Susceptibility of pollinators to landscape change depends on past changes and pollinator identity

Aguirre-Gutiérrez et al.

Electronic Supplementary Material

Supplementary Table S1. Land-use classes in the Netherlands used in the study. The suitability values per class were assigned in a scale ranging from 0 (no suitable) to 5 (highly suitable). We present the per land-use average suitability values given by 13 experts in the species groups analysed as presented in Vogiatzakis et al. (2015).

Land-use class	*Suitability value*
Sandy soils	3.6
Grassland	3.5
Moors/Peat	3.2
Deciduous Forest	2.8
Mixed Forest	2.5
Agricultural	2.3
Coniferous Forest	1.9
Urban	1.6
Water	0.6
Swamps	0.2

Vogiatzakis I.N., Stirpe M.T., Rickebusch S., Metzger M., Xu G., Rounsevell, M, Bommarco R., Potts, S.G. (2015) Rapid assessment of historic, future and current habitat quality for biodiversity around UK Natura 2000 sites. *Environmental Conservation*,**42**, 31-40.

Supplementary Table S2. Summary of the most relevant studies for our analysis related to the impacts of landscape composition and configuration on pollinators. We obtained these studies by means of a search in the ISI Web of Knowledge with the following data entrance: "Title=(land use cover change* bumblebee OR land use cover change* butterflies OR land use cover change* hoverflies). The search also included the following: "Title=(landscape* OR fragmentation* OR cover change*) AND Title=(pollinators* OR butterflies* OR hoverflies* OR Bees*)". The search was carried out on the 23th. of November 2012 and we only included studies from the year 2001 onwards. We do not include review papers in this table, for that check the references in the main document.

Author(s)	Year	Title	Summary of metrics used	Relevant findings
Aguirre et al.	2010	Effects of forest fragmentation on assemblages of pollinators and floral visitors to male- and female-phase inflorescences of Astrocaryum mexicanum (Arecaceae) in a Mexican rain forest	Patch size.	Fragmentation had no effect on species richness but negatively affected Shannon’s diversity index. Forest fragmentation correlates with changes in the composition of flower visitors Found reduction in the abundance of pollinators.
Benedick et al.	2006	Impacts of rain forest fragmentation on butterflies in northern Borneo: species richness, turnover and the value of small fragments	Patch size; Isolation; Percentage of vegetation cover; Tree height; Tree density.	Species richness in forest remnants was significantly positively related to remnants size and significantly negatively related to isolation.
Berg et al.	2011	Butterfly distribution and abundance is affected by var iation in the Swedish forest-farmland landscape	Proportion of landscape of forest/(arable fields + forest); Sum of proportion of landscape of all open habitats.	Power-line corridors highly important for the butterflies distribution. The surrounding habitat effects were weaker than the local effects. Forested landscapes contained higher abundance of low and intermediate mobility species.
Brosi et al.	2008	The effects of forest fragmentation on bee communities in tropical countryside.	Patch size; Patch shape; Isolation; Landscape context (proportion of forest and pasture).	No effect of forest variables on bee diversity and abundance. Strong changes in bee community composition because of the forest variables. Contrasting responses to habitat fragmentation from different bee groups.
Chaplin-Kramer et al.	2011	A meta-analysis of crop pest and natural enemy response to landscape complexity	Percentage of natural habitat; Percentage of non-crop habitat; Percentage of crop area; Habitat diversity; Distance to natural habitat and amount of linear features.	None of the landscape metrics produced a significant response in pests. Positive response in natural enemies to landscape complexity metrics but not to percentage crop and landscape diversity. Landscape complexity is highly important.

Cozzi et al.	2007	How do local habitat management and landscape structure at different spatial scales affect fritillary butterfly distribution on fragmented wetlands?	Patch area; Proportion of forest land; Management type.	Matrix is important but not as much as fragmentation and management type.
Ekroos & Kuussaari	2012	Landscape context affects the relationship between local and landscape species richness of butterflies in semi-natural habitats	Arable field cover.	Local factors are more important than landscape factors in determining local species richness. Local species richness was limited by landscape factors in intensively cultivated landscapes.
Flick et al.	2012	Effects of landscape structure on butterfly species richness and abundance in agricultural landscapes in eastern Ontario, Canada	Patch density; Patch richness; Amount of butterfly habitat.	Butterfly species richness was higher in landscapes with more butterfly habitat and higher patch density. Butterfly abundance was higher in landscapes with lower patch richness.
Greenleaf & Kremen	2006a	Wild bee species increase tomato production but respond differently to surrounding land use in Northern California.	Distance between focus field and natural habitat; Proportion of natural habitat; Proportion of agricultural habitat.	The natural habitat must be close enough to fields in order to have an increase in production effect. Wild bees response differently to the surrounding land use.
Greenleaf & Kremen	2006b	Wild bees enhance honey bees' pollination of hybrid sunflower	Farm management type; Proximity to natural habitat; Proportion of natural habitat.	Proximity to natural habitat and crop-planting practices within the vicinity of the field explained significant variation in pollination services.
Hannon & Sisk	2009	Hedgerows in an agri-natural landscape: Potential habitat value for native bees	Habitat types (hedgerows, woodlands, fields, woodlot).	Hedgerows and woodland had a significant positive effect on native bees.
Hatfield & Lebuhn	2007	Patch and landscape factors shape community assemblage of bumble bees, Bombus spp. (Hymenoptera : Apidae), in montane meadows	Meadow area; Area to perimeter ratio; Composition of floral resources; Meadow wetness index; Livestock grazing; Proportion of the surrounding matrix that is meadow habitat; Elevation.	Percent meadow and Meadow wetness impacted positively the richness and diversity, grazing had a negative effect.

Herrando & Pa	2004	Butterfly species richness in the north-west Mediterranean Basin: the role of natural and human-induced factors	Climatology; Topography; Vegetation structure; Proportion of built-up areas; Proportion of agricultural area.	Human disturbance had a deleterious effect. Vegetation variables had almost no effect.
Holzschuh et al.	2010	How do landscape composition and configuration, organic farming and fallow strips affect the diversity of bees, wasps and their parasitoids?	Edge density; Proportion of non-crop habitats; Proportion of grassland; Proportion of forest; Farming system (organic vs. conventional).	High proportions of conventionally managed and large crop fields threaten pollination. Bees were enhanced by high proportions of non-crop habitat in the landscape.
Jauker et al.	2009	Pollinator dispersal in an agricultural matrix: opposing responses of wild bees and hoverflies to landscape structure and distance from main habitat	Type of matrix surrounding the focal area.	The grassland cover amount is important (positively related) for wild bees. Hoverflies were not impacted by grassland cover amount. Responses differ between the groups analysed.
Kennedy et al.	2013	A global quantitative synthesis of local and landscape effects on wild bee pollinators in agro-ecosystems.	Nesting and floral resources within foraging distances, patch shape, inter patch connectivity, habitat aggregation, farm management.	Diversified and organic fields benefit bee richness and abundance. High-quality surrounding land cover is also important. Landscape configuration effects were weak.
Kivinen et al.	2007	Effects of land cover and climate on species richness of butterflies in boreal agricultural landscapes	Annual temperature sum above 5C; Mean temperature of the coldest month; Land cover classes.	Climate is a fundamental driver for butterfly species richness. Species richness of declining butterflies was positively related to the amount of grasslands. Positive contribution of small-scale agriculture and mix with forest mosaic. Strong positive effect of species richness of stable butterflies with the amount of deciduous and mixed forests. Negative relationship with the amount of grasslands. reflect the fact that the majority of stable butterflies are associated with forest edges and clearings.

Krauss et al.	2003	How does landscape context contribute to effects of habitat fragmentation on diversity and population density of butterflies?	Area; Isolation index; Landscape diversity index; Percentage grassland in the landscape.	Butterfly species increased with habitat area. Generalists showed a significant increase with landscape diversity
Krauss et al.	2010	Habitat fragmentation causes immediate and time-delayed biodiversity loss at different trophic levels.	Connectivity; Patch size (current); Landscape area (current); Past patch area; Past landscape area.	The patch area is important together with connectivity.
Kremen et al.	2007	Pollination and other ecosystem services produced by mobile organisms: a conceptual framework for the effects of land-use change	Patch area; Species nesting type; Floral resources; Local presence of bare ground; Potential nesting cavities; Steeply sloping ground; Plants with pithy stems; Pre-existing holes; Matrix surrounding the focal area.	Bee abundance and species richness is positively related with the abundance and richness of flowering plants. Reduced landscape diversity is associated with the decreased of bee abundance at the community level. Larger pollinators were more sensitive to land-use change.
Kremen et al.	2002	Crop pollination from native bees at risk from agricultural intensification.	Type of agriculture (organic/inorganic); Distance to closest oak woodland and chaparral habitat (near vs far)	Agricultural intensification reduced the diversity and abundance of native bees.
Kremen et al.	2004	The area requirements of an ecosystem service: crop pollination by native bee communities in California.	Proportion of areas of Upland, Riparian and Wild habitat at different radii; Toxicity index; Farm management type; Field size.	Native bees were positively related to the proportion of natural habitat close to farms. Stability increased with increasing natural habitat area.
Krewenka et al.	2011	Landscape elements as potential barriers and corridors for bees, wasps and parasitoids	Grass strips measure; Isolation	Semi-natural habitats act as sources of bee and wasp diversity. Grass strips act as sinks and not as corridors when high quality patches are nearby.
Lentini et al.	2012	Supporting wild pollinators in a temperate agricultural landscape: Maintaining mosaics of natural features and production	Percentage of flowering ground cover; Percentage of native ground cover Trees; Land use in adjacent field; Proportion of conservation	Areas closer to conservation reserves and further from infrastructure will support more diverse bee communities. Tree cover and the matrix quality are important variables important for the abundance of individual species.

			land; Proportion of infrastructure; Average rainfall.	
Lütolf et al.	2009	History Matters: Relating Land-Use Change to Butterfly Species Occurrence	Farm size; Proportion of agricultural area; Proportion of arable land; Proportion of intensively cultivated grasslands; Proportion of orchards area; Proportion of Wetlands; Proportion of livestock; Proportion of residential building.	For dry grassland species, the variables related to change rate are more important than state variables. Small-to-large farm transformation has positive effects on persistence of two groups of butterfly species.
Mandelik et al.	2012	Complementary habitat use by wild bees in agro-natural landscapes	Field type (agriculture, forest, old fields); Species richness and abundance of blooming plants; Air temperature; Wind velocity; Cloud cover.	Natural forest presented a low number of bees (most commonly visitors of non-crop plants). Old fields are an important system feature in arable landscapes that can maintain pollination services.
Montero-Castaño & Vilà	2012	Impact of landscape alteration and invasions on pollinators: a meta-analysis	Fragment size; Nature of the surrounding matrix (disturbed versus non-disturbed or continuous); Distance to other fragments of same cover type; Continuity; Matrix disturbance.	Disturbance of the surrounding matrix is negatively related to pollinator visitation rates. Matrix is more important than fragment size. Responses of pollinators vary among taxa and ecosystem types.
Öckinger et al.	2012a	The landscape matrix modifies the effect of habitat fragmentation in grassland butterflies	Patch area; Patch isolation; Index of land use in the landscape matrix (ratio forest/(forest + arable land); Matrix composition around focus area.	There were general effects of the matrix land use across landscapes. Increasing the matrix quality can render positive results for butterflies.

Öckinger et al.	2012b	Landscape matrix modifies richness of plants and insects in grassland fragments	Patch area; Isolation; Percentage of different LULC classes in the landscape.	Patch area impacts positively species richness, while isolation negatively but only for hoverflies. The matrix effect is variable.
Ricketts, T. H.	2001	The Matrix Matters: Effective Isolation in Fragmented Landscapes	Land use/cover types in the matrix.	The matrix and the isolation between patches is highly important as it might have negative impacts.
Schüepp et al.	2011	Differential effects of habitat isolation and landscape composition on wasps, bees, and their enemies	Amount of woody habitat in the landscape; Isolation; Percentage of open area near-natural habitats in the landscape; Altitude; Local temperature; Humidity.	Both, habitat amount at the landscape level and patch connectivity are important predictors for wasps, bees and other insects.
Schweiger et al.	2005	Quantifying the impact of environmental factors on arthropod communities in agricultural landscapes across organizational levels and spatial scales	Proportion of semi-natural elements (‘green veining’); Landscape diversity (number of green veining habitat types); Area weighted mean proximity index of green veining elements.	Connectivity between suitable patches is one of the most important predictors for arthropod species richness and changes.
Soga & Koike	2012	Life-history traits affect vulnerability of butterflies to habitat fragmentation in urban remnant forests	Patch area; Shape; Isolation; Distance to closest forest patch.	The host plant type, host plant range, voltinism, and adaptability to the matrix affect the effect of habitat fragmentation on butterflies.
Steffan-Dewenter	2003	Importance of Habitat Area and Landscape Context for Species Richness of Bees and Wasps in Fragmented Orchard Meadows	Patch area; Connectivity; Matrix importance value.	Species richness increased with habitat area. Mutualistic bees are more affected by the area amount. Connectivity highly influential for habitat specialists. Generalist benefit from a more heterogeneous matrix.
Steffan-Dewenter et al.	2002	Scale-Dependent Effects of Landscape Context on Three Pollinator Guilds	Proportion of semi-natural habitat; Landscape type (simple/modified).	Solitary bees richness is higher with the increase of the proportion of semi-natural habitat but only in small patches. Honeybees get higher species richness values in simple habitats.

Summerville & Crist	2001	Effects of experimental habitat fragmentation on patch use by butterflies and skippers (Lepidoptera)	Fragmentation treatment; Area remaining.	The area remaining is classified as an important predictor. Patch quality (i.e. floral resources) compensates for patch size Rare species may be especially vulnerable to fragmentation.
Taki et al.	2010	Effects of landscape metrics on Apis and non-Apis pollinators and seed set in common buckwheat	Area of forest cover; Area of forest and grassland cover.	Abundances of native honeybees, and wild non-honeybee insects were significantly related to the area variables
Thomas et al.	2001	The quality and isolation of habitat patches both determine where butterflies persist in fragmented landscapes	Habitat quality; Patch area; Patch isolation.	Within habitat quality and site isolation are both important for persistence. Habitat quality is more important than patch area or isolation.
Tscheulin et al.	2011	Influence of landscape context on the abundance and diversity of bees in Mediterranean olive groves	Suitability; Mean patch area of each land cover; Total area of each land cover; Number of patches of each land cover; Mean patch perimeter of each land cover; Mean patch perimeter-area ratio of each land cover.	Small bees are impacted at smaller scales than larger bees. The responses vary depending on the taxa analysed.
Uehara-Prado & Freitas	2009	The effect of rainforest fragmentation on species diversity and mimicry ring composition of ithomiine butterflies	Forest type (Pristine forest and fragmented forest).	Forest type causes different responses. Forest fragmentation affects the composition of the ithomiine mimicry rings.
Uehara-prado et al.	2007	Species richness, composition and abundance of fruit-feeding butterflies in the Brazilian Atlantic Forest: comparison between a fragmented and a continuous landscape	Forest type (Pristine forest and fragmented forest).	Butterflies species richness differ depending on the fragmentation status. The responses may sometimes be detected at species and subfamily levels.
Van Dyck Hans et al.	2009	Declines in Common, Widespread Butterflies in a Landscape under Intense Human Use	Vegetation types: open dunes, heathland, semi-natural grassland, farmland, urban area, and woodland.	Decline in abundance of the common species in vegetation types outside nature reserves, including farm- land, urban areas, and woodland

Watson et al.	2011	Forested Landscapes Promote Richness and Abundance of Native Bees (Hymenoptera: Apoidea: Anthophila) in Wisconsin Apple Orchards	Proportional area of landscape and habitat categories in different radius.	Forests near apple orchards increase the numbers and diversity of bees
Westphal et al.	2003	Mass flowering crops enhance pollinator at a landscape scale densities	Mass flowering crops; Distance to semi-natural habitats.	Bumblebee were positively related to the availability of mass flowering crops. The mass flowering crops are not an effective determinants for bumblebees when grown at small local scales.
Williams M. R.	2010	Habitat resources, remnant vegetation condition and area determine distribution patterns and abundance of butterflies and day-flying moths in a fragmented urban landscape, south-west Western Australia	Area; Connectivity; Vegetation condition; Habitat resources.	Area and vegetation condition are the dominant determinants of species presence.
Winfree et al.	2008	Wild bee pollinators provide the majority of crop visitation across land-use gradients in New Jersey and Pennsylvania, USA.	Proportion of woodland; Distance to the nearest patch of woodland; Farm management (organic\conventional); Floral availability related variables.	There weren't strong associations between land-use intensity and wild bee visitation to crops. Solitary species were positively associated with the abundance of weedy flowers in the farm field.
Winfree et al.	2009	A meta-analysis of bees' responses to anthropogenic disturbance	Loss and/or fragmentation of habitat surrounding the study site: Agriculture area, Logging, Grazing, Fire, Pesticide use, Tillage.	There was a significant negative effect of anthropogenic disturbance on the abundance and species richness of wild, unmanaged bees. Bee abundance and richness declined significantly only for habitat loss.

Supplementary Table S3. The General model implementation. Forward and backwards stepwise model selection was applied to the general starting model containing the below specified terms. All two-way interactions between the T1 and change terms were tested. Landscape ID (geographic location of the cell) and Period (1,2,3) were included as random effects.

T1 terms	**Change terms**	**Random terms**
ED Man-Nat T1	Δ Proximity	Landscape ID
ED T1	Δ PR	Time period
Patch Area T1	Δ ED Man-Nat	
PR T1	Δ ED	
Proximity T1	Δ Patch Area	
PSH T1	Δ PSH	

Fragmentation and composition variables descriptors= Proximity: Proximity index between patches of suitable habitat; PR: Number of land-use classes in the landscape; ED Man-Nat : Edge density between managed and natural systems; ED: Total edge density in the landscape; PA: average weighted mean patch's area of suitable habitat; PSH: Percentage of suitable habitat in the landscape. Δ: Change; T1: Time 1 or original landscape state.

Supplementary Table S4. Spatial autocorrelation results.

Moran's I test under randomisation

Group: Bumblebees
Moran I statistic standard deviate = -1.2819, p-value = 0.9001
sample estimates:

Moran I statistic	Expectation	Variance
-0.105004777	-0.025641026	0.003833271

Group: Other bees
Moran I statistic standard deviate = -0.8694, p-value = 0.8077
sample estimates:

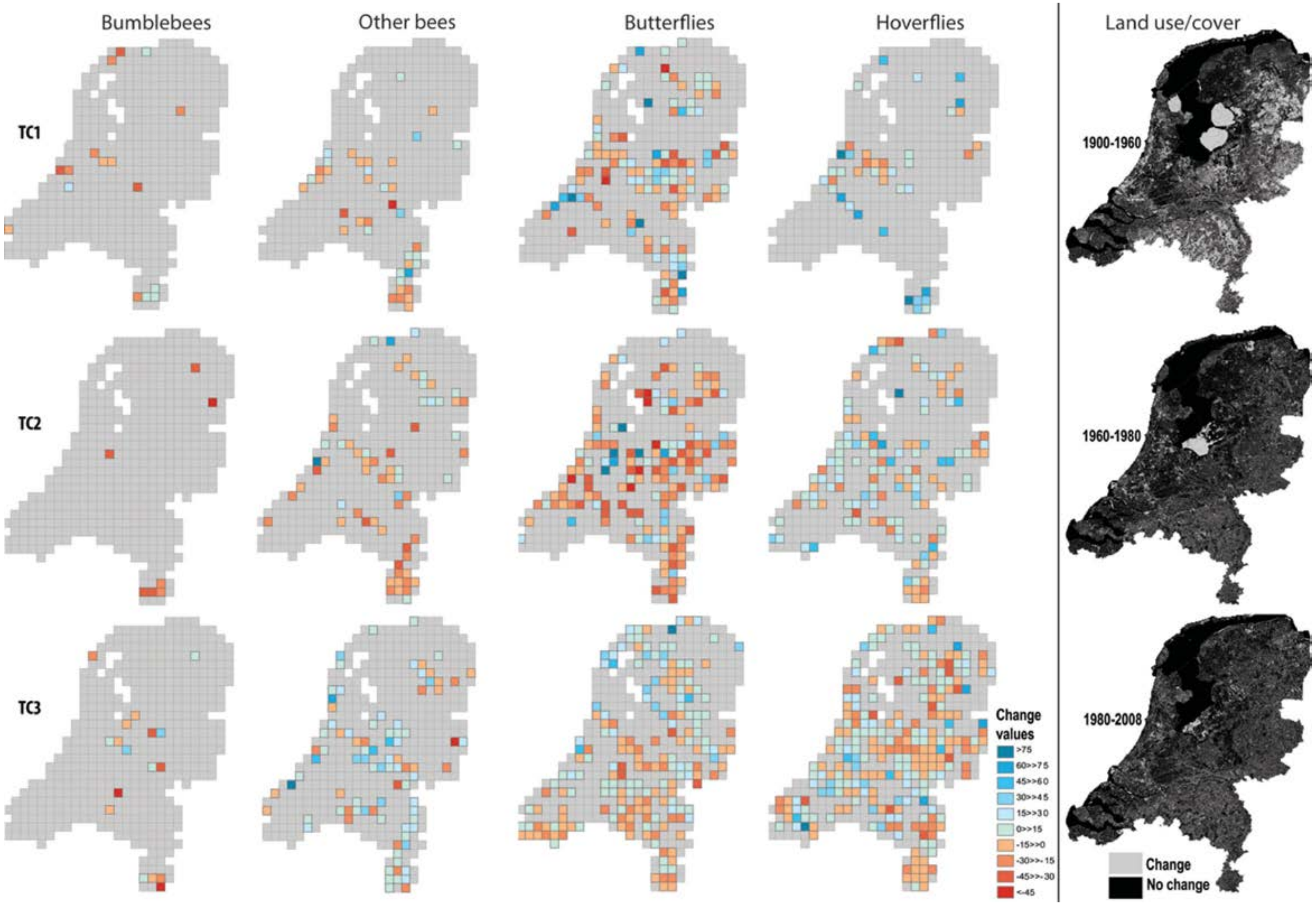
Moran I statistic	Expectation	Variance
-0.033570938	-0.005235602	0.001062190

Group: Butterflies
Moran I statistic standard deviate = -0.5108, p-value = 0.6952
sample estimates:

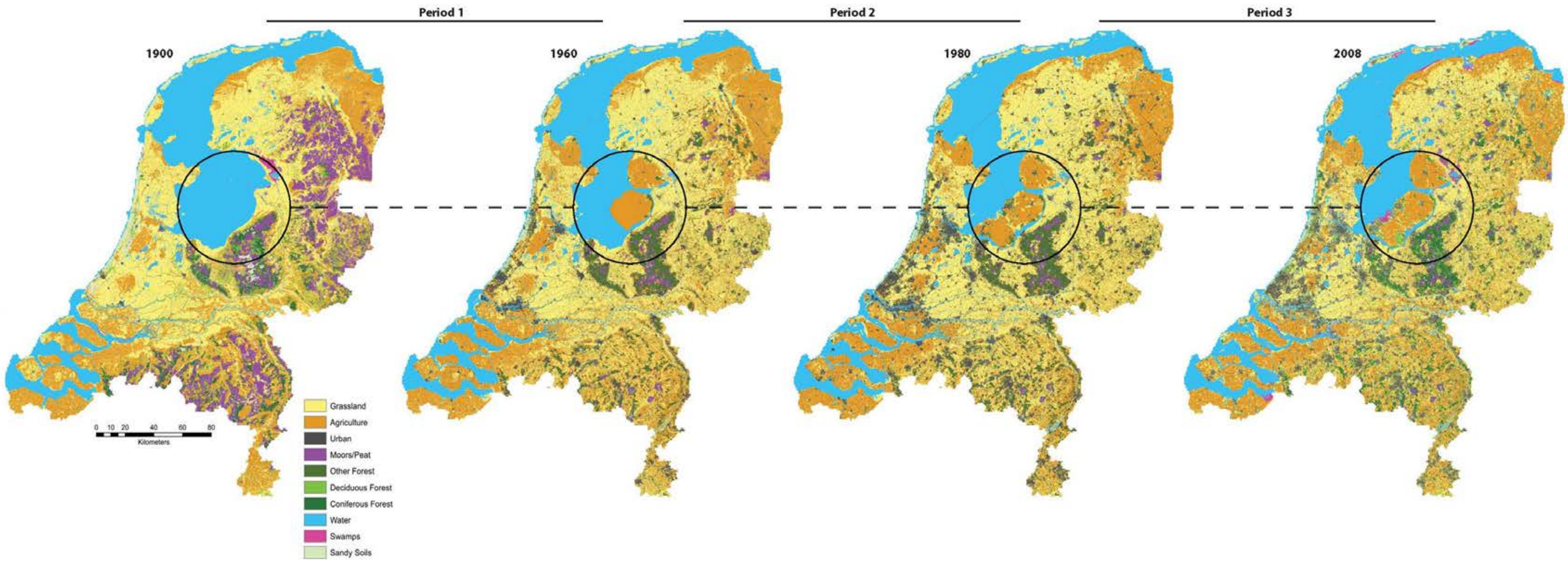
Moran I statistic	Expectation	Variance
-0.0132956362	-0.0021739130	0.0004740954

Group: Hoverflies
Moran I statistic standard deviate = 1.5218, p-value = 0.06403
sample estimates:

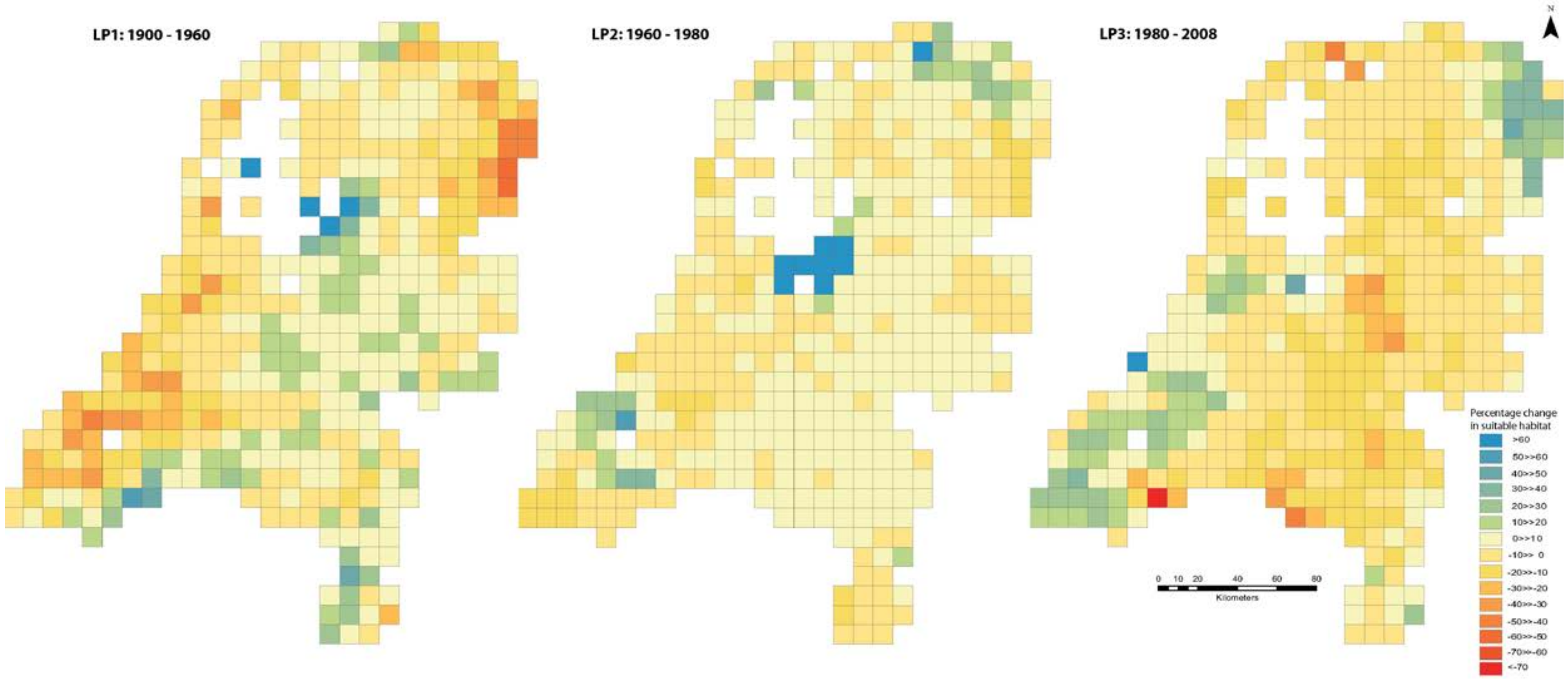
Moran I statistic	Expectation	Variance
0.0328885189	-0.0024937656	0.0005405688



Supplementary Figure S1. Changes in richness of several important pollinator groups in the Netherlands and the changes in land-use for the same areas. In the left side the maps with cells (10x10km) for which we have values of species changes, for each three time comparisons of species richness and pollinator groups. Species richness comparisons, TC1: 1930–1949 vs. 1950–1969; TC2: 1950–1969 vs. 1970–1989; TC3: 1970–1989 vs. 1990–2009. Blue colours represent positive species richness changes while red colours represent negative changes. The right side of the image contains the maps presenting the areas in the Netherlands that experienced changes (grey) in land-use and the ones that did not experience changes (black) for the three time periods analysed.



Supplementary Figure S2. The distribution of the ten land-use classes present in the study area for the three time periods analysed after the land-use classes reclassification process. The circles linked by the dotted line enclose some of the most noticeable changes in land-use in the study area. These changes are represented in the first period by the conversion of a water environment to a firm land one (mostly agriculture), and followed in the next periods by changes to other land-use classes. For a more specific description of the land-use types see Table S1, Knol et al. (2004) and Hazeu et al. (2010).



Supplementary Figure S3. The changes in the percentage of suitable habitat in the landscape between the periods analysed. Most of the landscapes experienced changes in the amount of suitable habitat ranging from the +20% to -20% in the three periods. During period one most of the negative changes took place in the western of the country and also in the northeast areas. In period two there were still losses of suitable habitat in these areas but to a lesser degree, also showing the increases of suitable habitat in the centre of the country where a polder was established. Especially during period three the amount of suitable habitat has declined considerably in the central-south region of the country. However, in this period important increases in suitable habitat have occurred, mostly in the same areas that during period one had experienced important suitable habitat declines.

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