LULC class. Besides, each service-specific InVEST model requires specific input data, details of which can be found in Table 2. For each ecosystem service, the models were simulated for the two scenarios.

Table 2.

Input datasets and constant values (including sources) used per InVEST model: 'Pollinator Abundance: Crop Pollination' (CP); 'Nutrient Delivery Ratio' (NDR); 'Seasonal Water Yield' (SWY); and 'Sediment Delivery Ratio' (SDR).

Required data	**Data-sets and sources**	**InVEST model**
Land-use/land-cover (Scenario A and B, respectively)	Corine Land Cover (CLC_5) 2018 (GeoBasis-DE / BKG 2020), 1:100,000, minimum mapping unit: 5 ha)	SWY, CP, NDR & SDR
	Corine Land Cover (CLC_5) 2018 (GeoBasis-DE / BKG 2020), 1:100,000, minimum mapping unit: 5 ha) and VEG04-Vegetationsmerkmal (DWD Climate Data Center (CDC) 2022a, 1:25,000, minimum mapping unit: 1 ha)	
Biophysical table (CP)	nesting_availability_index, floral_resources_index based upon Koh et al. (2015), Groff et al. (2016), Jähne (2016), Fernandes et al. (2020), Wentling et al. (2021)	CP
Guild table	species, nesting_suitability_index, foarging_activity_index, alpha (average travel distance) and relative abundance based upon Gebhardt and Röhr (1987), Wesserling (1996), Gathmann and Tscharntke (2002), Knight et al. (2005), Hagen et al. (2011), Jähne (2016)	CP
Precipitation (monthly)	grids_germany_multi_annual_precipitation_1991-2020 (DWD Climate Data Center (CDC) 2022b), resolution: 1 km)	SWY
Evapotranspiration (monthly)	grids_germany_multi_annual_evapo_r_1991-2020 (DWD Climate Data Center (CDC) 2022a), resolution: 1 km)	SWY
DEM	European Digital Elevation Model (EU-DEM), version 1.1 (EEA 2016, resolution: 25 m)	SWY, NDR & SDR
Soil group	HYSOGs250m (Ross et al. 2018b, resolution: 250 m)	SWY
Watershed	European river catchments (EEA 2008)	SWY, NDR & SDR

Required data	Data-sets and sources	InVEST model
Biophysical table (SWY)	Integer curve number (CN) values for each combination of soil type and LULC (NRCS-USDA 2007, Ostrowski et al. 2014, NRCS-USDA 2017, Jaafar et al. 2019, Sharp et al. 2020) and Floating point monthly crop/ vegetation coefficient (Kc) values for each LULC (Nistor et al. 2018)	SWY
Rain events table (monthly)	Proxy values for Kiel (https://de.climate-data.org/)	SWY
Threshold flow accumulation	1000 [calibration based upon a comparison between intermediate outcome stream and AX_Gewaesserachse from the DLM250 (GeoBasis-DE / BKG 2020)]	SWY, NDR & SDR
Proportion of upslope annual available local recharge available each month (alpha_M)	1/12 [InVEST default value]	SWY
Proportion of upgradient subsidy available for downgradient evapotranspiration (beta_i)	1 [InVEST default value]	SWY
Proportion of pixel local recharge available to downgradient pixels (gamma)	1 [InVEST default value]	SWY
Nutrient runoff proxy (Scenario A and B, respectively)	Quickflow index [Calculated using InVEST Seasonal Water Yield model run without LSE]	NDR
	Quickflow index [Calculated using InVEST Seasonal Water Yield model run with LSE]	
Biophysical table (NDR)	load_n as nitrogen surplus (Bicking et al. 2018), eff_N (maximum retention efficiency as nutrient regulation potential (Müller et al. 2020), crit_len_n (Griffin et al. 2020), proportion subsurface_n (default InVEST - 0)	NDR
Borselli k parameter (constant)	2 [InVEST default value]	NDR, SDR
Subsurface critical length (constant)	200 [InVEST default value]	NDR
Subsurface maximum retention efficiency (constant)	0.8 [InVEST default value]	NDR

Required data	Data-sets and sources	InVEST model
Rainfall erosivity index (R)	R_FAKTOR_RADKLIM_v.2017_002_postproc (Fischer et al. 2019), resolution: 1 km)	SDR
Soil erodibility (K)	Soil Erodibility (K- Factor) High Resolution dataset for Europe (Panagos et al. 2014, resolution: 500 m)	SDR
Biophysical table (SDR)	usle_c and usle_p values for each LULC (Panagos et al. 2015, Griffin et al. 2020)	SDR
Borselli IC_0 parameter, maximum slope length parameter (L) and maximum SDR value (SDR_{max})	0.5, 122, 0.8 [InVEST default values]	SDR

Each service-specific InVEST model produces a number of outputs in the form of raster layers (herein, service variables; Table 3, cell size: 625 m²), which were then handled in QGIS 3.6.3. InVEST model results are highly dependent on the selected input data, in terms of, for example, quality, spatial scale and resolution (Nelson et al. 2009, Benez-Secanho and Dwivedi 2019) and, furthermore, there is no readily available direct validation technique for most of the model outcomes (Benez-Secanho and Dwivedi 2019). To mitigate the reliance on absolute numerical model outcomes, for evaluation and visualisation of each ecosystem service, the output data were classified into five classes, ranging from very low to very high supply, which, for means of comparability, were distributed using quantile classification, based on the layer without LSE (herein, quantile supply classes). No data values were omitted from the classification and all subsequent evaluation steps. Data from the raster layers were consolidated in a point vector layer and extracted to .csv files for further analysis and visualisation. The changes in spatial distribution of ecosystem service supply across the landscape were visualised by mapping the quantile supply classes (very low to very high supply) for the two scenarios.

Table 3.

Overview of considered output data (service variables) from the InVEST modelling (Sharp et al. 2020).

Service variable	Description	InVEST model	Ecosystem service
Total pollinator abundance (herein: Pollinator abundance)	The pollinator abundance describes the activity of the pollinators in the study area. It is estimated, based upon the availability of floral resources and the species-specific estimated nesting potential of the landscape. The InVEST model estimates the pollinator abundance for each species. In this study, we only consider the total pollinator abundance across all species.	CP	Pollination

Service variable	Description	InVEST model	Ecosystem service
N total export (herein: Nutrient export)	The nutrient export (here nitrogen only) corresponds to the estimated quantity of the nutrients that eventually reach the stream. It is the sum of the surface and subsurface contributions.	NDR	Nutrient regulation
Baseflow	The baseflow corresponds to the local amount of precipitation that gradually enters the sub-surface flow.	SWY	Water flow regulation
Quickflow	The quickflow corresponds to the amount of precipitation that runs off of the land directly, mostly during or shortly after a precipitation event.	SWY	Water flow regulation
Avoided erosion	The avoided erosion presents the contribution of the vegetation to the reduction of erosion.	SDR	Erosion regulation

Ecosystem services analysis

The post-GIS assessment steps related to data processing, quality control, statistical analysis and presentation were performed in R (version R-4.0.4) , mainly using the packages dplyr, plotly and ggplot2. The summary statistics for all variables were calculated and, for each variable, in the context of data quality control, outliers outside of the range of three standard deviations were deleted. Then, the relative share of land area for each quantile supply class and each service variable was determined for our landscape without and with LSE.

Based upon the shifted distribution of the quantile supply classes and general summary statistics, the landscapes were compared for the supply patterns of each considered ecosystem service. The change in ecosystem service supply with LSE in the landscape was calculated for each variable at data points next to LSE (50 m), near to LSE (100 m) and for all data points in the study region.

Finally, to assess the multifunctionality of LSE on agricultural areas and, hence, the potential impact on agricultural production, the change in the mean value of each service variable across non-irrigated arable lands and pastures (agricultural areas) was plotted. To allow a more intuitive comparison with the other service variables, the inverse of the variables quickflow and nutrient export was calculated, i.e. “avoided quickflow” and “avoided nutrient export” (i.e. turning them from an ecosystem disservice into a service).

Results

The spatial distribution of the quantile supply classes differed the greatest between the landscapes of scenario A and B for the ecosystem services nutrient regulation and pollination, i.e. for the variables nutrient export and pollinator abundance (Fig. 3). Smaller changes were detected for the ecosystem service water flow regulation (baseflow and quickflow), while the spatial distribution of the erosion regulation variable showed little to no response to the inclusion of LSE (Fig. 3).

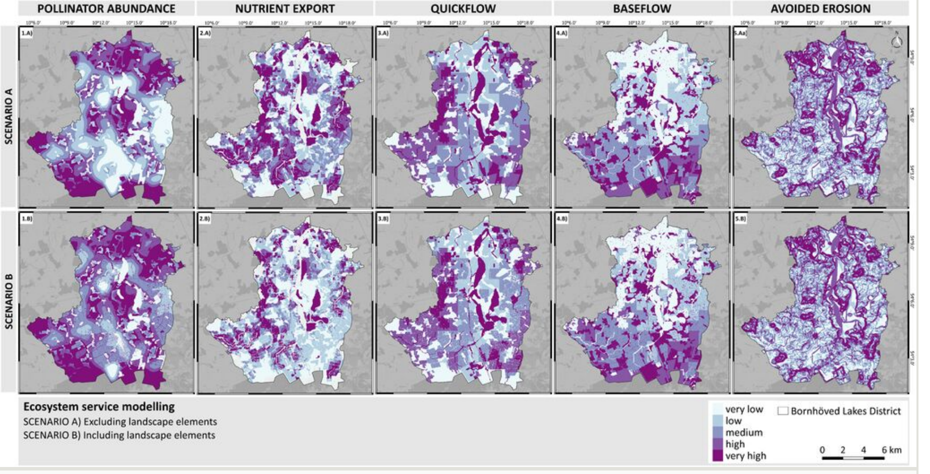

Figure 3.

Spatial distribution of the quantile supply classes for the service variables:

1. pollinator abundance;
2. nutrient export;
3. quickflow;
4. baseflow and
5. avoided erosion;

in scenarios A and B. For means of comparability, for each service variable, a quantile classification based upon the scenario A layer has been applied (background: OpenStreetMap contributors 2020).

Referring to pollination, large patches with very-low to low pollinator abundances were identified in the centre as well as along the southern and northern borders in landscapes under scenario A. Higher pollinator abundance values were, in particular found in and around the forested areas (see Fig. 1). Under scenario B, the pollinator abundance increased in these areas so that much of the same spatial extent supported medium to high abundances. These changes can be attributed to the approximate location of newly-included LSE, but moreover, increased abundances in the surrounding areas. The inclusion of LSE increased the mean pollinator abundance across the study region by 21.4% (see Suppl. material 1 for summary statistics). The relative area of very-high pollinator abundance increased from 20% of the study area to 38%. Similarly, the relative area with high pollinator abundance increased from 20% to 24%. Furthermore, the relative area with very-low pollinator abundance decreased from 20% to 6% and the relative area with low abundance decreased from 20% to 11% (Fig. 4). The observed relative change in pollinator abundance was greatest next to LSE (50 m), where it increased by 37%. The effect of LSE inclusion also extended to at least 100 m, where relative pollinator abundance increased by 27% (Fig. 5).

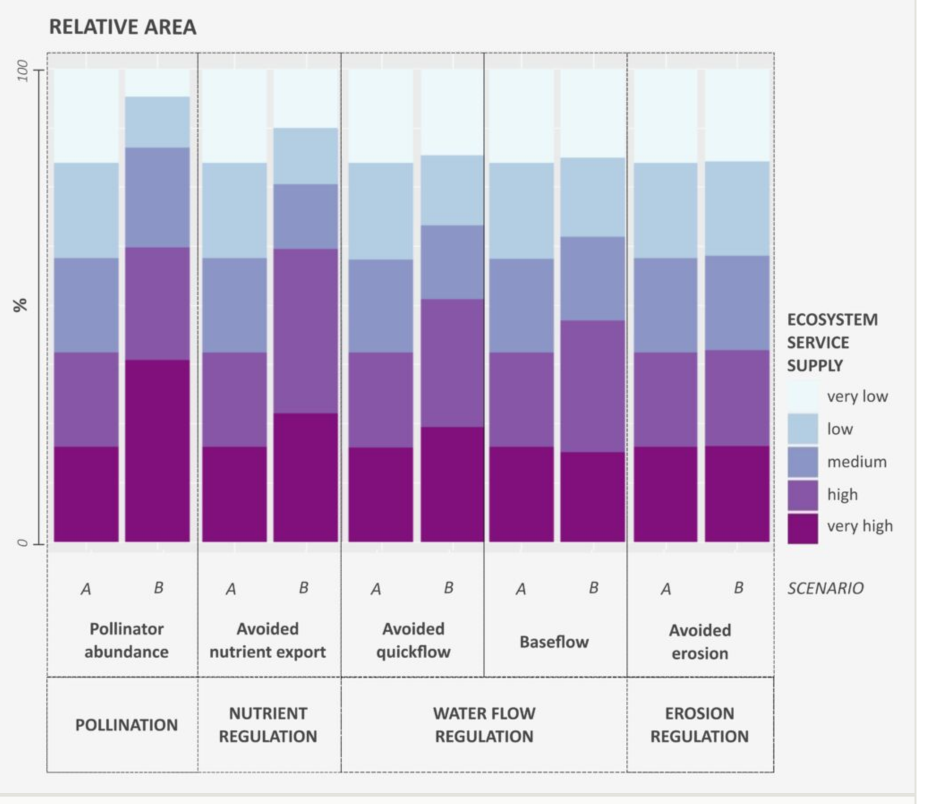

Figure 4.

Distribution of quantile supply classes with respect to the service variables pollinator abundance, avoided nutrient export, avoided quickflow, baseflow and avoided erosion values in scenarios A and B. For means of comparability, for each service variable, the quantile classification based upon the scenario A layer has been applied.

In terms of nutrient export, the study area was dominated by medium to very high rates previous to LSE inclusion, with the exception of a few patches in the centre and the borders (scenario A). The spatial pattern very roughly followed the spatial distribution of the calculated quickflow values. The few patches with relatively low nutrient export values spatially matched forested areas. Once LSE were included, nutrient export decreased throughout the whole study region (Fig. 3, scenario B). The largest area to benefit from reduced nutrient export was identified in the southeast of the Bornhöved Lakes District. Mean nutrient export decreased by 25% across the study region in scenario B (Suppl. material 1). For means of comparability with the other ecosystem services, in the following, the inverse distribution of the variable nutrient export, herein avoided nutrient export, has been considered. The relative area of the study region classified as high avoided nutrient export increased from 20% to 35% and very high from 20% to 27%, resulting in land area classified as very low, low or medium to decrease to approximately 12-14% each (Fig. 4). The observed relative change in avoided nutrient export was greatest next to LSE (50 m), where the ecosystem service supply increased by 36%. Increased avoided nutrient export with LSE also extended to at least 100 m, where it increased by 30% relative to scenario A (Fig. 5).

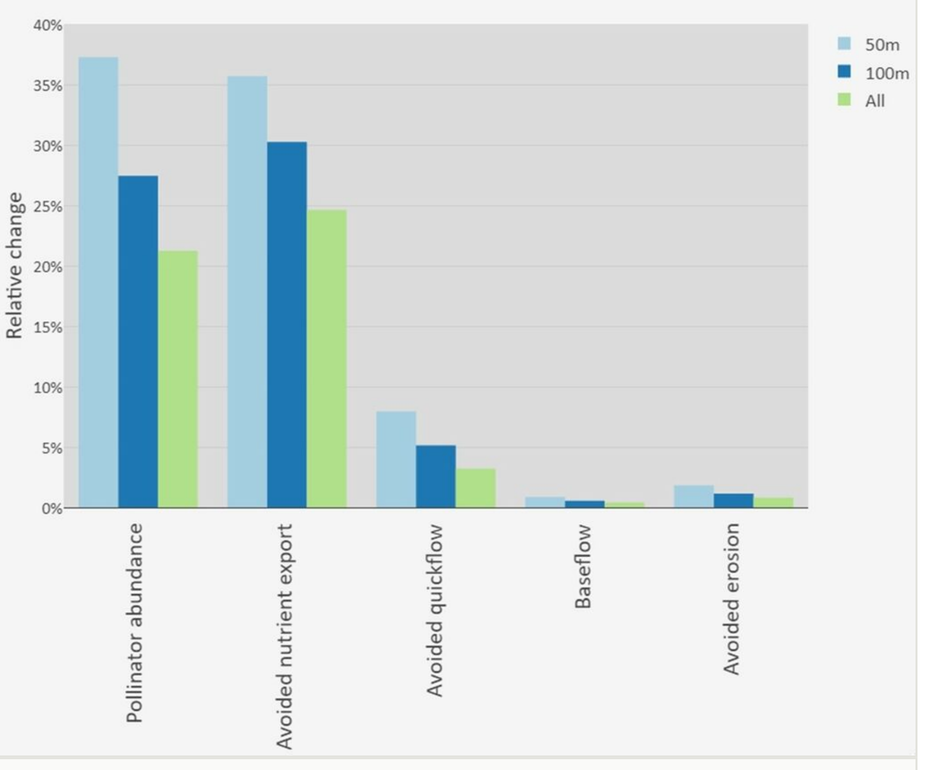

Figure 5.

Relative changes in service variables in 50 m (light blue) and 100 m (dark blue) distance to the linear semi-natural landscape elements (LSE) and for the total Landscape (green) for average pollinator abundance, avoided nutrient export, avoided quickflow, baseflow and avoided erosion through the integration of landscape elements.

In terms of the water flow regulation variable baseflow, very low to low values were found in the northern part of the study area, whereas the southern part was dominated by medium to high values under scenario A. Through the inclusion of LSE in the assessment under scenario B, values along the newly-included LSE changed to high baseflow, however, with little or no change in the surrounding areas (Fig. 3). Generally, the relatively low baseflow values corresponded to the more hilly part of the study area (see Suppl. material 2) and to areas where, according to the hydrological soil group classification, the soils were estimated to have a moderately high runoff potential (see Suppl. material 4, Ross et al. (2018a)). Under scenario A, high to very high quickflow values were identified along the western and eastern part of the region, whereas the centre of the area, around the lakes, was characterised by medium to low quickflow values. Under scenario B, values along the newly-included LSE were reduced to very low quickflow, while little or no change was identified in the surrounding areas (Fig. 3). Overall, the spatial pattern of relatively high quickflow values largely coincided with soils classified as having a moderately high runoff potential (see Suppl. material 4, Ross et al. (2018a)). Relatively low quickflow values were found in the more forested areas. The effect of including LSE in the landscape only marginally changed the supply of baseflow and avoided quickflow, the two service variables associated with the ecosystem service water flow regulation (see Table 3). Baseflow increased by 0.4% in landscapes considering LSE, whereas quickflow decreased by 3.2% (Suppl. Material 2). For means of comparability with the other ecosystem services, in the following, the inverse distribution of the variable quickflow, herein avoided quickflow, has been considered. Both baseflow and avoided quickflow followed similar patterns under scenario B. Once LSE were included, the relative area contributing to high baseflow supply increased from 20% to 28% and, in avoided quickflow, increased from 20% to 27% (Fig. 4). Very high avoided quickflow also increased from 20% to 24% of the relative area under scenario B; however, baseflow was found to deliver similar values under scenario A and B. This resulted in the relative share of area classed as very low, low or medium decreased from 60% to 53% for baseflow and from 60% to 48% for avoided quickflow. The relative change in avoided quickflow was greatest next to the newly-included LSE (50 m) where it increased by 8%, extending at least 100 m from LSE, where avoided quickflow increased by 5% relative to the landscape assessment under scenario A (Fig. 5).

Concerning erosion regulation, the avoided erosion (corresponding to soil retention) is characterised by a heterogeneous spatial distribution of the quantile supply classes, whereby the spatial pattern seems to follow the general topography of the region (see Suppl. material 2). The inclusion of LSE did not change the spatial distribution of the quantile supply classes (Fig. 3, scenario B). For the ecosystem service erosion regulation, only marginal differences were observed. For the variable avoided erosion, the mean increased by 0.8% under scenario B (Suppl. material 1). As the visual comparison of the spatial pattern (Fig. 3) already showed, there are very small shifts in the distribution of the quantile supply classes between scenario A and B (Fig. 4). The relative changes of the variables showed slight variation with regard to the proximity to the newly-included LSE (1.8% at 50 m and 1.2% at 100 m distance, Fig. 5).

The inclusion of LSE had a net positive effect on ecosystem service supply to agricultural areas (non-irrigated arable lands and pastures). Avoided nutrient export on agricultural grounds displayed a strong positive response to LSE (Fig. 6), increasing by 22.9%. For pollinator abundance, a comparable pattern was detected with an increase of 15.4% between scenario A and B. A weak positive response to LSE on agricultural lands was also observed in avoided quickflow (2.5%). However, the inclusion of LSE had no observed effect (< 0.5%) on baseflow. Additionally, for avoided erosion, no relevant change was detected on agricultural lands between scenario A and B.

Discussion

We showed that considering linear semi-natural landscape elements (LSE) as part of the green infrastructure (GI) increased the modelled multifunctionality of agricultural landscapes. The five per cent of the landscape, assigned to LSE, particularly increased the model results with regard to the supply of the ecosystem services pollination and nutrient regulation, whereas water regulation and erosion control did not respond that much. While recent studies identified InVEST results to be highly dependent on data quality, spatial scale and resolution (Nelson et al. 2009, Benez-Secanho and Dwivedi 2019) and criticised the lack of direct validation (Butsic et al. 2017, Benez-Secanho and Dwivedi 2019), we only regard the here-presented relative changes in the ecosystem service supply between two scenarios of the same study area with LSE included or excluded. For this purpose, in the process, for evaluation and visualisation of each ecosystem service, the output data were classified into the five "quantile supply classes". In our analysis, we further improved the reliability of the results by removing outliers from the modelling outputs before the evaluation, ensuring that extreme values did not unduly influence the quantile classification and the subsequent comparison of ecosystem service supply between the two landscape scenarios. Unlike quantile classification, the use of natural Jenks breaks would prioritise minimising the variability within classes without direct consideration of relative differences between the scenarios. This could be suboptimal when the primary goal is to focus on the relative impacts of landscape scenarios on ecosystem service supply. While we have arrived at this decision for the specifics of this evaluation, it is important to point out that the application of a quantile classification is also accompanied with drawbacks (Burkhard 2017). Compared to equal interval and natural breaks (Jenks) classifications, quantile classifications commonly result in more heterogeneous distributions, with potentially numerous classes portraying middle value ranges. In maps, it could lead to displaying a pseudo-heterogeneity (Burkhard 2017, Burkhard and Kruse 2017). Therefore, both author and reader need to be aware of the specifics of the classification and its effects.

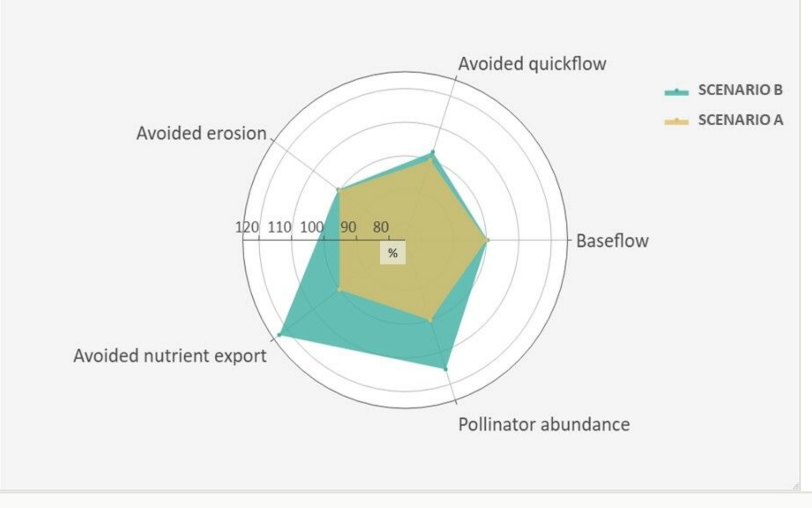

Figure 6.

Change in multifunctionality through the integration of linear semi-natural landscape elements (LSE) expressed as relative profiles for average pollinator abundance, avoided nutrient export, avoided erosion, avoided quickflow and baseflow on agricultural grounds (non-irrigated arable lands and pastures).

Our results show that the common current exclusion of LSE in national GI planning disregards valuable LSE and their potential to supply ecosystem services. Of the four ecosystem services tested, pollination and nutrient regulation showed strong positive responses to including LSE in the modelled landscape. The area that was positively influenced corresponds not only to the spatial extent of the LSE themselves, but extends beyond their location, on to adjacent agricultural fields. This confirms that the supply of ecosystem services to agriculture is highly dependent on the distribution of LSE, such as hedgerows, in the surrounding landscape (Power 2010, Dainese et al. 2016). In line with general trends in literature (BLE 2018, BfN 2019, Perennes et al. 2020), the strongest positive effects of LSE on the ecosystem services supply could be identified in the proximity of the LSE themselves. Although changes could also be identified beyond that area, peak changes in ecosystem service supply can be attributed to the area next to LSE (50 m) and to a reduced extent near to LSE (100 m). In this vicinity, the LSE has the largest effects on the microclimate and a large share of the species that origin from the LSE are active in this area (Wildermuth 1978, BfN 2019).

Historically, hedgerow networks were established to mark boundaries and enclose fields and meadows, rather than for the supply of specific ecosystem functions or services (Merot 1999, Reiß 2005). Yet, LSE, such as hedgerows, have been shown to foster biodiversity (LLUR 2008, Diekötter and Crist 2013, Eigner and Gerth 2020), counteract – at least to some extent – the negative effects of agricultural intensification on biodiversity (Dainese et al. 2015, Dainese et al. 2016) and promote the supply of ecosystem services (Irmler et al. 2008, Batáry et al. 2010, Merckx et al. 2012, Haenke et al. 2014, M'Gonigle et al. 2015, Perennes et al. 2020, Eigner and Gerth 2020, Müller and Lange 2022). This is, because LSE provide foraging resources, nesting sites as well as overwintering habitats for many species (Bianchi et al. 2006, Coll 2009, Chaplin-Kramer et al. 2011, Garibaldi et al. 2011), including wild bees (Hannon and Sisk 2009, Dar et al. 2017). Furthermore, more complex landscapes, in which habitat fragments are connected by LSE, provide ecological corridors for dispersal (Forman and Baudry 1984, Dondina et al. 2016, Staley et al. 2019). The movement of animals along such corridors may enhance gene flow (Lange et al. 2011), facilitate the dispersal of plant species (Tewksbury et al. 2002) and increase the biotic flow of nutrients (Ellis-Soto et al. 2021).

Hedgerows are attractive foraging habitats for native bees, especially in early summer (Hannon and Sisk 2009) and have been shown to promote less-common species of wild bees that were not found on flowers at weedy, unmanaged edges (Morandin and Kremen 2013). Yet, not only do hedgerows provide valuable foraging resources, but also act as net exporters of native bees into adjacent fields (Morandin and Kremen 2013). Particularly, when connected to source habitats of bees, hedgerows increase the pollination service (Castle et al. 2019). While other studies did not show local effects of hedgerows on pollination in adjacent crops (Albrecht et al. 2020), high coverage of hedgerows at the landscape scale enhance visitation rate and seed set in phytometer plants irrespective of local margin quality (Dainese et al. 2016). Through the permanent character of the LSE vegetation and associated alterations in the local climate or matter flow (Forman and Baudry 1984, LLUR 2008, BfN 2019), the ecosystem may be influenced beyond biodiversity and pollination. Perennes et al. (2021) assessed, amongst others, the ecosystem service pollination in the Bornhöved Lakes District, integrating bioclimatic information through a hierarchical modelling approach. In particular, in the central and southern part of the study area, the spatial pattern of their predicted pollination service potential (Perennes et al. 2021, Supplementary material, Fig. 2) resembles the pattern of our pollinator abundance quite well, whereas in the northern part of the study area, we obtained relatively higher values.

By reducing the slope gradient and the effective slope lengths of the landscape, LSE may be expected to reduce soil erosion and nutrient runoff. In our study, though, the ecosystem services modelling results with regard to erosion regulation and water flow regulation were only marginally affected by the inclusion of LSE, even though previous results suggest otherwise (Forman and Baudry 1984, Müller 1990, Dreibrodt et al. 2009, Power 2010, Schindewolf 2012, Sitzia et al. 2014, Eigner and Gerth 2020). To effectively support water flow regulation and erosion regulation, LSE must be configured along soil boundaries and/or perpendicular to hillslopes, which can help decrease the speed of runoff water, modulate stream flow and decrease soil erosion (Baudry et al. 2000, Fan et al. 2015, Eigner and Gerth 2020, Meng et al. 2021). While some of these functions may purposefully or incidentally have been fulfilled in historic times (Beyer and Schleuß 1991, Dreibrodt et al. 2009, Montgomery et al. 2020), the indiscriminate removal of hedgerows to increase cropping area (Robinson and Sutherland 2002, LLUR 2008) likely affects the hydrology of the affected landscapes (Baudry et al. 2000).

Thus, contrary to our findings, hedgerows are expected to significantly increase both the lateral flow of water, decreasing surface runoff, as well as evapotranspiration, affecting soil water content, especially within close proximity (Holden et al. 2019, Eigner and Gerth 2020, Montgomery et al. 2020). These effects are further enhanced with higher densities of trees in the LSE (Thomas et al. 2012). Through field studies on the hedgerow systems in northern Germany, colluviums were discovered (Reiß 2005). It was found that a part of the hedgerow system reduces the above-ground water catchment area in a way that it serves as erosion protection. We observed that parts of the study area with steep slopes are covered by forest or grassland, rather than being used for cropland (see Fig. 1). The Landesamt für Umwelt des Landes Schleswig-Holstein (2013) identified that the agricultural fields in the more hilly parts of the study area have a very high risk for erosion by water (see Suppl. material 3). When visually comparing the spatial distribution of the LSE and the inclination of the landscape in the study area (see Suppl. material 2), we found that, even though there are some perpendicular LSE on several of the more pronounced slopes, generally, LSE are relatively scarce in the northern, more hilly area compared to the southern and flatter parts of the study area. These findings provide some degree of evidence for the limitied influence of (LSE) on the outcomes with reference to soil erosion.

It needs to be considered that, in our study, LSE also included wooded strips, isolated trees, trees in line and groups and field copses whereof some are likely less effective at regulating both surface flow and soil moisture content. Even though InVEST provides powerful and relatively transparent means for the quantification and valuation of multiple ecosystem services (Polasky et al. 2010), specific limitations arise from the general composition of the InVEST model suite and the specifications of the individual applied models (Lüke and Hack 2018). Generally, within the InVEST model suite, spatial and tabular data (commonly derived from field surveys, literature and/or expert evaluation) are combined in biophysical models to spatially assess the supply of ecosystem services (Polasky et al. 2010, Benez-Secanho and Dwivedi 2019).

The accuracy and reliability of ecosystem service assessments in general, as well as through InVEST models, are strongly influenced by the quality, resolution and minimum mapping unit (MMU) of available input data (Nelson et al. 2009, Bicking et al. 2018, Benez-Secanho and Dwivedi 2019, Sharp et al. 2020). Varying data accuracy and precision can lead to both overestimation and underestimation of ecosystem services. The MMU, which refers to the smallest size or area that can be distinguished and mapped in a given dataset, can significantly influence the results (García-Álvarez et al. 2019, Sieber et al. 2021). When considering narrow LSE, it is imperative to utilise high-resolution data that can accurately capture the LSE, otherwise models might significantly underestimate the services they contribute, which could result in a general undervaluation of LSE and overlooking of their importance in decision-making processes (Sieber et al. 2021). Even though the LSE information utilised in this study originated from a high quality dataset, it needs to be mentioned that the respective data, originally available as polylines, required rasterisation to be incorporated into the assessment, which introduced some loss of precision (Sharp et al. 2020). Next to the high dependence on and sensitivity to the available input data (Nelson et al. 2009, Benez-Secanho and Dwivedi 2019) and the lack of a readily available direct validation technique (Benez-Secanho and Dwivedi 2019), further uncertainties arise from the level of abstraction, in particular with regard to hydrological processes, used within the assessment (Lüke and Hack 2018) compared to more elaborated and complex hydrological models (such as the widely applied hydrological model “Soil and Water Assessment Tool” (SWAT; Arnold and Fohrer (2005)); see Vigerstol and Aukema (2011) for a comparison of hydrological and freshwater-related ecosystem services models).

In line with our study, hedgerows have been proposed to reduce nutrient losses from agricultural land (Holden et al. 2019). Yet, experimental evidence is scarce. Recently, Lei et al. (2021) have shown for China that compound mulberry hedgerows significantly reduced nutrient losses in an intercropping system. Similarly, Xia et al. (2013) showed contour *Toona sinensis* hedgerows to significantly reduce sediment N or sediment P losses. The potential of oak hedgerows to counteract groundwater contamination with nitrate through excess agricultural fertiliser application was also shown for France (Thomas and Abbott 2018). This way, hedgerows may provide nature-based or eco-engineered solutions for mitigating the impacts of anthropogenic environmental pressures (Collier 2021).

With this study, the assessed multifunctionality of LSE has been restricted to four regulating ecosystem services. In order to obtain a more coherent and integral understanding of the functionality of LSE, related ecosystem services synergies and potential trade-offs on the landscape scale, additional ecosystem services need to be assessed. Besides, different methodological approaches, data and models of different complexity and spatio-temporal resolution should be applied. Comparing the results will increase the holistic understanding of LSE at the landscape scale. Furthermore, it will be possible to identify minimum requirements for such assessments with regard to, for example, input data, resolution, complexity, abstraction and stakeholder involvement to ensure reliable results. Additionally, future assessments should integrate an analysis of the condition of the linear semi-natural landscape elements. Information on the condition of the LSE will improve the quality of the assessments and allows more accurate and robust conclusions about the specific functionalities of the assessed structures in the landscape context.

Conclusions

This study addresses the multifunctionality of agriculturally-dominated landscapes and the role of GI, more precisely semi-natural linear landscape elements, in that context. Concluding from the results obtained in this model test, the following can be stated in regard to the research hypotheses:

1. Including or excluding linear semi-natural landscape elements changes the landscape's modelled ecosystem service supply. The modelling demonstrated potentially increasing ecosystem service supply through the integration of the linear semi-natural landscape elements. Even though positive impacts have been modelled for the whole study area, the largest changes have been identified in the close surrounding (in 100 m and 50 m distance) to the LSE. Thus, the influence of LSE on the modelled supply of the ecosystem services changes according to the distance to the LSE. Furthermore, the modelling revealed potentially increasing ecosystem service supply specifically on agricultural areas.
2. The extent of these changes depends on the ecosystem services considered. The changes of the four ecosystem services differed in magnitude and spatial extent. In particular with regard to the spatial extent, only small changes in the modelling results have been identified for water flow regulation and soil erosion. Considering both spatial extent and magnitude, the greatest changes have been found with regard to the supply of the ecosystem services pollination and nutrient regulation.

In order to support sustainable approaches to agriculture, ecological processes and ecosystem functions must be preserved to supply ecosystem services (Bergez et al. 2022). This involves the strategic planning of GI to maximise these benefits for producers. However, if elements are undervalued or not considered, inappropriate land-use policy and land management may be implemented (Malinga et al. 2015). The European Commission (2013b) recognises that the diverse environmental features of the GI network function on different scales, from small-scale structures to entire functional ecosystems. Thereby, the European Commission (2013a) specifically identifies natural landscape elements such as small streams, ponds, hedgerows and woodlands, which serve as ecological corridors, as potential components of GI. Nevertheless, LSE are typically excluded from official national GI (BfN 2017) as they are considered not to have sufficient critical mass nor connectivity potential to effectively contribute to the GI network. Leastwise, the recent regional biodiversity strategy of the federal state of Schleswig-Holstein mentions the relevance of structurally complex landscapes, as landscapes with a rich historic hedgerow system (MELUND 2021). As evidenced by our findings, LSE support landscape multifunctionality and support the supply of essential ecosystem services to adjacent agricultural land. Therefore, we highlight the importance of semi-natural linear landscape elements as a potentially integral and previously often overlooked part of the GI and, moving forward, advice to consider them on the regional as well as supra-regional scale, as an official and important element in the planning and management process of GI and beyond.

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Conflicts of interest

The authors have declared that no competing interests exist.
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Supplementary materials

Suppl. material 1: Summary statistics doi

Authors: Lange et al.
Data type: table
Brief description: Overview of summary statistics for each considered output variable from the InVEST assessment (post outlier removal).
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Suppl. material 2: LSE and landscape's slope doi

Authors: Lange et al.
Data type: map
Brief description: Location of inland water bodies as well as LSE and the calculated landscape's slope.
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Suppl. material 3: LSE and the threat to erosion by water doi

Authors: Lange et al.
Data type: map
Brief description: Location of LSE in the study area and the threat to erosion by water on agricultural land.
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Suppl. material 4: LSE and hydrologic soil groups doi

Authors: Lange et al.
Data type: map
Brief description: Location of LSE and hydrologic soil groups in the study area.
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Endnotes

*1 When a slope is divided by stable structures orientated perpendicular to the gradient (e.g. agricultural paths, hedges, grass strips or field edges) that can divert water or significantly slow down its flow, both the runoff volume and water transport force decrease. This has particular significance for erosion processes on the lower slope, as the entire slope length is no longer effective in causing erosion (Los et al. 2001, Geologischer Dienst NRW 2015). The length of the slope, in the direction of the gradient, between two stabilising structures that divide the slope is referred to here as the effective length. A shorter effective length reduces erosion activity.