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Effects of linear landscape elements on multiple ecosystem services in contrasting agricultural landscapes

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ABSTRACT

Linear landscape elements, such as field margins, are agricultural practices whose adoption is supported by agri-environmental climate measures (AECMs). AECMs are meant to improve ecological conditions on farms and surrounding areas. The effectiveness of AECMs to enhance the supply of multiple ecosystem services (ESs) is still debated and knowledge on the resulting ESs bundles under different practices stemming from AECMs is still lacking. We aimed at assessing the potential of AECMs that promote the implementation of linear landscape elements to provide high levels of multiple ESs and at analyzing bundles at landscape level in different geographical contexts. We assessed the potential effects of linear landscape elements (woody, grassy, flower and a mix) on six ESs (food and feed provision, pollination, pest control, climate regulation, aesthetics, and habitat maintenance), combining scenarios and spatially explicit modelling approaches. Our results showed the positive effects of linear landscape elements on all regulating and cultural ESs. The more abundant the linear elements, the higher the overall ESs supply. However, the effect of linear landscape elements on multiple ESs depended on the types of linear elements and the geographical context of their implementation. When the supply of the ES was already high in the baseline situation, the changes induced by the implementation of the linear elements were much lower than when the baseline situation showed a lower initial supply of one or several of the ESs. Our analyses give insights on the efficiency of AECMs on multiple environmental targets. Our approach is a first step towards a general framework for an ex-ante integrated analysis of AECMs that can be used to design agri-environmental policies. From a more practical perspective, our results can form a basis for additional payments for AECMs. Our study also confirms the relevance of the EU biodiversity strategy that commits to ensure at least 10% of agricultural area as high-biodiversity landscape features such as linear landscape elements, and the relevance of the enhanced conditionality and eco-schemes in the reformed Common agricultural Policy targeting non-productive elements and biodiversity.

1. Introduction

Mixed small scale agricultural (mosaic) landscapes play a crucial role in global food security and contribute to human well-being through the supply of food and fodder and a wide range of ecosystem services (ESs) (Rusch et al., 2013; Kirchweger et al., 2020). In agricultural areas, trade-offs occur between provisioning and regulating and cultural services (Millennium Ecosystem Assessment, 2005) (Power, 2010), making sustainable management of food systems difficult.

Several policy instruments have been introduced in Europe to incentivize farmers to manage their land more sustainably (Villanueva et al., 2015). For example, agri-environmental climate measures (AECMs) contracts are an important instrument of the Common Agricultural Policy (CAP). AECMs are meant to contribute to climate change mitigation and adaptation, and to improve ecological conditions on farms and surrounding areas for halting and reversing biodiversity loss,

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enhancing ecosystem services (ESs) and preserve landscapes (O. J. of the European Union, 2021). In the case of AECM contracts farmers commit themselves on a voluntary basis to adopt environmentally friendly farming practices or measures that go beyond the cross-compliance level (i.e., the set standards and requirements for receiving direct EU income support). In return, farmers receive payments that offset the additional costs of implementing these measures. Farmers are also compensated for possible lost income due to lower yields because of applying those environmentally friendly farming measures, for example lower or no use of agrochemicals, specific modes of crop rotation, organic farming and the protection of landscapes or species by conserving their habitats (Uthes and Matzdorf, 2013).

Several agri-environmental measures exist, such as the construction and maintenance of nature-friendly (river) banks, delayed mowing, conservation grazing, the introduction or restoration of linear elements or buffer strips along agricultural fields and making use of specific crop rotations. Each measure has specific requirements that the land manager must meet. For example, in linear elements, also called buffer strips, next to a field, a certain percentage of the surface must be covered with flowers or grass species during a certain period.

The effectiveness of these policy instruments to enhance ESs is however still debated. On the one hand, studies assessing the effectiveness of environmentally friendly measures have generally determined positive effects on various aspects and indicators of biodiversity (Dietschi et al., 2007; Aviron et al., 2009; Kampmann et al., 2012). Other ecological benefits of these measures have been demonstrated as well, for example on water quality regulation and erosion prevention (Galler et al., 2015). On the other hand, several studies have found that AECM contracts were not sufficient for generating environmental benefits (Kleijn et al., 2001; Kleijn et al., 2004; Pe'er et al., 2014) and the environmental benefits that were demonstrated were highly context-dependent (Wallander and Hand, 2011; Uthes and Matzdorf, 2013; Moxey and White, 2014).

Despite a growing literature on the possible environmental benefits of environmentally friendly measures, we identified four main knowledge gaps. First, AECM contracts often target one specific ES. Yet, measures implemented to improve the supply of one specific ES might have added value for other ESs while the supply of other ESs might decrease. Olivieri et al. (2021) underlined the difficulty of designing and implementing one single type of AECM contract that enhances all ESs produced by agriculture, independently of the geographical context. More knowledge about bundles of ESs ("sets of ESs that repeatedly appear together across space or time" Raudsepp-Hearne et al., 2010) within different landscapes is required to assist policy makers and land-use planners in effectively implementing AECM contracts. Second, little is still known about the variability of the effect of AECMs across geographical contexts. As ESs supply is highly site- and management-specific in agricultural landscapes (Le Clec'h et al., 2019b), a better understanding of effects of geographical contexts is critical to assess the reproducibility of case studies and the universality of the effects of measures. Third, a specific set of measures, spatially targeted to locations with high ESs supply potential could increase the effectiveness of the measures (Frueh-Mueller et al., 2018). However, it is unknown how multiple ESs are influenced by spatial targeting and by the total area of land under AECMs contracts. Finally, only very few scientific studies conduct ex-ante analyses of the impacts of environmentally friendly measures on multiple environmental targets. Several studies focus on the policy performance of AECMs contracts, for example through the total uptake of the AECM contracts measured in the share of area covered or number of farmers participating. However, the literature on modelling and analysing impacts of measures on the supply multiple ESs is still limited. However, such knowledge would also help to discuss implications of policy targets (Verburg et al., 2016).

This paper aims at assessing the potential of agri-environmental measures to provide high levels of multiple ES in three landscapes and to analyse their bundles at landscape level in different geographical contexts. We are not analysing actual ES production, but we are answering the following two questions that cover the four above-mentioned research gaps: 1) How does the type and proportion of linear elements change the potential supply of multiple ESs? And 2) How do the effects of linear elements differ among contrasting landscapes with different baseline situations? We answered these questions by using environmental data for agricultural fields in three European study regions to estimate the potential supply of six ESs indicators and evaluating the changes in the potential ESs supply, under different scenarios, i.e., when applying agri-environmental measures.

We restricted our analyses to linear landscape elements in field margins. More specifically, we focused on the effects of shares of 1) flower strips, 2) un-mowed grass strips, 3) hedgerows at the edges of the agricultural fields and 4) an equal mixture of flower and un-mowed grass and trees. Several studies have demonstrated the effects of linear landscape elements on pollination (Krimmer et al., 2019; Geppert et al., 2020), biodiversity (Van Vooren et al., 2017), pest control (Tschumi et al., 2016), carbon sequestration (Van Vooren et al., 2017), energy production (Smith et al., 2021) and aesthetics (Bullock et al., 2021), in various agricultural landscapes across Europe. While linear elements can be implemented in combination with other management measures (e.g., extensification), we did not consider such combinations.

Our analyses shed light on ES bundles in agricultural landscapes and give insights on the environmental efficiency of AECM contracts which include linear elements. Our approach is a first step towards a general framework for an ex ante integrated analysis of AECM contracts. Our study regions build a promising basis to scale up our assessment to other agricultural landscapes facing the wide-spread trade-off between agricultural intensification and overall potential ESs supply. From a more practical perspective, our results could help optimizing the supply of multiple ESs in different agricultural landscapes and thus be a basis for additional payments for environmentally friendly measures, for example in the form of carbon credits.

2. Material and methods

2.1. Study areas

This paper relies on three study regions across Europe: Achterhoek (the Netherlands), Bornholm (Denmark) and Őrség National Park (Hungary). The three study areas are characterized by their small-scale agricultural landscapes and the presence of Natura2000 areas (Fig. 1).

The Achterhoek is located, in the eastern part of the Netherlands. It spans over 1,476 km^2. Its topography is relatively flat (Fig. 2), with an elevation of around 28 m. The landscape is dominated by agriculture taking up 54 % of the area and built-up area and infrastructure covering 21 % of the area. Forests cover 13 % of the area, dry nature types cover 5 % of the area and wet nature types cover 1 % of the area. Urban green covers 3 % of the area and water covers 2 % of the area. In the eastern part of the region some small areas are allocated as Natura2000 sites. The agricultural landscape is characterized by hedgerows (bocage) and small agricultural parcels. The main land-use in the region is grassland (70 % of the agricultural area). The main crops are maize, used for animal feed (20 % of agricultural area) and potato (3 % of agricultural area). Dairy farming is the most important farm type managing 58 % of the farms, cereal farming covers 25 % of the farms, pig farming covers 11 % of the farmers and goat farming covers 5 % of the farms (cbs.nl, 2022). The average field size in the Achterhoek is 2.1 ha. The region is known for its aesthetics and scenery. Since 2016 the Dutch farmers can only jointly apply for CAP-AECMs, organized with help of agri-environmental collectives. The certified collectives are the link between the individual farmers who implement the environmental

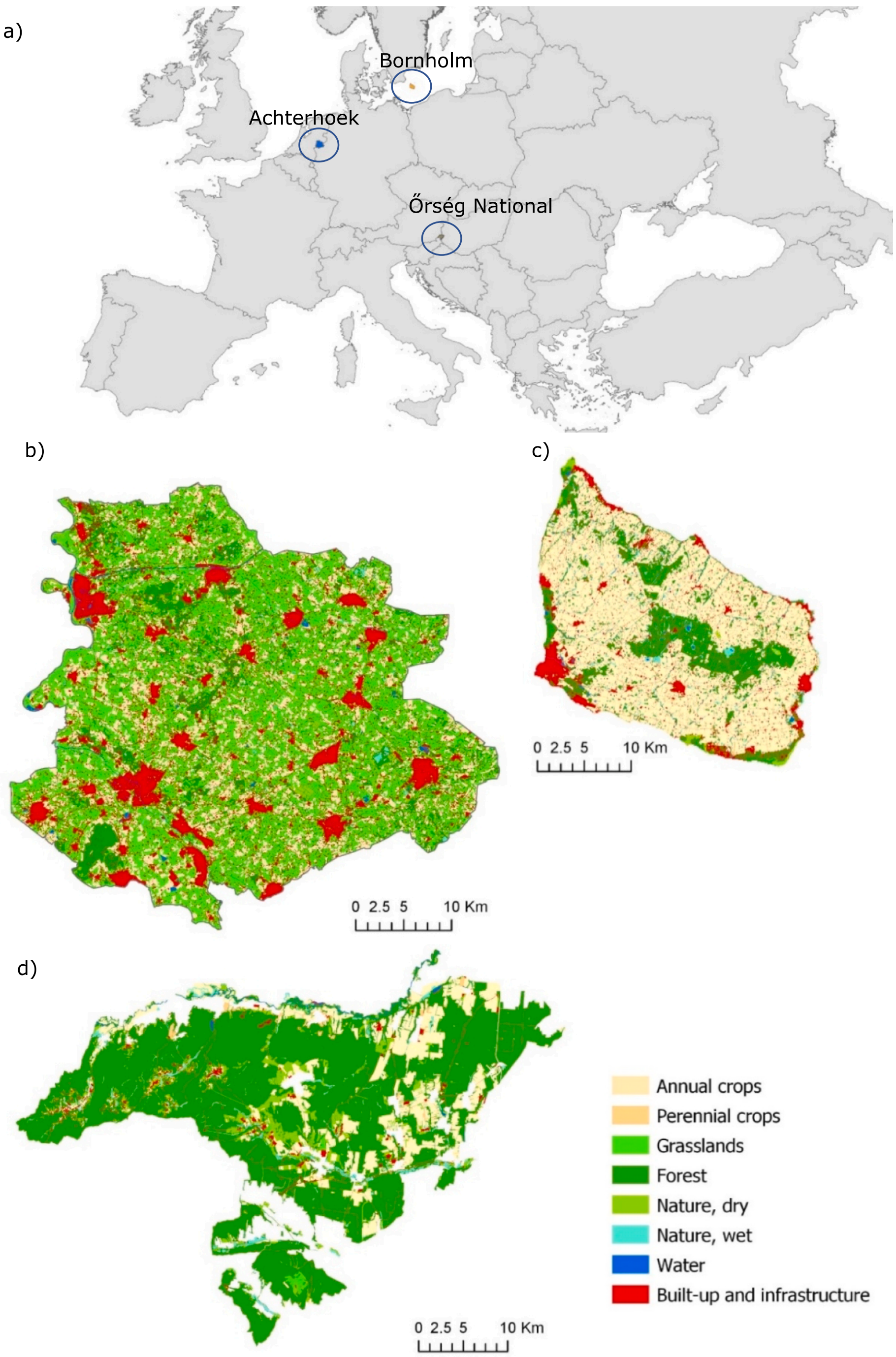

Fig. 1. Location (a) and current land-use of the three study areas: (b) Achterhoek (the Netherlands), (c) Bornholm (Denmark) and (d) Őrség National Park (Hungary). Sources: Corine Land Cover (2018).

friendly measures and the government that provides the subsidies (see for more details: Boonstra et al. (2021)). In the Achterhoek one collective is active, the Vereniging Agrarisch Landschap Achterhoek (VALA; https://de-vala.nl/) that aims to increase biodiversity through conservation and development of the Achterhoek cultural landscape.

Bornholm is a Danish Island in the Baltic Sea. It spans over 588 km^2 inhabited by 40 thousand people. Its topography is undulating, with an elevation ranging between 0 and 163 m. The landscape is dominated by agriculture taking up 60 % of the area and forest covering 17 % of the area. Built-up area and infrastructure cover 13 % of the area, dry nature types 5 % and wet nature types 1 % of the area. The island has several areas designated as Natura2000 sites, with the largest covering 61 km^2. Pig farming is the most important farm type managing 37 % of the agricultural area, arable farms cover 17 % of the agricultural area and cattle farms, mainly dairy, manage 17 % of the agricultural area. The average farm size is 92 ha with the largest 13 % of the farms managing 52 % of the agricultural area. The main crops are wheat (35 % of the agricultural area), barley (25 %) and seed production and grass in rotation (both covering 8 % of the agricultural area). The average field size on Bornholm is 4.9 ha. In terms of AECMs, organic farming is the

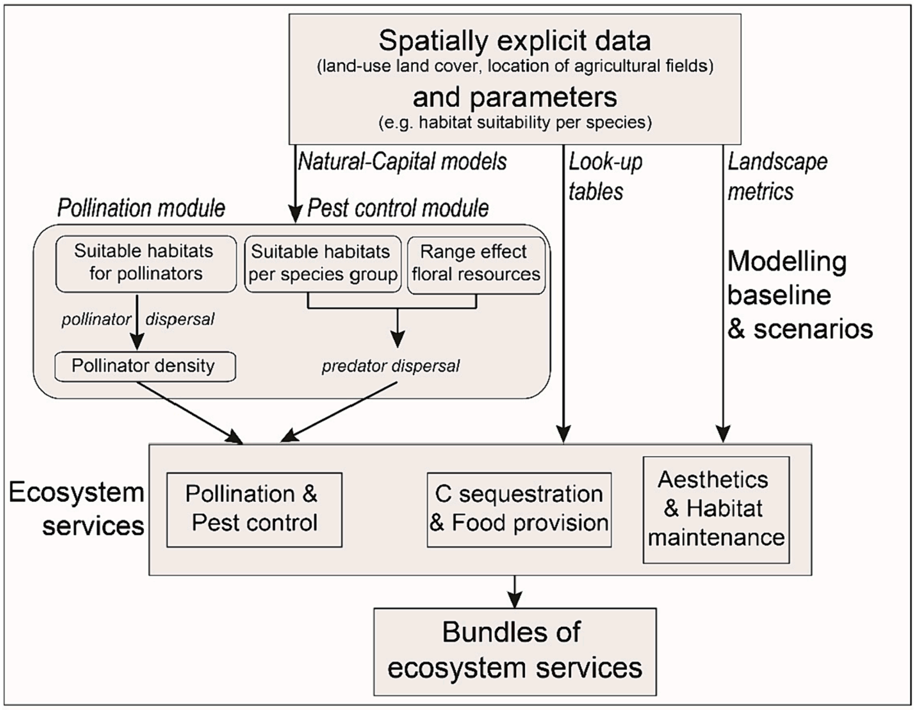

Fig.2. Three-step methodological approach: From spatially explicit data and parameters, we modelled the potential supply of six indicators of ecosystem services, in a baseline scenario and in scenarios with increasing share of linear elements. We analysed the bundles of ecosystem services under the baseline scenario and the scenario with the highest share of linear elements.

most important involving 5 % of the agricultural area. Agreements on conservation grazing covers almost 600 ha, corresponding to 43 % of the permanent grassland. AECMs targeting the establishment of hedgerows are currently not available in Denmark but will be included in an eco-scheme from 2023.

Őrség National Park is both a nationally protected area and a Natura2000 site, situated in the West of Hungary, close to the borders of Slovenia and Austria. It covers 440 km^2 with a hilly topography, ranging between 200 and 390 m. The landscape has kept its natural character due to its location within the Iron Curtain buffer zone. It is characterized by a mosaic of land-covers, dominated by forests (65 %) and followed by grasslands (11 %) in the valleys and arable fields (20 %) on the higher elevation. Farming practices are typically traditional and extensive, due to poor soil quality, irregular topography, and scattered ownership structure. The average field size in Őrség is 2.4 ha. Being a Natura2000 site, obligatory measures already exist for grassland, such as prohibition of ploughing or overseeding, elimination of invasive plants, use of nature-friendly mowing and leaving uncut refuge grass areas on 5–10 % of the field. Voluntary agri-environmental schemes are also available since 2002, but only 3 % of the agricultural area has been enrolled in one of the three schemes High Nature Value (HNV) grassland for birds, HNV grasslands for butterflies or HNV arable fields over the last 10 years. In the first two schemes, measures include the unmown grass-strips, in the last one field margins without any use of chemicals. Since the establishment of Őrség National Park in 2002, tourism has become a major activity.

2.2. Targeted ecosystem services and agri-environmental measures

While a range of ESs are provided by small-scale agricultural landscapes (Kirchweger et al., 2020), we focused on quantifying six indicators of ESs, as classified in the CICES (Common International Classification of Ecosystem Services; (Haines-Young, 2018)). We analysed potential effects of linear landscape elements on indicators of pollination, pest control, climate regulation, food and feed provision, habitat maintenance, and aesthetics. Table 1 presents the list of ESs and their respective indicators.

These six indicators were chosen for three main reasons. First, previous studies have shown that the ESs characterized by these indicators are likely to respond to land-use land-cover change in an agricultural landscape (Krimmer et al., 2019; Van Vooren et al., 2017; Tschumi et al., 2016; Bullock et al., 2021). This makes them interesting to analyse when looking at the potential effects of changing agricultural land into semi-natural elements on the agro-ecological systems. Secondly, the bio-physical processes and ecological functions, underpinning these ESs were very different, making these ESs complementary to each other. Finally, the indicators had been used in previous studies to characterize the ESs considered in our analyses.

2.3. Input data for the simulations

The supply of ESs in agricultural landscapes depends on both management and environmental drivers (Le Clec'h et al., 2019b). We combined data on land-use, including the location of the fields and type of agricultural production, land-cover, soil type and various environmental features related to the land-use land-cover. Sources of the data is given in Table 2 for the three study areas.

Land-use land-cover (Table 3 and Table A1): Models for indicators of pollination, pest control, climate regulation, aesthetics, and habitat maintenance required information on the land-use land-cover. We used maps of 2020, 2018 and 2019, for the Dutch, Danish and Hungarian cases respectively, as input maps. The Dutch land-cover map was available as a Geotiff with a 2.5 m resolution (see Table 2 for information on the data source). The Danish and Hungarian maps were available as vector maps (Table 2). For better comparison, and to comply to the need of raster maps as input for the pollination and natural pest control

Table 1
Presentation of the six ESs, their CICES category and code and the indicators modelled in this study, as well as references to other studies using similar indicators.

ES category	ES (CICES V5.1 code)	ES definition used in this study	Indicators*	Description of the indicator	References
Regulation and maintenance	Pollination (2.2.2.1)	Ecosystem's contribution to the fertilization of crops by pollinators. It leads to increases in crop production by providing nesting habitats and floral resources to wild bees and bumble bees.	Pollination potential in crops (%).	Potential of ecosystems to contribute to avoided production loss of pollinator dependent food crops due to pollination by wild pollinators in absence of domestic honey bees. The avoided production loss is based on the relative pollinator visitation rate. This relative visitation rate is based on the suitability of the LULC for nesting sites and floral resources and the distance of suitable LULC to the agricultural fields.	De Knegt et al., 2022
	Natural pest control (2.2.3.1)	Ecosystem's contributions to the prevention or reduction of effects of pests on crop production by providing shelter and alternative food sources to natural enemies of pest species.	Relative density of natural enemies in agricultural crops (%).	Potential pest control level in absence of pesticides that are harmful for the natural enemies. A density of 100 % indicates a density of natural enemies equal to the density of natural enemies in the most suitable natural habitat and a density of 0 % indicates the absence of natural enemies. This contribution is based on the LULC and on the distance to the crops.	(Rega et al., 2018) De Knegt et al., 2022
	Global climate regulation (2.2.6.2)	Sequestration of carbon from the atmosphere by the vegetation.	Sequestrated carbon in the vegetation (tC/ha).	Actual carbon sequestration by all vegetation types.	(Quijas et al., 2019; Bullock et al., 2021)
	Habitat maintenance (2.2.2.3)	Ecosystems' contribution in providing suitable habitat, refuge from predation, and food resources for several species.	Index built from:Proportion (%) of cropland and orchards, pastures, (semi-) natural ecosystems and artificial surfaces.Shannon's Diversity Index (-) at landscape level indicating the richness of land-cover types in the landscape.the Euclidean Nearest-Neighbour Distance to semi-natural habitat (m) .	Composite index that captures the landscape complexity through its composition, configuration, and heterogeneity.	(Nowak and Grunewald, 2018; Van Bussel et al., 2020)
Cultural	Aesthetics (3.1.2.4)	Enjoyment felt through the observation and experience of the landscape.	Index built from:Shannon's Diversity Index (-) .Patch Density (per km2) .mean Shape Index (-) . The land-cover types were clustered using the concept of "hemeroby", describing the extent of human impact on ecosystems as a measure of naturalness and in 17 diversity groups to evaluate landscape diversity. The Shannon's Diversity Index and Patch Density with diversity group as input. Mean Shape index was computed with the degree of hemeroby as input.	Composite index that captures the landscape diversity and the complexity of the shapes of the patches in the landscape.	(Frank et al., 2013; Van Bussel et al., 2020)
Provisioning	Food and feed provision (1.1.1.1)	Contribution of cultivated plants to the provision of food for human consumption or feed for livestock.	The total market price of main crops (euro/ha).		(Vermaat et al., 2021)For grassland systems (Huber et al., 2022)

*For habitat maintenance and aesthetics, we used the sum of normalized results of the three mentioned indicators for our analyses. Climate regulation was assessed through the carbon sequestrated by vegetation in above- and below-ground biomass. Because we consider sequestration only, soil carbon stock was excluded.

models, we rasterized the land-use land-cover maps of the Danish and the Hungarian case study areas into a Geotiff with 2.5 m resolution. The level of detail of the (semi) natural habitats in the land-use maps ranged respectively from high detail in the Dutch and Hungarian land-use map to low detail in de Danish land-use map. We expanded the category "(semi-)natural habitat" in the Danish case-study by adding the information from the Corine Land Cover map of 2018, i.e., to get more detailed information on land-cover in the classes Nature, Dry and Nature, Dry; Agriculture, extensive. For instance, the class 'Nature dry' could, among others, be classified as heather or forest (see for more detail Appendix - crosswalk Denmark). For better comparison among the case studies, the typology of each land-use land-cover map was simplified to a set of 34 land-use land-cover types (Table 3, crosswalks can be found in Appendix).

Table 2
Overview of input data of the ESs models; data type (spatial/no-spatial), ESs models they are used in, and, per case study, short description and data source.

Data type	Inputs in ESs models	Short description and sources Denmark	Hungary	The Netherlands
Land-cover (spatially explicit)	All	Base map Denmark, 2018, with 80 categories. Source: https://envs.au.dk/en/research-areas/society-environment-and-resources/land-use-and-gis/basemap	Habitat map of Őrség National Park, 2019, with 79 categories. Source: internal data obtained from personal communication.	Ecosystem type map of the Netherlands, 2020, with 107 categories. Source: https://www.cbs.nl/nl-nl/maatwerk/2022/49/ecosysteemtypenkaarten-2013–2020
Field location (spatially explicit)	All	Source: the Agricultural Agency, 2020.(https://lbst.dk/landbrug/genetiske-ressourcer/kort-og-markblokke/)	Source: internal data obtained from personal communication, 2019.	Source: Netherlands Enterprise Agency, 2020. Source: https ://www.pdok.nl/downloads/-/article/basisregistratie-gewaspercelen-brp-
Crop type (spatially explicit)	Food and feed production, pollination, pest control	Crop type map, 2020, in 23 categoriesSource: the Agricultural Agency(https://lbst.dk/landbrug/genetiske-ressourcer/kort-og-markblokke/)	Crop type map of Őrség National Park, 2022, in 40 categories. Source: internal data obtained from personal communication.	Crop type map, 2020, in 147 categories. Source: Netherlands Enterprise Agency. Source: https://www.pdok.nl/downloads/-/article/basisregistratie-gewaspercelen-brp-
Agricultural yield (non-spatial)	Food and feed production	Yield per hectare and per type of crop and grassland. Time series 2017–2021.Source: Statistikbanken (https://www.statistikbanken.dk/statbank5a/default.asp?w=1920)	Yield per hectare and per type of crop and grassland. Time series 2017–2021. Source: Hungarian Central Statistical Office (https://www.ksh.hu/stadat?lang=hu&theme=ara)	Yield per hectare and per type of crop and grassland. Time series 2017–2021. Source: Statistics Netherlands and WUR, 2020. Source: https://www.cbs.nl/nl-nl/publicatie/2021/22/natuurlijk-kapitaalrekeningen-nederland-2013-2018
Price of agricultural yield (non-spatial)	Food and feed production	Price per hectare of each crop and grassland type. Time series 2017–2021. Source: Statistikbanken (https://www.statistikbanken.dk/statbank5a/default.asp?w=1920)	Price per hectare of each crop and grassland type. Time series 2017–2021. Source: Hungarian Central Statistical Office https://www.ksh.hu/stadat?lang=hu&theme=ara	Price per hectare of each crop and grassland type. Time series 2017–2021. Source: Wisman, A., 2020. NSO-typering agrarische bedrijven 2020; Normen en uitgangspunten bij typering agrarische bedrijven in Nederland. Wageningen, Wageningen Economic Research, Nota 2021–012; https://edepot.wur.nl/537610

Field location: All ESs models required information on the location of the agricultural fields, these consisted of arable fields, meadows, and perennial crops. Maps of agricultural fields or parcel were available as vector maps, for the three study areas (Table 2). These maps were also converted to raster maps with a 2.5 m resolution, to match the land-use land-cover maps. These maps were used as a separate input data to some of the ESs models (for instance crop pollination). All information contained in these maps spatially overlapped with agricultural classes from the land-use land-cover maps but provided us with additional data on the limits of the agricultural parcels, which was used to generate the linear elements at the field margins, and in some cases on the type of crops.

Crop type, yield and price: We also used information on crop types present in the three study areas, from National Statistics (Table 2 and Table A2). For the pollination and the natural pest control service the location of crop fields was used. For the food and feed production service only the total area in use per crop and grassland type was used. For the Netherlands this was derived from the field parcel map, for Denmark and Hungary this was provided as a table. Information from statistical offices enabled us to estimate the potential crop yield and price, for each crop type present in the study areas. Yield and price data were a five year average (2017–2021) for the Hungarian and Danish case study. Price data were a five year average (2017–2021) for the Dutch case study. Only the main crops, in terms of the area they covered, were kept in our analyses.

2.4. Modelling and statistical approaches

We developed a three-step spatially explicit modelling approach (Fig. 2). First, we used environmental data for agricultural fields in three European study regions to estimate the potential supply of ESs. Second, we estimated the change in the potential ESs supply, under different scenarios, i.e., when changing the type and proportion of linear elements across the landscapes. Once all ESs indicators were estimated spatially, each of them was aggregated into an average number for the whole case study area. Third, we analysed bundles of ecosystem services under the baseline scenario and the scenario with the highest share of linear elements.

2.4.1. Spatially explicit estimation of ecosystem services

Pollination and natural pest control

To estimate effects of linear landscape elements on the potential supply of pollination and natural pest control. we used the Natural Capital Model (NC-Model) (de Knegt et al., 2022). The NC-Model comprises of a set of thirteen ES developed to assess ESs supply for the Netherlands for a baseline situation and scenarios (de Knegt et al., 2022), used for national policy applications for the Dutch Environmental Assessment Agency. The Pollination and Natural Pest Control model of the NC-Model are process-based models. They model spatial explicit distribution of pollinators and natural enemies based on the location and quality of source habitats and the mean dispersal abilities of pollinators and predators. To do so, the NC-Model requires a land-use map and inputs (reference values) on habitat quality for pollinators and natural enemies, to predict the potential pollination (%) or relative abundance of natural enemies (%) in crop fields. Appendix 1 shows the maps of the spatial distribution of pollination and pest control services for the baseline scenario and for the situation where 12.5 % of the whole utilized agricultural area was covered by hedgerows.

The pollination service is primarily provided by the ecosystems in the landscape surrounding the crop fields (de Knegt et al., 2022). In the crop pollination model the potential pollination by wild pollinators was estimated based on the availability of resources in the agricultural landscape and the mean dispersal abilities of pollinators (Ricketts et al., 2008). The pollinators required suitable nesting habitats as well as

Table 3a
Harmonized Land-use land-cover classification used for the three case studies and the parametrization for the NC-models for pollination (value between 0 and 100 indicating the habitat quality for nesting and alternative floral resources for wild insect pollinators), pest control (for a simplified classification of four source habitat types for natural enemies of crop pests (see Table 3b) for parameterization of habitat quality of these habitat types in the natural pest control model) and carbon sequestration (ton C/ha/yr), related to the capacity for each land-use land-cover category to supply each of the services.

Land-use land-cover	Habitat suitability for pollination	Habitat type for predators	Carbon sequestration
NODATA	0	0	0
Forest, deciduous	89	3	1.8
Forest, coniferous	44	3	0.5
Forest, semi-natural coniferous	44	3	0.8
Forest, mixed	66	3	1.1
Forest, semi-natural mixed	66	3	1.4
Hedges/tree lines	89	4	0.9
Hedges/tree lines, coniferous	44	4	0.4
Hedges/tree line, mixed	66	4	0.55
Scattered trees	89	4	0.36
Heathland	100	1	0.19
Low vegetation	26	2	0.18
Transitional woodland-shrub	100	3	0.9
Tall herb	48	1	0.18
Scrub	48	2	0.9
Marshes	36	2	0.22
Salt marshes	36	2	1.5
Cropland, annual	0	0	0
Cropland, extensive	41	0	0
Cropland, biodiverse	41	2	0.18
Flower strip	80	1	0.18
Perennials, regular	0	2	0.92
Perennial, extensive	58	2	0
Pasture, regular	26	0	0.18
Pasture, extensive	53	0	0.18
Pasture, extensive, with flowers	53	2	0.18
Sand/fallow land	26	2	0
Built-up/ infrastructure	0	0	0
Built-up, with vegetation	0	2	0
Urban green	41	2	0.26
Bare land	0	0	0
Water	0	0	0
Water, with vegetation borders	0	2	0

sufficient floral resources. Parameterization of habitat suitability was based on a global meta- analysis (Kennedy et al., 2013). The indicator used for the pollination service was potential pollination (%), which relates to the percentage of the productivity of the crop that depends on insect pollination that could be provided by the surrounding landscape. This indicator could be combined with crop specific values for potential production loss in the absence of pollinators, to get a measure for avoided production loss in ton/ha or euro/ha.

Similar to pollination, the potential for natural pest control also depends on (semi-)natural ecosystems in the landscape surrounding the crop fields. The model estimates the potential pest control level assuming that no pesticides are applied. The contribution of the ecosystem types depends on the quality of the ecosystem as source habitat for natural enemies of crop pest species (Table 3b)) and the distance between these source habitats and the cultivated crop. In the NC-Model the relative densities of three natural enemy groups (crawling predators, flying predators and flying predators that require nectar) in crop fields were estimated based on possible source habitats (e.g., overwinter habitats) in the surrounding landscape combined with the dispersal abilities of the natural enemies (de Knegt et al., 2022). The indicator used for potential pest control supply was relative predator density (%) of the three natural enemy groups combined. This density was scaled relative to the standardized density of 100 % of the most suitable source habitat (e.g., forest edges). The relative density was not linked to the actual contribution of natural enemies to pest control in the field, but it indicated the potential for natural pest control. Similar to the pollination model the distribution of the natural enemies is described with a negative exponential, and that natural enemies from all suitable habitats in the local landscape contribute to natural pest control. One of the predator groups, the flying natural enemies that depend on nectar, also required floral resources to provide the service. For this predator group, an additional spatial relation was modelled that assumed that the effectivity of pest control is highest at the floral resources and decreases with distance from the floral resources. The same parameterization of the habitat quality per land-use land-cover type was used across the three case studies, as the parameterization was based on international scientific literature covering a wide range of geographical areas (Table 3b, de Knegt et al., 2022). For more information about the NC-Model, and about the parameterization of the dispersal processes in the pollination and the natural pest control model see de Knegt et al. (2022). *Global climate regulation*

Table 3b
Parameterization of habitat quality for the 3 groups of natural enemies considered in the natural pest control model. Where values between 0 and 100, indicate the habitat quality of the simplified land use class as source (i.e. overwintering) habitat for the 3 classes of natural enemies of pest species (crawling predators (e.g. carabid beetles), flying predators (e.g. assassin bugs, ladybugs), flying predators that require nectar (e.g. Syrphidae), and the quality of the habitats to provide floral resources to the flying predators that require nectar.

	Source habitats			Floral resources
Simplified land-use class (habitat type for predators from Table 3a)	Crawling predators	Flying predators	Flying nectivores	Flying nectivores
No data/not suitable (0)	0	0	0	0
Herbaceous, flower rich (1)	10	70	70	100
Herbaceous, flower poor (2)	10	40	40	60
Forest edge* (3)	10	100	100	70
Hedgerows / tree lines (4)	2	50	50	0
Agricultural fields**	5	0	0	2

* only the edges (30 m) of forests are considered source habitat,
** location of agricultural fields is based on the crop type map.

For global climate regulation we used as indicator the sequestrated carbon in the vegetation (tC/ha). The approach from Natural Capital Accounting in the Netherlands (Statistics Netherlands and WUR, 2021) was used to quantify the change in total carbon sequestrated per year in the linear landscape elements. This model required input of land-use data and combined this input with carbon sequestration rates in above and below ground biomass per land-use category. The parameterization for the Netherlands was also used for the study sites in Denmark and Hungary. Because the study focuses on the additional carbon sequestration by the added linear elements, and not on the comparison between countries, we assumed that the same species would be used in the linear elements and that therefore the sequestration would be similar. For the flower strips we assumed that these remained at the same location multiple years, and carbon would be stored in below ground biomass.

Food and feed production

We estimated food and feed production using a lookup table that linked the main crops and grasslands in each study area with their average productivity (yield per hectare in ton/ha) and price (Euro / ton). Information about the average productivity and prices were derived from national statistics. To evaluate the effects of linear landscape elements on food and feed provision, we first multiplied the total cultivated land by the average productivity, to get the total production per crop and grassland and per scenario. In order to aggregate the information for all crops, we subsequently multiplied the total yield, for croplands and grasslands by the price of the crop or fodder and added up these numbers. The change in the value of the food and feed production was due to the fact that the linear elements would take up land until then used for production.

Aesthetics and habitat maintenance

Following Van Bussel et al. (2020), we computed several landscape metrics to capture landscape aesthetics and habitat maintenance. We used ArcGIS® software and Patch Analyst v5.1.0.7 software (Rempel et al., 2012) –to calculate all landscape metrics, based on the land-cover maps. The land-cover maps were resampled into a 10 x 10 m spatial resolution because of computation times. To quantify the two ESs, no differences were made between the four different types of strips, because of lack of available data differentiating the four types of linear elements and because of the importance of landscape structure (i.e., spatial pattern of landscape elements and the connections between them) in the supply these two ESs (Dramstad et al., 2006; Van Bussel et al., 2020).

We estimated aesthetics based on three landscape metrics, as proposed by Frank et al. (2013): the Shannon's Diversity Index, the Patch Density and the Mean Shape Index, which are important indicators of landscape aesthetics. These three metrics capture the landscape diversity and the complexity of the shapes of the patches in the landscape. The metrics were computed from the land-use land-cover maps that we first clustered, based on diversity and hemeroby groups of the land-cover classes (Frank et al., 2013). To compute the Shannon's Diversity Index and the Patch Density metrics, we first re-classified the land-use land-cover based on the degree of diversity of each of the land-use land-cover classes. To compute the Mean Shape Index, we re-classified the land-use land-cover based on the degree of hemeroby (see Table A1). These diversity groups distinguish land-cover classes based on human impacts. An aesthetics index was computed from the three individual metrics after we normalised them. To do so, we identified the maximal value of each individual metrics across all scenarios, including the baseline situation, per country. We then divided the value of the three metrics by the maximal value identified in the previous step. We summed up the three normalized metrics to get the aesthetics index per study area. See Table A1 for additional information on the degree of hemeroby and diversity for each land-use land-cover class.

Landscape complexity is considered of vital importance to support ecological processes that enable biodiversity to persist (Estrada-Carmona et al., 2022). Following Estrada-Carmona et al. (2022), we considered three broad categories to define landscape complexity: composition, configuration, and heterogeneity. To capture the

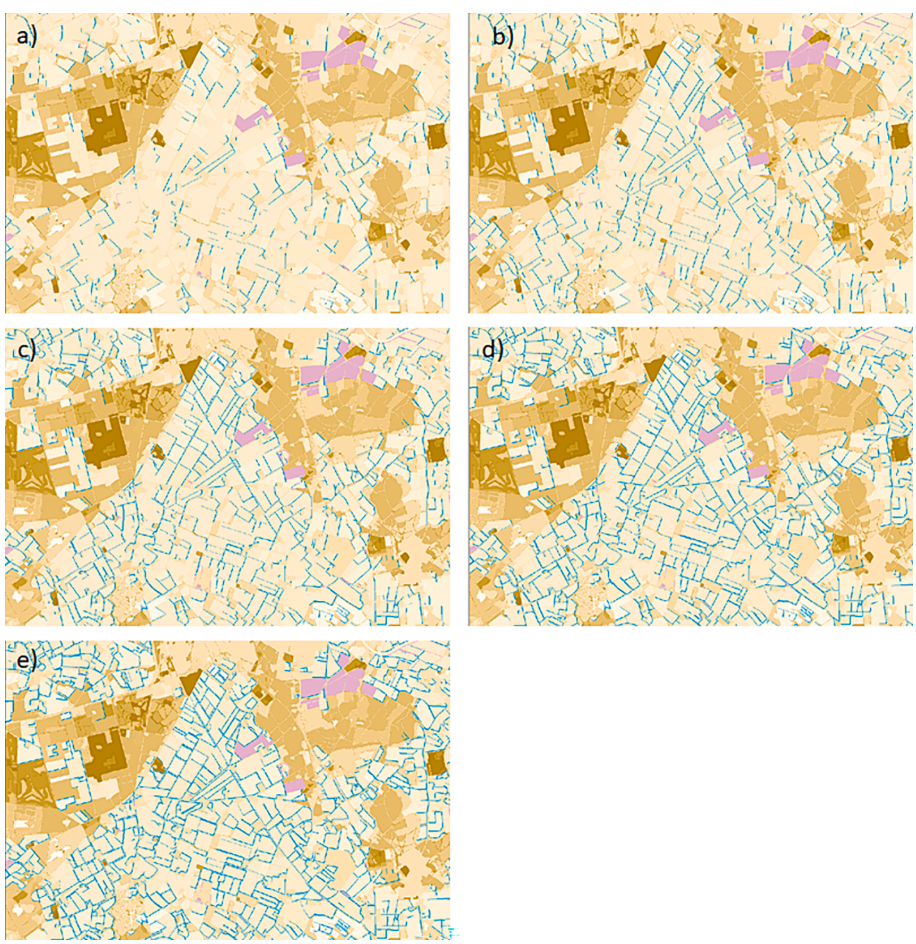

Fig.3. Schematic illustration of the random allocation of the linear elements in blue a) 2.5 %, b) 5.0 %, c) 7.5 %, d) 10.0 %, and e) 12.5 % of the whole utilized agricultural area covered by linear elements with a width of 10 m. The purple areas indicate parcels with existing agri-environmental measures. Different shades of brown indicate different land-covers.

composition of the landscape, we re-classified the land-use land-cover into four classes and computed the proportion of each (% of the total area): (semi-)natural ecosystems, cropland and orchards, pastures, and artificial surfaces (see Table A1 for the link between the land-use land-cover type and the four landscape composition classes). To capture the configuration of the landscape, we calculated the inverse Euclidean Nearest-Neighbour Distance between patches of (semi-) natural ecosystem (distance between centroids). The distance between patches of (semi-)natural habitats can be used as an indicator of landscape connectivity (Van Bussel et al., 2020). We then calculated the average distance at the landscape level. Landscape heterogeneity was included by the richness of land-cover types in calculating the Shannon's Diversity Index on the land-use land-cover data. We calculated an index per study area as indicator for habitat maintenance, by computing the sum of the three individual metrics, following the procedure described above to compute the aesthetics index.

2.4.2. Scenarios of linear elements allocation

We performed a scenario analysis to assess the effect of the type and proportion of linear elements on the potential supply of ESs (Fig. 3). The current land-cover maps for the three study areas were used as the baseline scenario. For the Danish and Hungarian study areas, no existing linear elements were displayed on the current land-cover maps, probably due to the resolution of the available maps. For the Dutch study area existing linear elements were displayed on the map and these elements were made part of the Dutch baseline scenario. For each of the study areas, we developed a script to add randomly 10 m wide linear elements to the current land-cover maps until a coverage of 2.5 %, 5 %, 7.5 %, 10 % and 12.5 % of the whole utilized agricultural area was achieved (see Fig. 3 for a schematic example). We defined utilized agricultural area as the total area, for each case study, primary used for agricultural purpose (i.e., annual and perennial croplands and temporary and permanent grasslands (meadows and pastures)). For each coverage four maps were created, with 100 % hedgerows (i.e., woody strips), 100 % grassy strips, 100 % flower strips and a balanced mix of woody (33 %), grassy (33 %) and flower (33 %) strips.

We arbitrarily decided to allocate linear elements to the eastern border of the agricultural fields displayed on the current land-cover maps. If a field was already bordered by a linear element (in the Dutch case), no additional element was added to this field. If the total area covered by elements was lower than our targeted coverage, we then also added elements to the southern or northern border of the fields. In the latter case, one field can thus be bordered by several elements. The linear element was always added to the agricultural field in focus, i.e., subtracted from the original agricultural area, without considering the type of agricultural use on that specific field nor the neighbouring land-cover class.

The location of the linear elements affects the level of potential ESs supply and biodiversity (Moonen and Marshall, 2001). However, farmers' decisions about where and which linear elements to implement on their fields encompass more factors than just the effect on the supply of ESs (Wang et al., 2021), that might mainly be dependent on practical considerations, such as soil quality, accessibility. Including this complex decision-making process is beyond the scope of our research, so we opted for a random assignment of the position of the linear elements, following Huber et al. (2022). We repeated this random distribution of the linear landscape elements five times. By applying five iterations, we accounted for uncertainties related to the decision making process by farmers. For each iteration, we estimated the potential supply of all individual ESs. We then estimated the average potential supply for each individual ES, across the five iterations for one given share of linear landscape elements (ranging from 2.5 % to 12.5 % covering the utilized agricultural area). Except for the agricultural land replaced by the linear elements, we assumed that the use of the remaining land did not change. By following this methodology, our results represent the range of potential effects rather than a prediction of actual land-use.

The new linear elements were included in the estimation of potential ESs supply. Grassy, flower and woody strips were considered as separated vegetation patches and their capacity to supply ESs was considered as the ones of semi-natural grasslands, natural grasslands (flower rich habitat), and deciduous forests, respectively.

To assess the change (i.e., additional or reduced potential supply of ESs) we used this formula:

$$Change = \frac{ES_{LS} - ES_{BL}}{ES_{BL}} \times 100\% \qquad (1)$$

With ES_{LS} being the estimated potential ES supply under one of the linear elements' scenarios and ES_{BL} the estimated potential ES supply under the baseline situation.

Finally, we calculated the standard deviation of the six ESs indicators for each type of linear landscape elements and scenario, across the five simulations. Standard deviation gives information about the variability of potential ESs supply over the five simulations and therefore insights in the robustness of our methodology of assigning landscape elements.

2.4.3. Bundles analyses

In the final step, we analysed ESs bundles at the landscape level, in the baseline situation and in the scenario with 12.5 % coverage of linear elements. Aligned with the work of Raudsepp-Hearne et al. (2010) we identified ESs bundles to analyse interactions among ESs.

We relied on the modelled potential supply of the six ESs indicators, in each of the three study regions. We performed a min–max normalization of the potential supply of the six ES indicators. To do so, we identified the maximal variation of each ES indicator among all considered scenarios (baseline and the scenarios with 12.5 % of landscape elements). We then divided the value of the six ESs by the maximal value identified in the previous step. Normalized values were comprised between 0 and 100 and were used to analyse the bundles.

3. Results

3.1. Effects of type and proportion of linear elements ES at the landscape level

Across the three study areas the increase of linear elements led to an increase in the potential supply of all six ESs, except for the food and feed provision. The variability across the five iterations per scenario was very low for all six ESs and all three study areas, showing that the location of the linear elements was not likely to affect the change in ESs indicators.

3.1.1. Pollination

Under the baseline situation the mean potential pollination by wild pollinators is close to its relative maximum in Őrség National Park (98 %) and reaching potential in the Achterhoek (95 %). In contrast, the current landscape of Bornholm provided a lower potential pollination of 62 %. The difference in potential pollination could be explained by the current land-use in the three study areas. In Őrség National Park, large parts of the area were covered by forest (Fig. 1), which was characterized by a rather high habitat suitability for wild pollinators. In the Achterhoek, large areas were covered by grasslands (Fig. 1) which also provided habitats albeit with a relatively low quality. In Bornholm the landscape was dominated by fields with arable crops, which were considered not suitable as habitat for wild pollinators. The spatial outputs of the pollination model for the three case studies, and for the baseline and the 12.5 % scenario can be found in the appendix (Fig. A1).

Fig. 4 shows that a higher coverage of agricultural land by linear

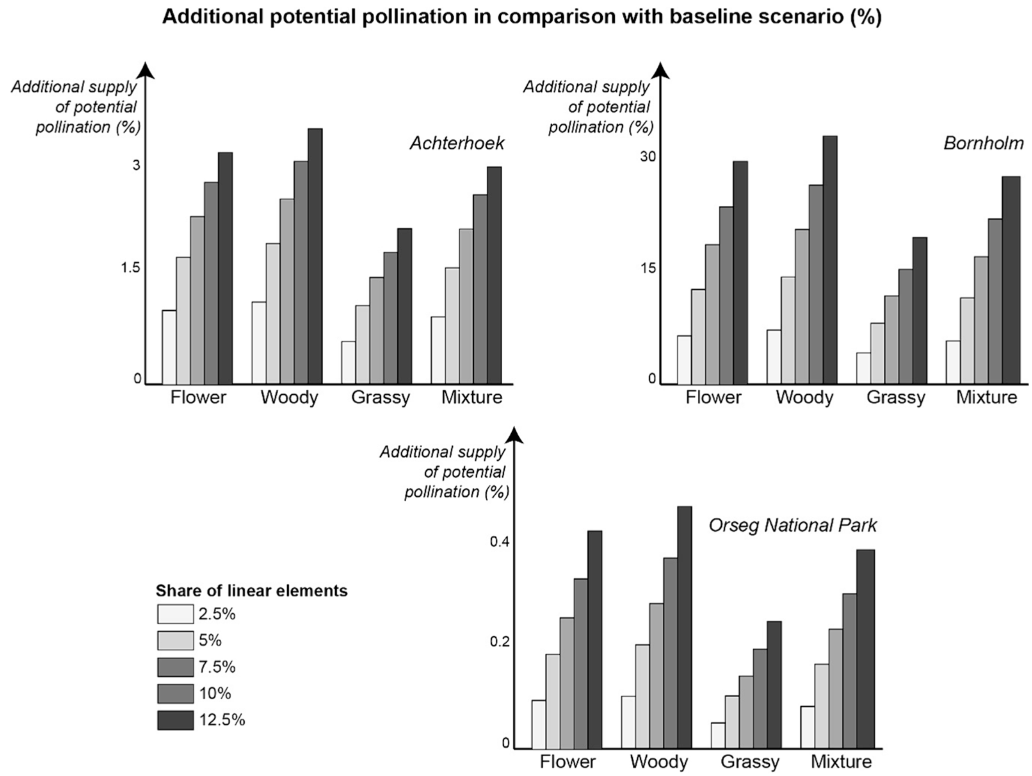

Fig.4. Additional pollination potential compared to the baseline scenario (%) for the Achterhoek, Bornholm, and Őrség National Park for the different coverages and different type of linear landscape elements (2.5%, 5.0%, 7.5%, 10.0%, and 12.5% of the whole utilized agricultural). The graph shows the average ES supply across the five iterations, for each scenario and study area. Please note the different scales of the y-axis. The total pollination potential reached 95%, 62% and 99% for the Achterhoek, Bornholm, and Őrség National Park respectively, under the baseline scenario. The potential of ecosystems to contribute to pollination by wild pollinators is represented by the indicator avoided production loss, which is based on the relative pollinator visitation rate (see also Table 1).

landscape elements resulted in a higher potential supply of the ES pollination. We observed diminishing returns, as the relative benefits of linear landscape elements were lower in areas that already had high habitat suitability under the baseline situation. Largest increases were simulated for Bornholm, smallest for Őrség National Park. The different types of linear landscape elements showed similar trends across coverages: a higher coverage implied higher potential ES supply, for any types of linear elements. Implementing hedgerows was most beneficial to supply additional pollination. In all three case study areas a coverage of 2.5 % with hedgerows provided approximately the same additional potential supply as a coverage of 5.0 % with grassy strips.

3.1.1. *Natural pest control*

The differences between the study areas in the potential supply of natural pest control were much smaller than for the potential pollination supply. Under the baseline scenario the relative predator density was the highest in the Achterhoek (15 %) and the lowest in Bornholm (10 %). Adding linear landscape elements considerably enhanced the potential supply of natural pest control (Fig. 5). In the Achterhoek, 10 % extra coverage of the agricultural landscape with flower strips or hedgerows more than doubled the relative predator density. In Bornholm, 5 % extra coverage of the agricultural landscape with flower strips, hedgerows or a mixture approximately doubled the relative density. The additional potential supply of natural pest control was smaller in Őrség National Park: 12.5 % additional coverage with flower strips or hedgerows gives approximately 90 % additional relative predator density. The smaller added value in Őrség National Park could be explained by the large variation in agricultural fields sizes in Őrség National Park. Even though the average field size of 2.4 ha was similar to the Achterhoek (2.1 ha), it consisted of many small fields (median 0.9 ha) and some very large fields (maximum size of 83 ha). Natural enemies had a smaller action radius than pollinators. Their relative density decreased with distance into the field. Consequently, large fields result in large areas with low relative densities, greatly reducing the added effect of the strips in these large fields.

As for the potential pollination, implementing hedgerows or flower strips provided a larger potential supply than grassy strips. A coverage of 2.5 % with hedgerows or flower strips provided approximately the same additional potential supply of natural pest control as a coverage of 5.0 % with grassy strips. The spatial outputs of the pest control model for the three case studies, and for the baseline and the 12.5 % scenario can be found in the appendix (Fig. A2).

Fig. 5 Additional relative predator density compared to the baseline scenario (%) for the Achterhoek, Bornholm, and Őrség National Park for the different coverages and different type of linear landscape elements (2.5 %, 5.0 %, 7.5 %, 10.0 %, and 12.5 % of the whole utilized agricultural). The graph shows the average ES supply across the five iterations, for each scenario and study area. Please note the different scales of the y-axis. The relative predator density reached 15 %, 10 % and 14 % for the Achterhoek, Bornholm, and Őrség National Park respectively, under the baseline scenario. The potential of ecosystems to contribute to pest control is represented by the density of natural enemies, which is based on the LUCL and on the distance to the crops (see also Table 1).

3.1.2. *Global climate regulation*

Carbon sequestration (ton carbon/km^2/year), as indicator for global

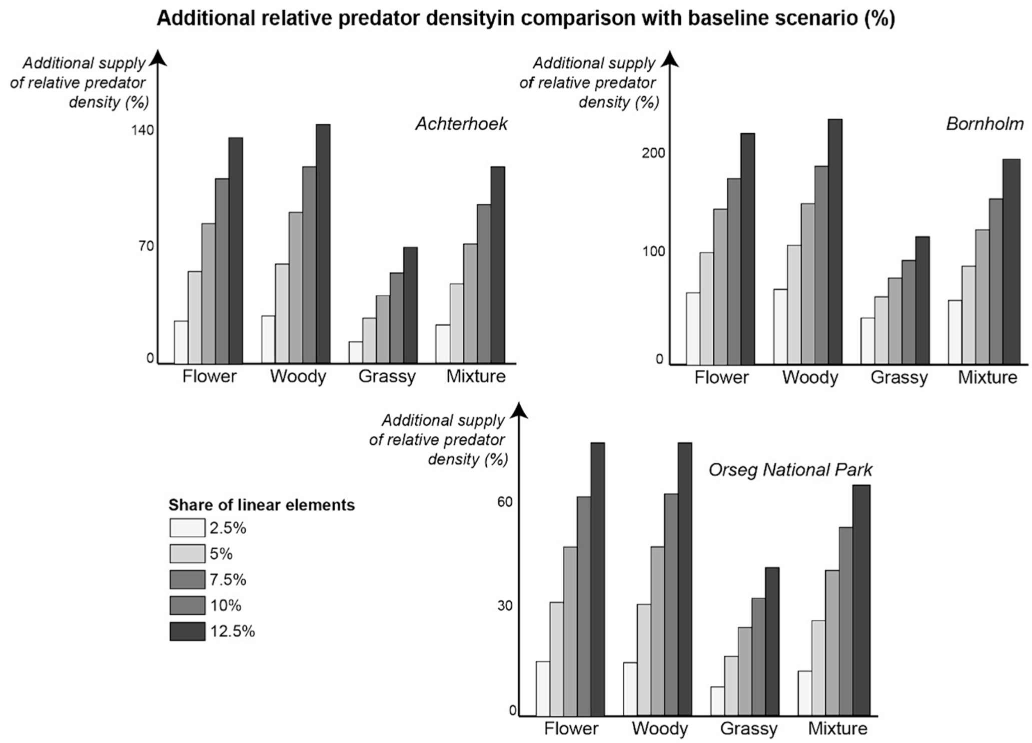

Fig. 5. Additional relative predator density compared to the baseline scenario (%) for the Achterhoek, Bornholm, and Őrség National Park for the different coverages and different type of linear landscape elements (2.5%, 5.0%, 7.5%, 10.0%, and 12.5% of the whole utilized agricultural). The graph shows the average ES supply across the five iterations, for each scenario and study area. Please note the different scales of the y-axis. The relative predator density reached 15%, 10% and 14% for the Achterhoek, Bornholm, and Őrség National Park respectively, under the baseline scenario. The potential of ecosystems to contribute to pest control is represented by the density of natural enemies, which is based on the LUCL and on the distance to the crops (see also Table 1).

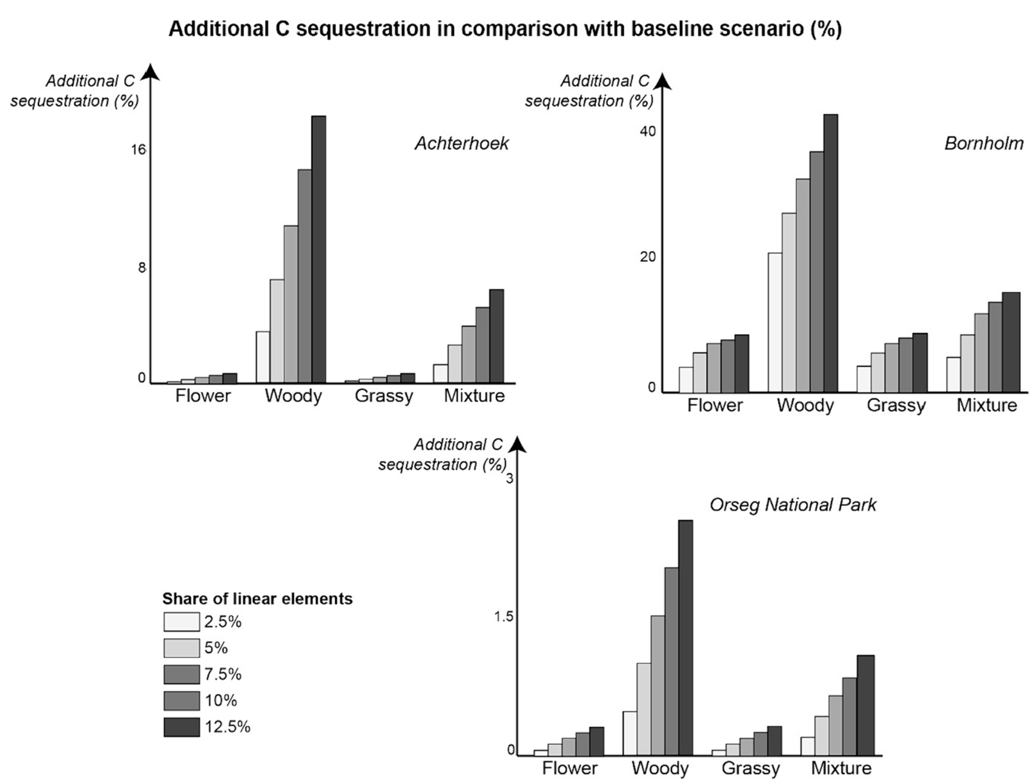

Fig. 6. Additional mean carbon sequestration to the baseline scenario (%) for the Achterhoek, Bornholm, and Őrség National Park for the different coverages and different type of linear landscape elements (2.5%, 5.0%, 7.5%, 10.0%, and 12.5% of the whole utilized agricultural). The graph shows the average ES supply across the five iterations, for each scenario and study area. Please note the different scales of the y-axis. The mean carbon sequestration reached 59 ton C/km^2/year, 26 ton C/km^2/year and 86 ton C/km^2/year for the Achterhoek, Bornholm, and Őrség National Park respectively, under the baseline scenario.

climate regulation, was highest in Őrség National Park, and considerably lower for Bornholm. This difference could be explained again by the current land-uses of the region (Fig. 1). Large parts of Őrség National Park were covered by forests, with a high carbon sequestration potential, while Bornholm is mostly covered by agricultural fields that have a low or zero net carbon sequestration. Note that information on farming practices relevant to carbon sequestration, such as catch crops, wintergreen fields, and conservation agriculture, is not included in the analysis. Fig. 6b shows that adding hedgerows to the landscape gave larger amount of additional carbon sequestration than flower or grassy strips. In Bornholm covering 2.5 % of the agricultural area with hedgerows resulted in a 20 % additional carbon sequestration and covering up to 12.5 % resulted in a 40 % additional carbon sequestration in comparison with the baseline situation. In the Achterhoek covering 12.5 % of the agricultural area with hedgerows led to an addition 18 % of carbon sequestration. In Őrség National Park 12.5 % coverage of the agricultural area led to only 2.5 % additional carbon sequestration in comparison with the baseline situation. This small increase could result from the high mean carbon sequestration in the baseline scenario in combination with the relatively large area of Őrség National Park.

3.1.3. *Food and feed provision*

The indicator for the ES food and feed provision decreased with an increase in the coverage of linear landscape elements in the three study areas. The decrease of food and feed provision was linear and much steeper in the Achterhoek than in the two other study areas. It is important to note that feedback loops, and therefore the potential positive effects of linear elements on crop yields through changes in other environmental parameters, such as micro-climate, and the positive impact of the pollination and pest control ESs were not taken into account in this study.

3.1.4. *Aesthetics*

Under the baseline situation the degree of human disturbance, or naturalness, was approximately the same for the three study areas. Landscape aesthetics in the baseline situation was the highest in the Achterhoek, where the landscape was already diverse and fragmented. While the mean shape index decreased in the three study areas, meaning that the shapes of the landscape elements were increasingly more regular, adding landscape elements to the landscape increased the values of the Shannon's diversity and of patch density. This means that for all three regions the landscape became more diverse and fragmented by adding landscape elements.

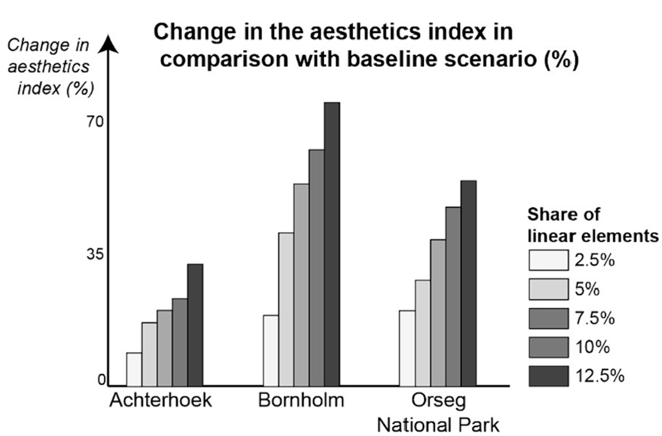

Fig. 7. Change in the aesthetics index based on three landscape metrics (mean shape index, Shannon's diversity, and Patch density) to estimate landscape for the different coverages and different type of linear landscape elements (2.5%, 5.0%, 7.5%, 10.0%, and 12.5% of the whole utilized agricultural). The graph shows the average potential ES supply across the five iterations, for each scenario and study area. The aesthetics index reached 193, 143 and 159 for the Achterhoek, Bornholm, and Őrség National Park respectively, under the baseline scenario..

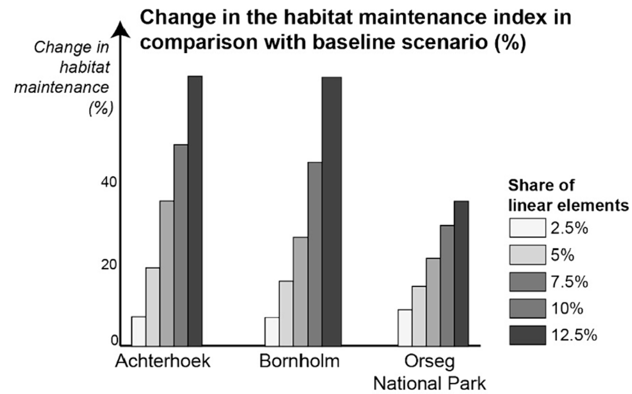

Fig. 8. Change in the habitat maintenance index based on three landscape metrics (landscape composition, Shannon's diversity, and distance to (semi-)natural habitats) to estimate habitat maintenance for the different coverages of linear landscape elements (2.5%, 5.0%, 7.5%, 10.0%, and 12.5% of the whole utilized agricultural). The graph shows the average potential ES supply across the five iterations, for each scenario and study area. The habitat maintenance index reached 181, 181 and 220 for the Achterhoek, Bornholm, and Őrség National Park respectively, under the baseline scenario.

3.1.5. *Indicator of habitat maintenance*

The indicator of habitat maintenance increased with an increase in the area covered by linear elements, for the three study areas (Fig. 8). The share of (semi-)natural habitats increased with an increase in the area covered by linear elements. This increase depends however on the study area. Whereas the increase was strong in the Achterhoek and in Bornholm, it was much lower in the Őrség National Park. The Shannon diversity index, showing the diversity of land-covers in the three study areas, was the highest in the Achterhoek, and the lowest in the Őrség National Park. Achterhoek became more divers with implementing linear landscape elements, but the change was larger in Bornholm. Őrség National Park became less diverse, as the presence of (semi-)natural was already very high. Similar patterns could be found with respect to the distance to semi-natural elements. Initially the distance was the smallest in Őrség National Park, and largest in Bornholm; in all study regions the distance decreased, when the share of linear elements increased.

3.2. *Bundles analyses*

Fig. 9 shows the bundles of the six ESs indicators. By showing what ESs are highly provided when the potential supply of another one is low, the bundle analysis allows us to observe a pattern of trade-offs between the provisioning and both regulating and cultural ESs. While all the indicators for regulating and cultural ESs show a positive trend with increasing coverage of linear elements, the indicator for provisioning ES decreased in the three case study areas. Hedgerows seemed to be the type of linear elements that minimizes the trade-offs between provisioning and the other types of ESs as it led to the same reduction of food and feed provision as the other types, while maximizing the increase of pollination, natural pest control, carbon sequestration, aesthetics and habitat maintenance.

The indicators for regulating and cultural ESs showed similar trends across the three study areas, all increasing overall with the implementation of linear elements, mainly with the increase in the woody linear elements. The changes induced by the adoption of the measures were overall higher for pest control in the Achterhoek, habitat maintenance in the Őrség National Park and for all other ESs in Bornholm.

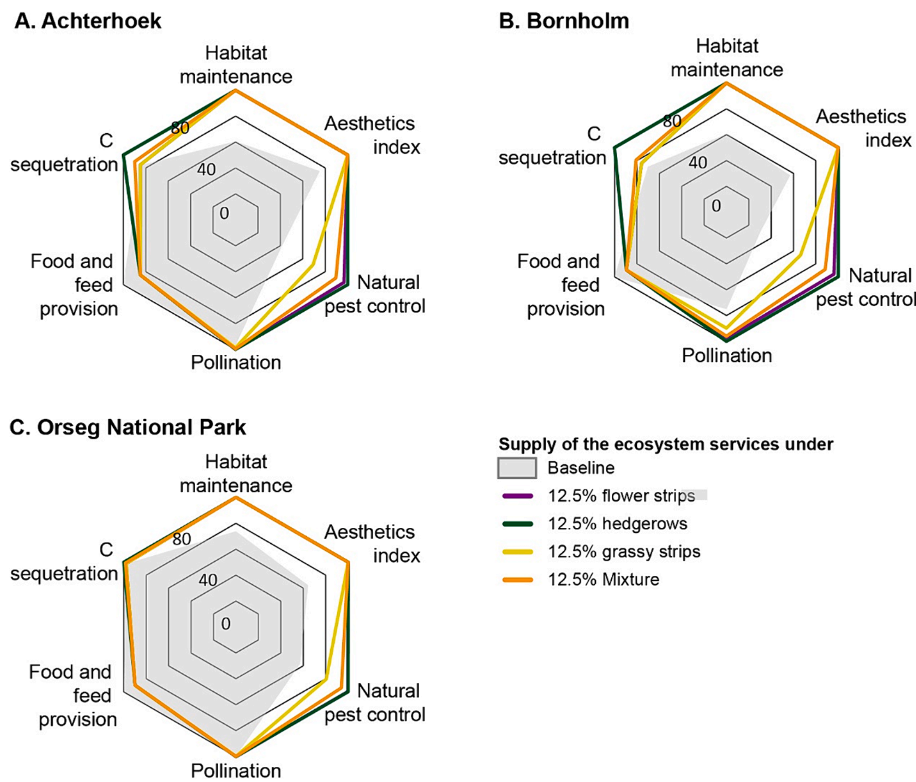

Fig. 9. Potential supply of the six ESs for the baseline situation and the 12.5% coverage and different type of linear landscape elements in (a) the Achterhoek, (b) Bornholm and (c) Őrség National Park.

4. Discussion and conclusion

In this study, we relied on existing modelling approaches and a rich multi-source dataset to assess the changes in the potential supply of six indicators of ESs under several management scenarios in three multi-functional agricultural landscapes with different baseline situations. We were not interested in the actual production of ESs, but in changes when adding more linear elements to landscapes with different baseline situations. We also analysed ESs bundles under these scenarios at the landscape level. Our results highlight that the implementation of linear landscape elements can support the increase in the potential supply of multiple regulating and cultural ESs and give insights on the potential effectiveness of AECMs to achieve multiple environmental targets.

Our study goes beyond the assessment of the effects of AECM contracts or measures on a single environmental parameter, usually related to biodiversity conservation (Kleijn et al., 2006; Blomqvist et al., 2009; Grondard et al., 2023) or ESs. Our study contributes to the scientific literature demonstrating the overall positive effects of linear elements and more generally on agri-environmental practices that can stem from a set of AECM on multiple environmental parameters (Van Vooren et al., 2017; Albrecht et al., 2020). To do so, we followed a scenario modelling procedure, that proved to be of particular relevance, because the parameters of concern are complex to measure in the field (Sang, 2020). In addition, scenario analyses allowed us to estimate the potential impacts of policy measures in order to advice decision making processes, with a particular focus on the landscape context.

4.1. *Overall positive, yet contrasted, effects of linear elements on multiple ESs*

Our results demonstrate the overall positive effects of linear elements on several ESs. Similarly to Verhagen et al. (2018) and Albrecht et al. (2020), we found that all measures could improve several environmental objectives simultaneously. We showed that the effects of the linear elements on potential ESs supply depended on the ESs. Whereas regulating and cultural ESs responded in a similar way to the implantation of linear elements, the ES of food and feed provision showed an opposite trend. The positive effects of any of the types of linear elements on regulating and cultural ESs gradually increased with the increase in the share of linear elements across the landscape. The increase of linear elements implied a decrease in the agricultural used area leading to a decrease in the provisioning ES. This result is aligned with other studies that highlighted the trade-offs between food and feed production and regulating and cultural ESs in agricultural landscapes (Ruijs et al., 2013; Verhagen et al., 2018) and an overall increase in ESs supply with an increased landscape heterogeneity (Botzas-Coluni et al., 2021). While our results cannot give advice on how to minimize this trade-off by implementing AECMs based on linear landscape elements, we showed that linear landscape elements can simultaneously support a high level of multiple regulating and cultural ESs.

Our results also suggest that, while all types of linear elements had great potential in supplying multiple ESs, their effect depended on the ESs, the types of linear elements and their share in the landscape. For instance, the increase in the potential pollination was most likely to occur with an increase of hedgerows, and to, a lesser extend with an increase of flower strips, and least with an increase of grassy strips. In addition, we demonstrated that ESs responded differently to the type of linear elements. Flowers strips, for example, showed limited effects on the potential supply of carbon sequestration, but contributed to a high level of natural pest control. A recent empirical study by Bishop et al. (2023) also showed that pollination and natural pest management are influenced by the type of linear element, attributed to the different habitat factors per type. However, in contrast to our study, Bishop et al. (2023) showed that hedgerows have a negative impact on the presence of wild bees, but this is probably because the farmers in this study manage their hedgerows in such a way that they limit flowering to prevent pome fruit disease. The potential of hedgerows to sequester carbon was in line with our study also demonstrated by Drexler et al. (2021) and Van Den Berge et al. (2021).

We found that the consideration of the geographical contexts is critical when assessing the effects of measures on multiple ESs. The effects of the linear elements on the potential supply of the six ESs were highly context-dependent, i.e., depended on the biophysical characteristics of the landscape and its environmental condition under the baseline scenario. When the potential supply of the ESs was already high in the baseline situation, e.g., pollination in the Achterhoek, the changes induced by the implementation of the linear elements were much lower than when the baseline situation showed a lower initial potential supply of one or several of the ESs, e.g., pollination in Bornholm. These results align with the previous findings from Tscharntke et al. (2005) and Krimmer et al. (2019) showing that linear elements are more effective in terms of potential ES supply in landscapes with a low share of (semi)-natural habitat (1–20 %) than in landscapes with a high share of (semi)-natural habitat, such as the Őrség National Park.

The location of those elements within the landscape did not affect the ESs, as reflected in the absence of variability of the potential supply of the multiple ESs across the five iterations of each scenario., Our random allocation process did not always created similar patterns when linear elements were added in very different locations across the landscape for the scenarios with small share of these elements (e.g. 2.5 % and 5 %). However, it is important to note that our study considered three landscapes with a very homogenous topography and that it did not account for the demand for these ESs. Yet, demand might vary across space, probably leading to an increased positive effect of the linear elements in some places and lower effects in others. In addition, although previous research has shown that the type of measures, i.e., related to the change in management practices, has stronger effects on farmland birds than the spatial clustering of the plots where these measures are applied (Grondard et al., 2023), this needs to be researched in more detail for the ESs investigated in this research.

4.2. Limitations of the study

Multiple challenges exist in ESs assessments (Burkhard et al., 2013), leading to uncertainty in the assessment outcomes. Despite its strengths, our study shows six main limitations, mainly related to methodological choices and to the use of models that are simplification of complex processes and phenomena. Our approach and outputs should therefore be considered carefully, because these limitations and inherent associated uncertainty could have resulted in uncertainty in the results. While we think our study has brought science further by developing a general framework for an ex-ante integrated analysis of AECM contracts in which several ESs and their trade-offs are investigated, careful consideration and communication of the limitations of such integrated analyses is critical, especially when used for decision making purposes.

The first limitation is related to the choice of the ecosystem services and of their indicators. We only considered a limited set of six ESs. Yet, agricultural areas provide a wider range of ESs, such as water quality regulation and erosion prevention (Zhang et al., 2007; Galler et al., 2015). Moreover, the selected indicators used to represent the ESs captured only a part of the complexity of the ESs, as 1) they only captured potential ESs supply, without considering demand, due to data constraints; 2) they were one of the possible indicators whose choice was partially arbitrary; and 3) they remained general, as opposed to specific for local requirements. For instance, habitat maintenance depends on habitat requirements, which can be quite different among species, whereas our indicator remains very general. Despites these limitations, the choice of the ESs and of their indicators relied on scientifically robust decisions. The studied ESs are diverse in terms of ES categories, as they cover regulating, provisioning, and cultural services, although the provisioning services are under-represented in comparison to the other categories. Additionally, we carefully chose the ESs and their indicators based on scientific literature, data availability and expert knowledge. All ESs indicators have previously been used in peer-reviewed scientific publications. Consequently, while the ESs indicators may be simple, they were suitable for modelling purposes, they are aligned with those that can be found in the literature and a certain replicability of the method to other agricultural landscapes is possible. Modelling the six chosen indicators allowed us to show changes in potential ES supply in the studied socio-ecological systems under different scenarios due to the implementation of linear landscape elements.

The second limitation is related to data availability and pre-processing, which is often necessary in modelling and for case studies with heterogenous data resources. Modelling for the three case studies relied on the same type of data, which came with challenges in terms of availability, terminology and level of detail of the datasets, e.g., of the land use land cover typologies, and differences in spatial resolution. Limitations related to data availability and pre-processing led to increased uncertainties, and uncertainties that are heterogenous across the case studies. Finding data can be more challenging in some areas than in others. For some areas, we were, for example, not able to link spatial data to actual agricultural yield and price data. In addition, other data, such as agricultural intensity, were not systematically available, while previous studies showed that intensity levels affect the supply of multiple ESs in agricultural landscape (Le Clec'h et al., 2019b). Similarly, we did not account for the diversity of farming systems, e.g., conventional vs. organic farming that affect the potential supply of ESs, nor did we consider practical management considerations that would affect the farmers' practices, such as the possible reduced field accessibility for tractors because of the application of linear elements. Data availability also conditioned the choice of modelled ESs and of their indicators. The potential supply of ESs other than the ones studied here, such as soil related ES, rely on more complex ecological functions and require more (detailed) data. Moreover, some land-use land-cover classes could be found under the same name in the typologies of the three case studies. Yet, while the terminology may be identical across the case studies, the actual ecological functioning and geographical characteristics of some of these classes may be different. Additionally, we had to transform data, as we rasterized the land use land cover of the Danish and Hungarian case studies. Such transformation was necessary to feed the NC-models, but possibly generated some distortions that led to possible data and accuracy losses. Finally, the level of detail of the data (thematic resolution) also varied from one study area to another. For instance, the land-use and land-cover classifications for the Dutch and the Hungarian case studies were much more detailed than the classifications of the Danish case study area. For that reason, we enriched the data on semi-natural ecosystem types in the Danish case, by replacing land-use classes with nature dry, with more the more detailed information from the Corine Land Cover maps.

The third limitation is related to the application of scenarios and models. We arbitrarily decided the types and coverage of the linear elements, as well as their location (eastern border of the agricultural fields). In areas where fields are large, considering field borders only may be very restrictive. Future research should investigate the added value of strips within a field. Additionally, while including this complex decision-making process is beyond the scope of our research, we acknowledge that doing so, we ignore the complexity of farmers' decisions about where and which linear elements to implement on their fields. Similarly, we did not distinguish the three types of linear elements when assessing their effects on landscape aesthetics and habitat maintenance, as such effects is still largely unknown and available data is therefore lacking. While our study relies on findings of existing studies that showed the importance of landscape configuration on such ESs (Dramstad et al., 2006), we acknowledge that it might have brought some uncertainties. For instance, landscape openness and aesthetics are strongly linked (Tveit et al., 2006) and some linear elements such as hedgerows have a more visual impact on the landscape openness than other, e.g., grassy strips. Grassy strips located at the edges of grasslands might consequently bring lower benefits in reality than the ones modelled. Furthermore, we used models that were initially created for the Dutch context, such as the carbon sequestration model. This could lead to biases in the total assessment of the potential ESs supply, for the Danish and the Hungarian case studies, especially when the forest types differ in species composition and age. However, for the comparison of the added effect of hedgerows, it could be assumed that these will be similar species and have the same age and are therefore carbon sequestration of the linear elements will be comparable between case studies. For pollination the parameterization, i.e., the values for habitat quality and pollinator home ranges, was based on *meta*-analyses studies (Ricketts et al., 2008; Kennedy et al., 2013). Further research should investigate if the increasing open availability of species presence, absence, and abundance data (e.g., the Global Biodiversity Information Facility) can help to improve the parameterization of local natural pest control models. Even though using local data could improve the reliability of the models, the goal was to compare the added effect of agri-environmental schemes in different landscapes, using the same parameterization ensures that the differences found are mainly related to differences in the landscape configuration and not to differences in parameters. Our analyses in the Hungarian case study might have overestimated the pollination potential due to the presence of large forest areas. However, as a very large share of the case study was covered with semi-natural habitat vs. a small share used for agriculture, the pollination potential was expected to be high. This point underlines the importance of using resulting figures from ESs assessment, cautiously, as order of magnitude or as indicators of trends.

The fourth limitation is related to the lack of consideration of the temporal dimension. Our models focused on general spatial trends and did not capture the temporal dimension, i.e., the time lap needed for vegetation to recover and / or grow. Therefore, they did not capture the time needed for the measures to take full effect, nor the resilience of agro-ecological systems to recover after disturbances. Yet, pollination and pest control services depend on the resilience of the species contributing to the potential supply of the ESs. Consequently, our study should be seen as highlighting general trends happening after the measures had come to full effect and the vegetation in the buffer strips had fully grown, which depend on the type of linear elements. While grassy strips overall showed lower potential to support a high potential supply of multiple ES, they also reached their ability to supply ESs much earlier than hedgerows.

The fifth limitation is related to the lack of consideration of the feedback loops that might occur when enhancing the potential supply of one ES. For instance, we did not consider the positive effects of increased natural pest control on the use of pesticides which can have beneficial effects on pollinators. Food and feed production is a result of a combination of artificial inputs, e.g., human labour, machinery and seed, with ecosystem services, e.g., pollination and natural pest control. Due to limited available data on avoided yield losses due to (enhanced) ESs we could not consider this effect on yields. Further research could concentrate on disentangling human and ESs inputs and in particular the possible economic advantage of enhanced potential supply of ESs across landscapes with a higher share of linear landscape elements. In addition, we also did not consider the possible negative effects of linear elements on crop yields due to, for example, spreading of weeds and rodents in the cropping area (Uyttenbroeck et al., 2016), nor the effect of shadows created by the hedgerows.

The sixth limitation is related to (relative) scaling. Our indicators characterized very different ESs and were consequently informed in different units. They needed to be normalized to allow the bundle analysis that synthesised the supply of multiple ESs within each case study. The normalization of the six ESs allowed us to transform them into dimensionless values and aggregate them to provide information on bundles (Alam et al., 2016). This normalization process might have led to statistical bias, especially for the indicators that were composite indicators themselves, as it can lead to loss of information, or unintended shifts in the relationships between variables. Aggregating ESs indicators into bundles may lead to the overestimation or underestimation of some of the indicators, and therefore a possible bias in the analysis and visualisation of the bundles. Moreover, the three case studies did not cover the same area and may experience context-dependent drivers of multiple ESs (Mouchet et al., 2014), leading to potential scaling issues as well as challenges for generalisation to other regions. Despites biases related to the normalization and to the differences in size of the case studies, our bundle analysis allowed us to capture the interactions between the ESs (Raudsepp-Hearne et al., 2010) and the complexity of the socio-ecological systems (Mouchet et al., 2017). It did not allow us to compare the three case studies, especially as previous works showed the influence of local context in ESs bundles (Hicks and Cinner, 2014). However, through our bundle analysis we could emphasize the linked nature of the ESs (Rodríguez et al., 2006) and the overall positive effects of agri-environmental measures on multiple ESs, as we determined their change under the scenario with 12.5 % of linear elements, as in comparison with the current situation (baseline) in each case study.

Assessments related to environmental management questions and in particular ecosystem services modelling come with inherent uncertainties (Burkhard et al., 2013; Le Clec'h et al., 2019a). Before using outcomes of such assessments in decision making processes, identification of uncertainties, their acknowledgement and communication should be systematic (Jacobs et al., 2017). In that sense, our approach should be seen as a step further for the development of a general framework for an ex-ante integrated analysis of AECM contracts. Further consideration of the impacts of modelling choices more specific data, and input of stakeholders in the research design should be consider before using this framework for local decision making on the ground.

4.3. Management and policy implications

From the results from our analysis four recommendations for land managers and policies addressing agricultural management in European agriculture can be made. First, our study demonstrates the potential of linear elements to enhance pollination, natural pest control, climate regulation, landscape aesthetics and habitat maintenance, across three study areas and types of linear elements. The enhancement of these ESs increases with the share of land covered by the linear landscape elements. This result supports the relevance of the EU biodiversity strategy for 2030 (Commission and Environment, 2021) published by the EU in 2021, the relevance of the enhanced conditionality and eco-schemes in the reformed Common agricultural Policy targeting non-productive elements and biodiversity, and the relevance of the Dutch "Aanvalsplan landschapselementen" published at the invitation of the Dutch Ministry of Agriculture, Nature and Food Quality (Samen voor Biodiversiteit, 2022). These strategies commit to ensure that at least 10 % of agricultural area is under high-biodiversity landscape features such as buffer strips, hedgerows, ponds, and non-productive trees.

Second, the diversity and the level of ESs provided by linear landscape elements imply that these linear elements can help reducing several environmental pressures. For instance, improving the ES pest control can reduce the need for pesticides. Yet, these pressures might vary from one area to another and the potential of linear elements to tackle them might vary from one type of linear elements to another. The type of linear elements suggested in AECMs should be carefully considered, with regard to the most pressing challenges to be addressed in the targeted landscape. In the Dutch and Hungarian case studies, opportunities for tourism and biodiversity conservation are desired. By contributing to the landscape diversity, linear elements may support these ambitions. Unmown grassy strips can provide an important habitat for species in intensive landscape and can contribute to mitigate the effects of agricultural intensification, which threatens the Hungarian case study. Hedgerows may be suitable habitats for a number of endangered species (e.g., moths, warblers; Merckx et al. (2010)) that are being threatened by the disappearance of shrubby habitats due to grassland reconstructions by Hungarian farmers. Hedgerows are capable to sequester considerable amounts of carbon and therefore contribute to climate regulation, making then an important element of climate neutral agricultural which is one of the ambitions of the Island of Bornholm. Future research could focus on understanding farmers' preferences and practical consideration underpinning the decision-making process to provide certain ESs to increase the adoption of AECMs and its fit in the broader context of the landscape in which the AECMs are implemented. In addition, further research should be conducted to bridge the gap between skewed distribution of the benefits for farmers and the society at large versus the costs by the farmers induced by the adoption of environmentally friendly practices, especially for ESs that currently have no markets.

Third, our results, showing that linear elements are more effective in terms of potential ES supply in landscapes with a small share of (semi)-natural habitat (1–20 %) than in landscapes with a high share of (semi)-natural habitat reveals that the EU target of 10 % agricultural area under high-biodiversity landscape features is likely to be more efficient in region such as Bornholm and the Achterhoek than in Őrség National Park. With this in mind, policy effectiveness of AECMs could be improved by targeting locations where the environmental benefits are expected to be higher than average. Contrasted effectiveness of policy measures due to contrasted environmental conditions also further rise the question of fair compensation to farmers that has been debated in the scientific literature on Payments for Environmental Services (Karsenty et al., 2017). Rewarding based on the efficiency of the agri-environmental practices could neglect farmers who have already adopted nature-friendly practices (Proctor et al., 2008). Rewarding good practices rather than economic efficiency may, however, encourage present and environmentally friendly behaviour and its longevity (Muradian, 2013; Karsenty et al., 2017).

Fourth, the absence of variability of the potential supply of the multiple ESs at the landscape level across the five iterations of each scenario suggests that spatial targeting of the AECMs is not critical. However, it is important to note that our landscapes only present homogenous and relatively flat topography. This might have implications with respect to the choice between action- and result- oriented schemes, as the expected potential supply of ESs is likely to be similar across one landscape and the risk of having lower potential ESs supply due to geographical differences in that landscape being minimal. Moreover, our models rely on simplification and some landscape characteristics were not considered in our analyses, e.g., wind direction, topography. Including these characteristics might affect the variability of our findings. Additionally, we considered in this study potential ESs supply, only. In reality, potential ESs supply, and demand are not separated and the consideration of the ESs demand in our analysis could have also affected our conclusion.

Our approach is a first step towards a general framework for an ex-ante integrated analysis of AECM contracts. Transferring it to larger areas, other agricultural landscapes and/or and more ESs could reconcile institutional as well as practical requirements e.g., when designing agri-environmental policies. This will allow to provide ex-ante information about incentive mechanisms supporting multiple ESs, ready to cope with the challenges for agriculture in the future. To validate the positive impact of our findings, as being part of an ex-ante analysis, it is of high importance to test our findings with stakeholders that have local knowledge and field experience before designing management plans.

CRediT authorship contribution statement

Solen le Clech: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Lenny G.J. van Bussel:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Marjolein E. Lof:** Writing – review & editing, Writing – original draft, Methodology. **Bart de Knegt:** Writing – original draft, Methodology. **István Szentirmai:** Writing – original draft, Resources, Methodology. **Erling Andersen:** Writing – original draft, Resources, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix

Fig. A1 Spatial distribution of potential crop pollination in the three study areas: a-b) Achterhoek (the Netherlands), c-d) Bornholm (Denmark) and e-f) Őrség National Park (Hungary), for the baseline (a, c, e) and for the situation where 12.5% of the whole utilized agricultural area was covered by hedgerows (b, d, f).

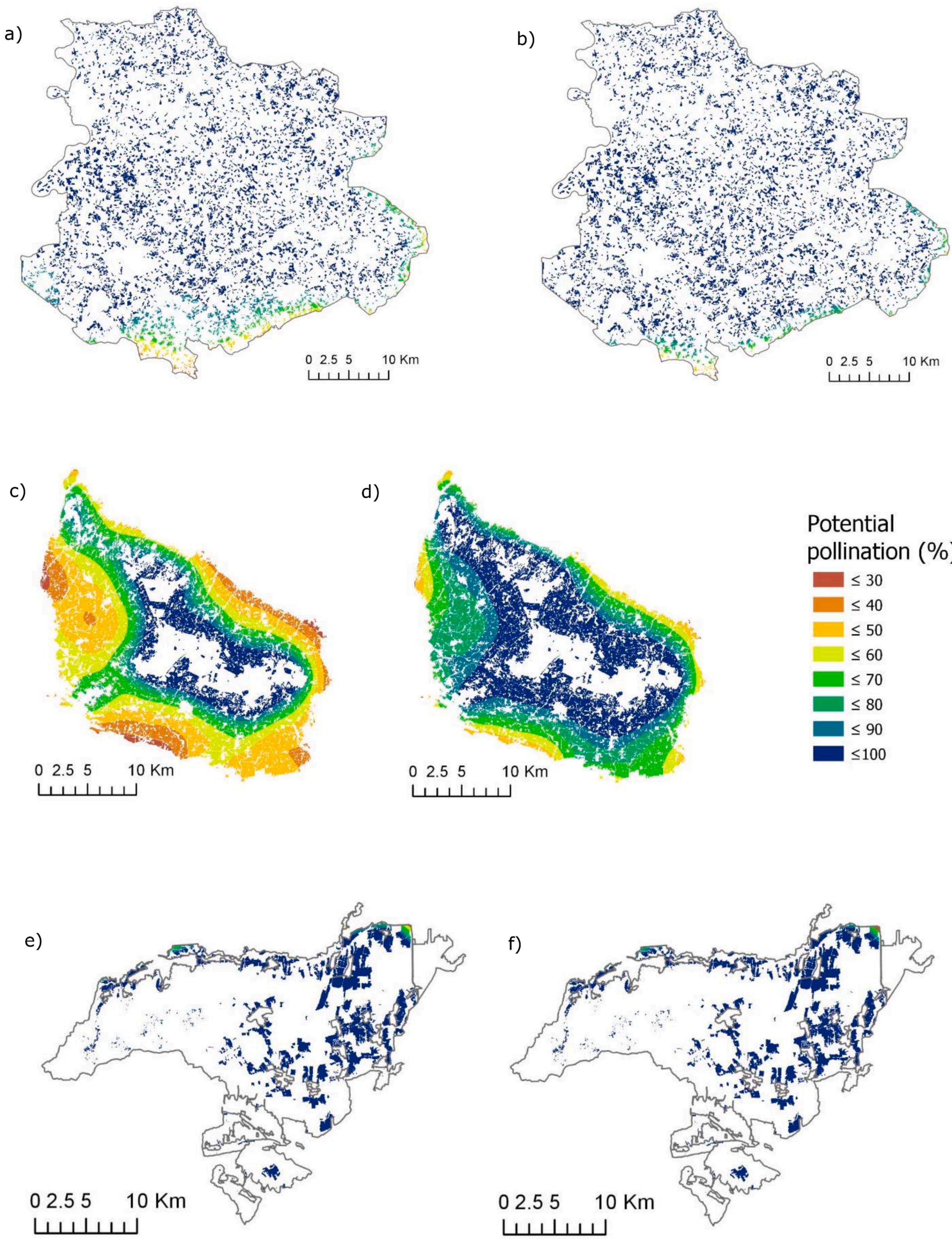

Fig. A2 Spatial distribution of relative predator density in crop fields in the three study areas: a-b) Achterhoek (the Netherlands), c-d) Bornholm (Denmark) and e-f) Őrség National Park (Hungary), for the baseline (a, c, e) and for the situation where 12.5% of the whole utilized agricultural area was covered by hedgerows (b, d, f).

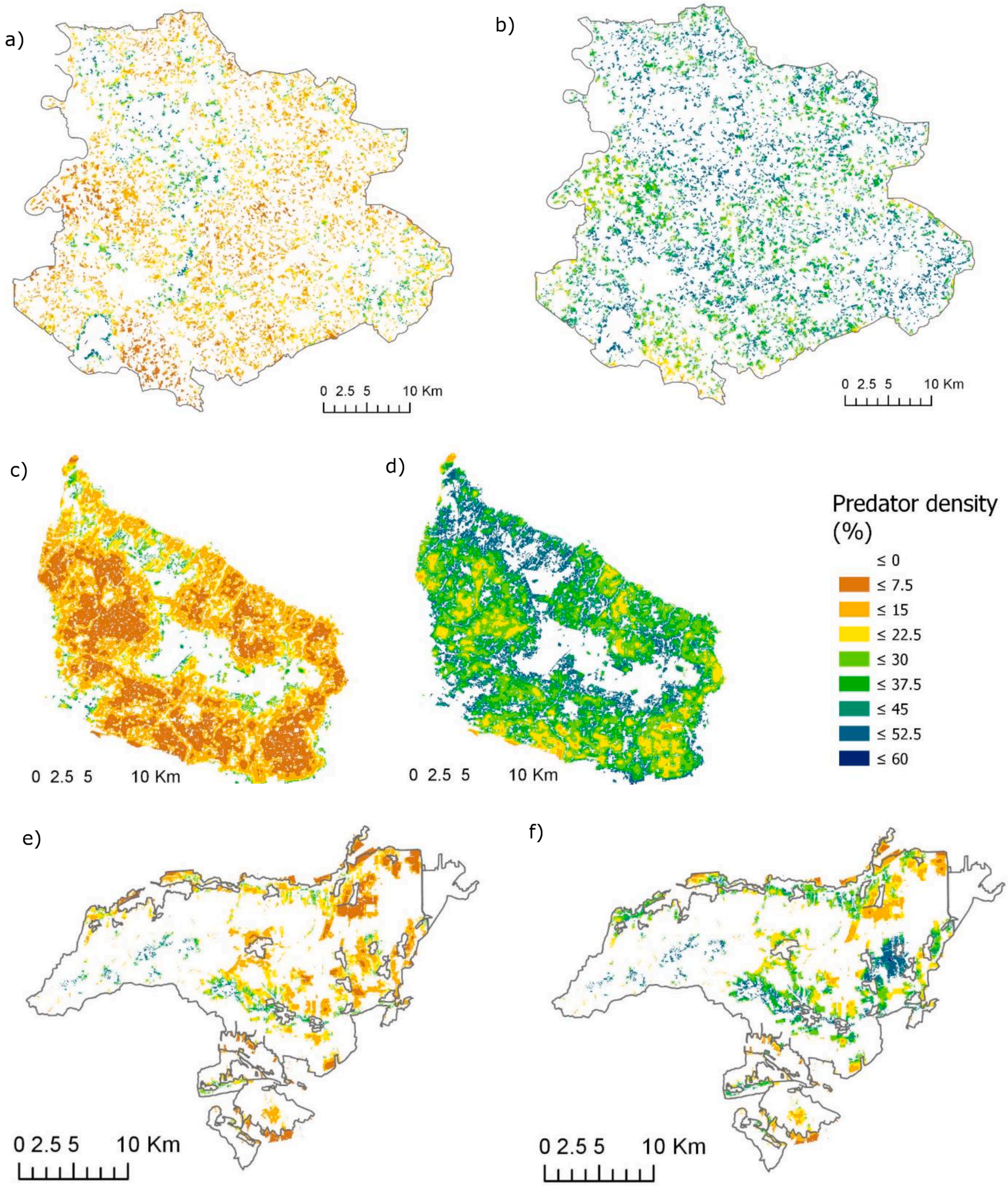

Table A1. Land-use land-cover classes in the Achterhoek (1), Bornholm (2) and Őrség National Park (3) and their parameterization (composition, hemeroby and diversity classes) to model landscape aesthetics and habitat quality and the crosswalk to the simplified classification that is used in the ESs models (see Table 3 in main text). Composition classes, class of hemeroby and degree of diversity were defined through the study of Van Bussel et al. (2020) and expert knowledge. Flower, tree and grass strips were considered as one land-use land-cover element for the landscape metrics and therefore have similar diversity and hemeroby values. In yellow are classes that were replaced by the classes the Corine Land Cover map (to add extra detail to the (semi)natural habitats in the Danish land use/ land cover map). In green are the classes from the Corine Land cover map that were used to refine the original land-use land-cover classes. In blue, additional classes created in our scenarios (related to the implementation of the linear elements). Acronyms: Eu- stands for "Euhemerobe", Meso- stands for "Mesohemerobe", Oligo- stands for "Oligohemerobe" and Poly- stands for "Polyhemerobe".

1. Achterhoek (the Netherlands)

ID	Land-use land-cover	Composition	Heme-roby	Diver-sity	Simplified class
0	NODATA				NODATA
114	Tall herbs	(Semi-)natural ecosystem	Oligo-	14	Tall herb
115	Heathland	(Semi-)natural ecosystem	Oligo-	13	Heathland
116	Drift sand	(Semi-)natural ecosystem	Oligo-	15	sand/fallow land
117	Semi-natural grassland	(Semi-)natural ecosystem	Oligo-	12	Semi-natural grassland
118	Biodiverse cropland	Cropland & orchards	Eu-	4	biodiverse cropland
122	Bogs	(Semi-)natural ecosystem	Oligo-	13	marshes
123	Fens	(Semi-)natural ecosystem	Oligo-	13	marshes
131	Streams and rivers	(Semi-)natural ecosystem	Eu-	16	water, with vegetation borders
132	Lakes	(Semi-)natural ecosystem	Eu-	16	water
133	Brackish	(Semi-)natural ecosystem	Eu-	16	water
141	Coastal dunes	(Semi-)natural ecosystem	Oligo-	15	sand/fallow land
142	Salt marshes	(Semi-)natural ecosystem	Oligo-	13	salt marshes
143	Beach	(Semi-)natural ecosystem	Oligo-	15	sand/fallow land
144	Intertidal and mud flats	(Semi-)natural ecosystem	Eu-	16	water
145	Shoals	(Semi-)natural ecosystem	Eu-	15	water
146	Estuaries	(Semi-)natural ecosystem	Eu-	16	water
147	North sea	(Semi-)natural ecosystem	Eu-	16	water
148	Wadden sea	(Semi-)natural ecosystem	Eu-	16	water
211	Cropland, regular	Cropland & orchards	Eu-	4	annual cropland
212	Cropland, extensive	Cropland & orchards	Eu-	4	cropland, extensive
213	Perennials, regular	Cropland & orchards	Eu-	4	perennials, regular
214	Perennials, extensive	Cropland & orchards	Eu-	4	perennials, extensive
221	Pasture, permanent	Pastures	Eu-	6	pasture, regular
222	Pasture, temporal	Pastures	Eu-	6	pasture, regular
223	Pasture, extensive	Pastures	Eu-	6	pasture, extensive
231	Greenhouse horticulture	Artificial surface	Poly-	1	built-up/infrastructure
232	Nursery container fields	Artificial surface	Poly-	1	built-up/infrastructure
241	Fallow land	(Semi-)natural ecosystem	Oligo-	1	sand/fallow land
242	Arable field margins	(Semi-)natural ecosystem	Meso-	8	flower strip
311	Built-up (urban)	Artificial surface	Poly-	1	built-up/infrastructure
312	Built-up (rural)	Artificial surface	Poly-	1	built-up, with vegetation
331	Infrastructural	Artificial surface	Poly-	1	built-up, with vegetation
411	Marine, other	(Semi-)natural ecosystem	Eu-	16	water
422	Grassland, other	Pastures	Oligo-	12	low vegetation
423	Other terrain	Artificial surface	Poly-	1	built-up, with vegetation
431	Other	Artificial surface	Poly-	1	built-up, with vegetation
1111	(Semi-)natural forest	(Semi-)natural ecosystem	Meso-	9	(Semi-)natural deciduous forest
1112	Hedges and tree-lines	(Semi-)natural ecosystem	Meso-	8	Hedges/tree lines
1113	Plantation forest	(Semi-)natural ecosystem	Meso-	9	deciduous forest
1121	Swamp forest	(Semi-)natural ecosystem	Meso-	9	(Semi-)natural deciduous forest
1321	Business park	Artificial surface	Eu-	1	deciduous forest
1322	Mining, landfills, etc.	Artificial surface	Eu-	1	deciduous forest
1341	Landscape garden	(Semi-)natural ecosystem	Meso-	3	deciduous forest
1342	Public park (large)	Artificial surface	Eu-	3	deciduous forest
1343	Public park (small)	Artificial surface	Eu-	3	deciduous forest
1344	Public green space, other	Artificial surface	Eu-	3	deciduous forest
1345	Semi-public green space	(Semi-)natural ecosystem	Eu-	3	deciduous forest
1351	Sport park	Artificial surface	Eu-	1	deciduous forest
1352	Residential recreation	Artificial surface	Poly-	1	deciduous forest
1421	Other forest	(Semi-)natural ecosystem	Meso-	9	deciduous forest
2111	(Semi-)natural forest	(Semi-)natural ecosystem	Meso-	10	semi-natural coniferous forest
2112	Hedges and tree-lines	(Semi-)natural ecosystem	Meso-	8	Hedges/tree lines, coniferous
2113	Plantation forest	(Semi-)natural ecosystem	Meso-	10	coniferous forest
2121	Swamp forest	(Semi-)natural ecosystem	Meso-	10	semi-natural coniferous forest
2321	Business park	Artificial surface	Eu-	1	coniferous forest
2322	Mining, landfills, etc.	Artificial surface	Eu-	1	coniferous forest
2341	Landscape garden	(Semi-)natural ecosystem	Meso-	3	coniferous forest
2342	Public park (large)	Artificial surface	Eu-	3	coniferous forest
2343	Public park (small)	Artificial surface	Eu-	3	coniferous forest
2344	Public green space, other	Artificial surface	Eu-	3	coniferous forest
2345	Semi-public green space	(Semi-)natural ecosystem	Eu-	3	coniferous forest
2351	Sport park	Artificial surface	Eu-	1	coniferous forest
2352	Residential recreation	Artificial surface	Poly-	1	coniferous forest
2421	Other forest	(Semi-)natural ecosystem	Meso-	10	coniferous forest
3111	(Semi-)natural forest	(Semi-)natural ecosystem	Meso-	11	semi-natural mixed forest
3112	Hedges and tree-lines	(Semi-)natural ecosystem	Meso-	8	hedges/tree line, mixed
3113	Plantation forest	(Semi-)natural ecosystem	Meso-	11	mixed forest
3121	Swamp forest	(Semi-)natural ecosystem	Meso-	11	semi-natural mixed forest
3321	Business park	Artificial surface	Eu-	1	mixed forest
3322	Mining, landfills, etc.	Artificial surface	Eu-	1	mixed forest
3341	Landscape garden	(Semi-)natural ecosystem	Meso-	3	mixed forest
3342	Public park (large)	Artificial surface	Eu-	3	mixed forest
3343	Public park (small)	Artificial surface	Eu-	3	mixed forest
3344	Public green space, other	Artificial surface	Eu-	3	mixed forest
3345	Semi-public green space	(Semi-)natural ecosystem	Eu-	3	mixed forest
3351	Sport park	Artificial surface	Eu-	1	mixed forest

(*continued on next page*)

(*continued*)

ID	Land-use land-cover	Composition	Heme-roby	Diver-sity	Simplified class
3352	Residential recreation	Artificial surface	Poly-	1	mixed forest
3421	Other forest	(Semi-)natural ecosystem	Meso-	11	mixed forest
4321	Business park	Artificial surface	Eu-	1	low vegetation
4322	Mining, landfills, etc.	Artificial surface	Eu-	1	low vegetation
4341	Landscape garden	Pastures	Meso-	3	low vegetation
4342	Public park (large)	Artificial surface	Eu-	3	low vegetation
4343	Public park (small)	Artificial surface	Eu-	3	low vegetation
4344	Public green space, other	Artificial surface	Eu-	3	low vegetation
4345	Semi-public green space	(Semi-)natural ecosystem	Eu-	3	low vegetation
4351	Sport park	Artificial surface	Eu-	1	low vegetation
4352	Residential recreation	Artificial surface	Poly-	1	low vegetation
5321	Business park	Artificial surface	Poly-	1	built-up/infrastructure
5322	Mining, landfills, etc.	Artificial surface	Poly-	1	built-up/infrastructure
5351	Sport park	Artificial surface	Poly-	1	built-up/infrastructure

2. Bornholm (Denmark)[2]

ID	Land-use land-cover	Composition	Heme-roby	Diver-sity	Simplified class
0	NODATA	Artificial surface	Poly-	1	NODATA
110,000	Building	Artificial surface	Poly-	1	built-up/infrastructure
121,000	Low built up	Artificial surface	Poly-	1	built-up, with vegetation
121,110	Low built up; Building	Artificial surface	Poly-	1	built-up/infrastructure
122,000	High built up	Artificial surface	Poly-	1	built-up/infrastructure
122,110	High built up; Building	Artificial surface	Poly-	1	built-up/infrastructure
123,000	City centre	Artificial surface	Poly-	1	built-up/infrastructure
123,110	City centre; Building	Artificial surface	Poly-	1	built-up/infrastructure
124,000	Other built up	Artificial surface	Poly-	1	built-up/infrastructure
124,110	Other built up; Building	Artificial surface	Poly-	1	built-up/infrastructure
125,000	Industry / business	Artificial surface	Poly-	1	built-up/infrastructure
125,110	Industry / business; Building	Artificial surface	Poly-	1	built-up/infrastructure
126,000	Airport / runway	Artificial surface	Poly-	1	built-up, with vegetation
126,110	Airport / runway; Building	Artificial surface	Poly-	1	built-up/infrastructure
130,000	Recreation area / sports ground	Artificial surface	Poly-	1	built-up, with vegetation
130,110	Recreation area / sports ground; Building	Artificial surface	Poly-	1	built-up/infrastructure
141,000	Road, paved	Artificial surface	Poly-	1	built-up, with vegetation
142,000	Road, not paved	Artificial surface	Poly-	1	built-up, with vegetation
160,000	Resource extraction	Artificial surface	Poly-	1	built-up, with vegetation
211,000	Agriculture, intensive, temporary crops	Cropland & orchards	Eu-	4	annual crops
212,000	Agriculture, intensive, permanent crops	Cropland & orchards	Eu-	4	perennial crops, regular
220,000	Agriculture, extensive	Cropland & orchards	Eu-	4	cropland, extensive
230,000	Agriculture, not classified	Cropland & orchards	Eu-	4	annual crops
240,000	Agriculture, flower strip	(Semi-)natural ecosystem	Meso-	8	flower strip
300,000	Hedgerow	(Semi-)natural ecosystem	Meso-	8	hedgerow/tree line
311,000	Forest	(Semi-)natural ecosystem	Meso-	9	mixed forest
312,000	Forest, wet	(Semi-)natural ecosystem	Meso-	10	deciduous forest
321,000	Nature, dry **	(Semi-)natural ecosystem			Added from CLC
321,220	Nature, dry; Agriculture, extensive **	(Semi-)natural ecosystem			Added from CLC
322,000	Nature, wet	(Semi-)natural ecosystem	Oligo-	12	marshes
322,220	Nature, wet; Agriculture, extensive	(Semi-)natural ecosystem	Meso-	8	marshes
411,000	Lake	(Semi-)natural ecosystem	Eu-	16	water
412,000	Stream	(Semi-)natural ecosystem	Eu-	16	water, with vegetation borders
800,000	Unmapped	Artificial surface	Poly-	1	NODATA
111	Continuous urban fabric	Artificial surface	Poly-	1	built-up, with vegetation
112	Discontinuous urban fabric	Artificial surface	Poly-	1	built-up, with vegetation
121	Industrial or commercial units	Artificial surface	Poly-	1	built-up/infrastructure

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[2] Field used to link with GIS data.

(*continued*)

ID	Land-use land-cover	Composition	Heme-roby	Diver-sity	Simplified class
123	Port areas	Artificial surface	Poly-	1	built-up/infrastructure
131	Mineral extraction sites	Artificial surface	Poly-	2	built-up/infrastructure
132	Dump sites	Artificial surface	Poly-	2	built-up/infrastructure
142	Sport and leisure facilities	Artificial surface	Poly-	1	low vegetation
211	Non-irrigated arable land	Cropland & orchards	Eu-	4	cropland, extensive
242	Complex cultivation patterns	Cropland & orchards	Eu-	7	cropland, extensive
243	Land principally occupied by agriculture, with significant areas of natural vegetation	Cropland & orchards	Meso-	8	biodiverse cropland
311	Broad-leaved forest	(Semi-)natural ecosystem	Meso-	9	deciduous forest
312	Coniferous forest	(Semi-)natural ecosystem	Meso-	10	Coniferous forest
313	Mixed forest	(Semi-)natural ecosystem	Meso-	11	Mixed forest
321	Natural grasslands	(Semi-)natural ecosystem	Meso-	12	Semi-natural grassland
322	Moors and heathland	(Semi-)natural ecosystem	Oligo-	13	heathland
324	Transitional woodland-shrub	(Semi-)natural ecosystem	Oligo-	14	Transitional woodland-shrub
331	Beaches, dunes, sands	(Semi-)natural ecosystem	Oligo-	15	sand/fallow land
412	Peat bogs	(Semi-)natural ecosystem	Oligo-	13	marshes
523	Sea and ocean	(Semi-)natural ecosystem	Eu-	16	water
223	Grassland extensive***	Pastures	Meso-	8	extensive pasture, with flowers

3. Őrség National Park (Hungary)

ID	Class	Composition	Heme-roby	Diver-sity	Simplified class
0	No data	Artificial surface	Poly-	1	NODATA
A1	Euhydrophyte	(Semi-)natural ecosystem	Oligo-	13	water
B1a	Eu- and mesotrophic reed and Typha beds	(Semi-)natural ecosystem	Oligo-	13	marshes
B2	Glyceria, Sparganium and Schoenoplectus beds	(Semi-)natural ecosystem	Oligo-	13	marshes
B4	Tussock sedge communities	(Semi-)natural ecosystem	Oligo-	13	marshes
B5	Non-tussock tall-sedge beds	(Semi-)natural ecosystem	Oligo-	13	marshes
BA	Fine scale mosaic or zonation of marsh communities	(Semi-)natural ecosystem	Oligo-	13	marshes
C23	Transition mires and raised bogs	(Semi-)natural ecosystem	Oligo-	13	marshes
D1	Rich fens	(Semi-)natural ecosystem	Oligo-	13	Semi-natural grassland
D2	Molinia meadows	(Semi-)natural ecosystem	Oligo-	13	Semi-natural grassland
D34	Mesotrophic wet meadows	(Semi-)natural ecosystem	Oligo-	13	Semi-natural grassland
D5	Tall-herb vegetation of stream banks and fens	(Semi-)natural ecosystem	Oligo-	13	Tall herb
E1	Arrhenatherum hay meadows	Pastures	Meso-	6	pasture, extensive (flower rich)
E2	Festuca rubra hay meadows and pastures	Pastures	Meso-	6	pasture, extensive (flower rich)
E5	Dry Calluna heaths	Pastures	Meso-	6	heathland
I1	Natural pioneer vegetetion of wet substrates	(Semi-)natural ecosystem	Meso-	10	marshes
J1a	Willow carrs	(Semi-)natural ecosystem	Meso-	10	scrub
J3	Riverine willow scrub	(Semi-)natural ecosystem	Meso-	10	scrub
J4	Riverine willow-poplar woodlands	(Semi-)natural ecosystem	Meso-	10	deciduous forest

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ID	Class	Composition	Heme-roby	Diver-sity	Simplified class
J5	Riverine ash-alder woodlands	(Semi-)natural ecosystem	Meso-	10	deciduous forest
J6	Riverine oak-elm-ash woodlands	(Semi-)natural ecosystem	Meso-	10	deciduous forest
K1a	Lowland oak-hornbeam woodlands	(Semi-)natural ecosystem	Meso-	9	deciduous forest
K2	Sessile oak-hornbeam woodlands	(Semi-)natural ecosystem	Meso-	9	deciduous forest
K5	Beech woodlands	(Semi-)natural ecosystem	Meso-	9	deciduous forest
L2b	Quercus cerris-Quercus robur woodlands	(Semi-)natural ecosystem	Meso-	9	deciduous forest
N13	Acidofrequent mixed coniferous forests	(Semi-)natural ecosystem	Meso-	9	semi-natural coniferous forest
OA	Uncharacteristic wetlands	(Semi-)natural ecosystem	Oligo-	12	low vegetation
OB	Uncharacteristic mesic grasslands	(Semi-)natural ecosystem	Oligo-	13	low vegetation
OC	Uncharacteristic dry and semi-dry grasslands	Cropland and orchards	Meso-	8	low vegetation
OD	Stands of invasive forbs	(Semi-)natural ecosystem	Oligo-	13	low vegetation
OF	Ruderal tall-herb vegetation	(Semi-)natural ecosystem	Oligo-	13	low vegetation
OG	Trampled and ruderal vegetation	(Semi-)natural ecosystem	Oligo-	13	low vegetation
P1	Saplings of native tree species	(Semi-)natural ecosystem	Meso-	9	semi-natural deciduous forest
P2a	Wet and mesic pioneer scrub	(Semi-)natural ecosystem	Meso-	10	scrub
P2b	Dry and semi-dry pioneer scrub	(Semi-)natural ecosystem	Oligo-	13	scrub
P2c	Stands of non-native shrubs or Reynoutria species	(Semi-)natural ecosystem	Oligo-	13	scrub
P3	New afforestation	(Semi-)natural ecosystem	Meso-	8	mixed forest
P45	Wood pastures and Castanea sativa woods	(Semi-)natural ecosystem	Meso-	9	deciduous forest
P6	Parks, botanical gardens, old churchyards	Artificial surface	Poly-	3	mixed forest
P7	Extensive orchards with ancient cultivars	Cropland and orchards	Eu-	4	perennials, extensive
P8	Cutting areas	(Semi-)natural ecosystem	Meso-	9	sand/fallow land
RA	Scattered native trees or narrow tree lines	(Semi-)natural ecosystem	Meso-	9	scattered trees
RB	Uncharacteristic or pioneer softwood forests	(Semi-)natural ecosystem	Meso-	9	mixed forest
RC	RC – Uncharacteristic hardwood forests and plantations	(Semi-)natural ecosystem	Meso-	9	deciduous forest
RD	forest plantation?	Cropland and orchards	Eu-	5	mixed forest
RDa	Coniferous forests and plantations mixed with native deciduous tree species	(Semi-)natural ecosystem	Meso-	9	coniferous forest
RDb	Non-native deciduous forests and plantations mixed with native tree species	(Semi-)natural ecosystem	Meso-	9	deciduous forest
S1	Robinia pseudoacacia plantations	(Semi-)natural ecosystem	Meso-	9	deciduous forest
S2	Populus × euramericana plantations	(Semi-)natural ecosystem	Meso-	9	deciduous forest
S3	Plantations of other non-native deciduous tree species	Cropland and orchards	Eu-	5	deciduous forest
S4	Scots and black pine plantations	(Semi-)natural ecosystem	Meso-	10	coniferous forest
S5	Plantations of other conifers	(Semi-)natural ecosystem	Meso-	10	coniferous forest
S6	Spontaneous stands of non-native tree species	(Semi-)natural ecosystem	Meso-	11	deciduous forest
S7	Scattered trees or narrow tree lines of non-natives tree species	(Semi-)natural ecosystem	Meso-	11	scattered trees
T1	Annual intensive arable fields	Cropland and orchards	Eu-	7	annual croplands
T10	New abandonments of arable lands	Cropland and orchards	Eu-	7	sand/fallow land
T11	Nurseries, Salix viminalis plantations	Cropland and orchards	Eu-	5	perennial, extensive
T2	Perennial intesive arable fields	Cropland and orchards	Eu-	4	perennials, regular
T3	Vegetable and flower plantations, greenhouses	Cropland and orchards	Eu-	4	annual croplands
T5	Sowed or fertilized grasslands, sports-grounds	Artificial surface	Poly-	1	low vegetation
T6	Extensive arable fields	Cropland and orchards	Eu-	4	cropland, extensive
T7	Intensive vineyards and orchards	Cropland and orchards	Eu-	5	perennials, regular
T8	Extensive vineyards and orchards	Cropland and orchards	Eu-	5	perennials, extensive
T9	Gardens	Artificial surface	Poly-	3	low vegetation

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ID	Class	Composition	Heme-roby	Diver-sity	Simplified class
U10	Farms	Artificial surface	Poly-	1	built-up, with vegetation
U11	Roads and railroads	Artificial surface	Poly-	1	built-up, with vegetation
U2	Suburbs and recreation areas	Artificial surface	Poly-	3	built-up, with vegetation
U3	Villages	Artificial surface	Poly-	1	built-up, with vegetation
U4	Yards, wastelands, dumping grounds	Artificial surface	Poly-	2	built-up/infrastructure
U5	Mine dumps, dumping grounds covered by ground	Artificial surface	Poly-	2	built-up/infrastructure
U6	Open mines	Artificial surface	Poly-	1	built-up/infrastructure
U7	Sand, gravel, clay and peat mines, loess walls	Artificial surface	Poly-	1	built-up/infrastructure
U8	Water streams	(Semi-)natural ecosystem	Oligo-	16	water, with vegetation borders
U9	Standing waters	(Semi-)natural ecosystem	Oligo-	16	water
U9b	Standing waters	(Semi-)natural ecosystem	Oligo-	16	water
U9d	Standing waters	(Semi-)natural ecosystem	Oligo-	16	water
Flower strip		(Semi-)natural ecosystem	Meso-	8	flower strip
hedgerow		(Semi-)natural ecosystem	Meso-	8	Hedges/tree-lines
Grassy strip		(Semi-)natural ecosystem	Meso-	8	extensive pasture, with flowers

Table A2. List of crops and the area they cover in the Achterhoek (1), Bornholm (2) and Őrség National Park (3). Please note that only crops whose area covered more than 75 ha are listed below. Achterhoek (the Netherlands).

Crop type	Area (ha)
Grassland, permanent	36224.8
Corn (Mais, snij-)	13910.8
Grassland, temporary	12922.9
Potato, consumption	1203.1
Grassland, nature. Primary function agriculture	1117.1
Corn (Mais, korrel-)	1024.4
Potato, reproduction (Aardappelen, poot NAK)	1009.9
Barley, summer	842.1
Beet, sugar	673.6
Corn (Mais, corncob mix)	658.5
Wheat, winter	578.8
Forest, permanent, with replanting duty	474.6
Potato, starch	441.5
Grassland, nature. Primary function anature	292.5
Barley, summer	258.5
Nature (including heath)	247.9
Triticale	170.9
Corn (Maiskolvensilage)	158.3
Beet, fodder	149.0
Wheat, summer	120.1
Rye	117.6
Alfalfa	101.1
Oat	93.6

1. Bornholm (Denmark)

Crop type	Area (ha)
Winter wheat	10887.3
Spring barley	6980.4
Winter canola	2565.7
Silage corn	1681.1
Winter barley	1473.6
Grass with clover/alfalfa, less than 50 % legumes. (rotation)	1423.0
Rye grass seed, common	1250.4
Permanent grass, normal yield	1136.3
Spring wheat	767.2
Spring oats	731.6
Grass below 50 % clover/alfalfa, low yield (rotation)	629.2
Horse beans	603.9

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Crop type	Area (ha)
Rye grass seed, ital. 1st year, put out in the autumn	378.3
MVJ no extraction, no agricultural area	369.2
308 MFO fallow, summer mowing	324.5
Rye grass seed, ital.	258.0
Winter hybrid rye	224.4
Recreational purposes	221.1
Clover seed	213.8
Permanent grass, low yield	203.1
Winter rye	138.8
Fenugreek seeds	130.2
Cereals and pulses, whole grain, less than 50 % pulses	117.2
Rye grass seed, common 1st year, autumn semester	111.6
Miljøgræs MVJ commitment (0 N), permanent	108.3
Grass without clover (rotation)	96.8
Timothy seeds	88.7
Permanent grass, very low yield	88.3
Christmas trees and greenery	86.5
Peas	86.1
Spring wheat, bread wheat	78.5

2. Őrség National Park (Hungary)

Crop type	Area (ha)
hay meadow	1930.8
winter wheat	1615.5
corn	1482.7
pasture	1114.2
soya beans	742.7
oilseed rape	579.6
winter barley	375.3
fallow	213.3
alfalfa	150.1
sorghum	132.7
mixed crops	132.1
clover	126.8
oat	125.3
spring barley	114.2
sunflower	81.1
triticale	75.7

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