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ORIGINAL ARTICLE

A validated expert-based habitat suitability assessment for eagle owls in Limburg, the Netherlands

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Abstract

Motivated by the high turnover rate of the Eurasian eagle owl (*Bubo bubo*) population in the south of the province of Limburg, the Netherlands, which is linked to extremely high concentrations of PCBs (polychlorinated biphenyls) and DDE (dichlorodiphenyldichloroethylene) found in owl carcasses, a habitat suitability (HS) assessment for this region was conducted to identify possible sources of PCBs in the environment. Twelve environmental characteristics (ECs) that are known to influence the presence of the species were selected. With each EC, a suitability index (SI) was associated and a uninorm was used to aggregate these individual SIs into one overall HS index value. The HS assessment was validated using GPS tracking data of six adult eagle owls. Further, Ivlev's electivity index and Manly's habitat selection index were used to compare the area used with what is available in the landscape. To describe the former, we considered both the probability of occurrence and the home range of the tracked individuals. The resulting HS map shows that quarries and vegetation structures, such as hedgerows or solitary trees, are the main attractors for the species, though also forest edges, orchards, and tree and fruit nurseries attract the species in the study area. Hence, further field sampling campaigns to identify possible sources of poisoning should focus on parcels with these land covers. Such a prioritization of parcels becomes possible using our approach.

Keywords Eagle owl · *Bubo bubo* · Habitat suitability map · Brownian bridge movement model · Ivlev's electivity index · Manly's habitat selection index · Continuous Boyce index

Introduction

Since 1997, the Eurasian eagle owl (*Bubo bubo*) has been present in Limburg, the southeastern province of the Netherlands, most likely following the dispersion of individuals from Germany after reintroduction programs (Wassink 2010b). Here, the suitable breeding locations are situated on the steep slopes of (former) quarries. These natural walls are similar to the ones found at German reintroduction sites. Thanks to their presence in Limburg and the fact that this province is located near the reintroduction sites, the region got colonized by the eagle owls. More generally, there has been an increasing number of breeding pairs reported over the last years in the Netherlands, Belgium, and Germany. Although quarries serve as nesting sites in Limburg and in many other regions, other nesting sites also can be exploited, such as abandoned nests of buzzards (*Buteo buteo*), industrial buildings, and forests (Wassink 2011b).

Based on the presence of a suitable breeding habitat, Limburg has the potential to sustain up to ten breeding pairs, but up until 2010 at most five pairs were recorded (Voskamp 2004; Wassink 2010b). Even though populations have increased throughout the years in neighboring regions, the population in Limburg has stagnated. This suggests that certain environmental factors in this region are constraining the eagle owl population size below its estimated maximum capacity (Wassink 2010b).

Moreover, during the period 1998–2010, 11 carcasses were found in Limburg, where the cause of death could not be identified in eight cases. Two of these individuals were examined and extremely high concentrations of PCBs (polychlorinated biphenyls) and DDE

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(dichlorodiphenyldichloroethylene) were found (van den Brink and Jansman 2005). The latter chemical compound is a breakdown product of dichlorodiphenyltrichloroethane (DDT), being forbidden since the 1970s in both the Netherlands and Belgium (UNEP and FAO 1991).

In order to locate the possible poisoning sources and to protect the eagle owl population, prey, water, soil, and other field sampling campaigns should be conducted in the study area. To optimize such campaigns, it is important to identify the most frequently visited areas and to get insight into the owls' motives for visiting a particular area (Martínez et al. 2003).

Therefore, we constructed a habitat suitability (HS) map for the species in the region on the basis of literature and expert knowledge. Here, it is expected that the species will spend relatively more time in more suitable regions. This map consists of a raster of pixels (or cells) organized in rows and columns, where each pixel is assigned the corresponding value of the so-called habitat suitability index (HSI).

In order to demonstrate the accuracy of an HS map, validation is crucial (Roloff and Kernohan 1999; Ottaviani et al. 2004; Hirzel et al. 2006), preferably using an independent set of data on the presence and absence of the species. Such data is, however, often not available, and also for this study only GPS tracking data were available of six adult eagle owls collected during 2010–2011 occupying three adjoining territories. In GPS tracking studies, individuals are followed in time, resulting in discrete observations of the continuous movement process. Since there is no information on species absence, one needs appropriate statistical tools to deal with presence-only data (Ottaviani et al. 2004; Hirzel et al. 2006).

In "Methods," the study area and tracking data are presented. Moreover, the habitat preferences and behavior of the Eurasian eagle owls are discussed in this section to underpin the construction of the HS map. Then, we present our methodology for constructing and validating the HS map. The results and discussion can be found in "Results" and "Discussion," respectively.

Methods

Study area and GPS tracking data

Tracking data of three breeding pairs, referred to in the remainder of this paper as pairs A, B, and C, settled in (former) quarries of the province of Limburg, the Netherlands, were available. Figure 1 shows the study area together with the tracking data that were collected between June 25, 2010, and July 20, 2011. The six adults were caught by a spring net baited with dead pigeons and equipped with tracking devices (GPS-UHF logger, E-obs, Gruenwald, Germany). Pair A lives in the surroundings of the village Meerssen, pair B is settled close to the city Maastricht, and finally, pair C lives in the surroundings of the village Cadier en Keer. The rectangular area enclosing all data points defines the study area. In a Universal Transverse Mercator (UTM) coordinate system, this corresponds to y-coordinates varying between 5 629 628.10 m and 5 642 918.10 m, and x-coordinates between 682 237.82 m and 698 047.82 m in UTM-zone 31N.

The topographical maps of the Netherlands (Het Kadaster 2016) and Belgium (Nationaal Geografisch Instituut 2010) were used to collect all the necessary geographical information. They are available at a scale of 1:5000 and 1:10,000, resp., and were merged appropriately. In our study, a pixel represents an area of 5 m $\times$ 5 m.

Figure 2 shows the tracking periods for the different owls together with some important time stamps defining their behavior, while Table 1 lists more information on the extent of the tracking dataset. Using all GPS tracking data, an entire yearly cycle can be covered. Since we wanted to arrive at an HS map that represents the suitability of the study area during any life stage, we considered all tracking data. The owls' locations were recorded every third night, from between 4–5 PM until about 5–7 AM (GMT +1), with a time resolution of 20 min. The male member of pair A was only tracked from 8 PM onwards. Missing data of females B and C can be linked to breeding, since there was no GPS coverage at the nesting site. In the remainder, the location where an individual was registered at a specific time stamp will be referred to as a "fix."

The Eurasian eagle owl

Eagle owls are active from dusk until dawn, with peak activity typically one hour before sunset and during sunrise (Penteriani 2002; König et al. 2010). During the day, they rest out of sight high in the trees or on rocks. Adult eagle owls are strictly territorial and are known to live in the same area for years. They prefer structured landscapes, with steep slopes, hills, and valleys, and a high prey availability throughout the year. Moreover, they prefer elevated structures, such as trees or ridges, where they can sit and wait until prey pass by (Wassink 2010a, 2011a, 2012, 2014b). Accordingly, they move through the landscape from one observation post to another, guided by structural elements in the landscape (Miosga et al. 2015).

Eagle owls tend to avoid interaction with humans, though several breeding pairs have been spotted in major cities, such as Helsinki, due to their high food availability (Alerstam et al. 2003). Still, they are very sensitive to disturbances near their nesting sites (Heintzenberg 2008; König et al. 2010).

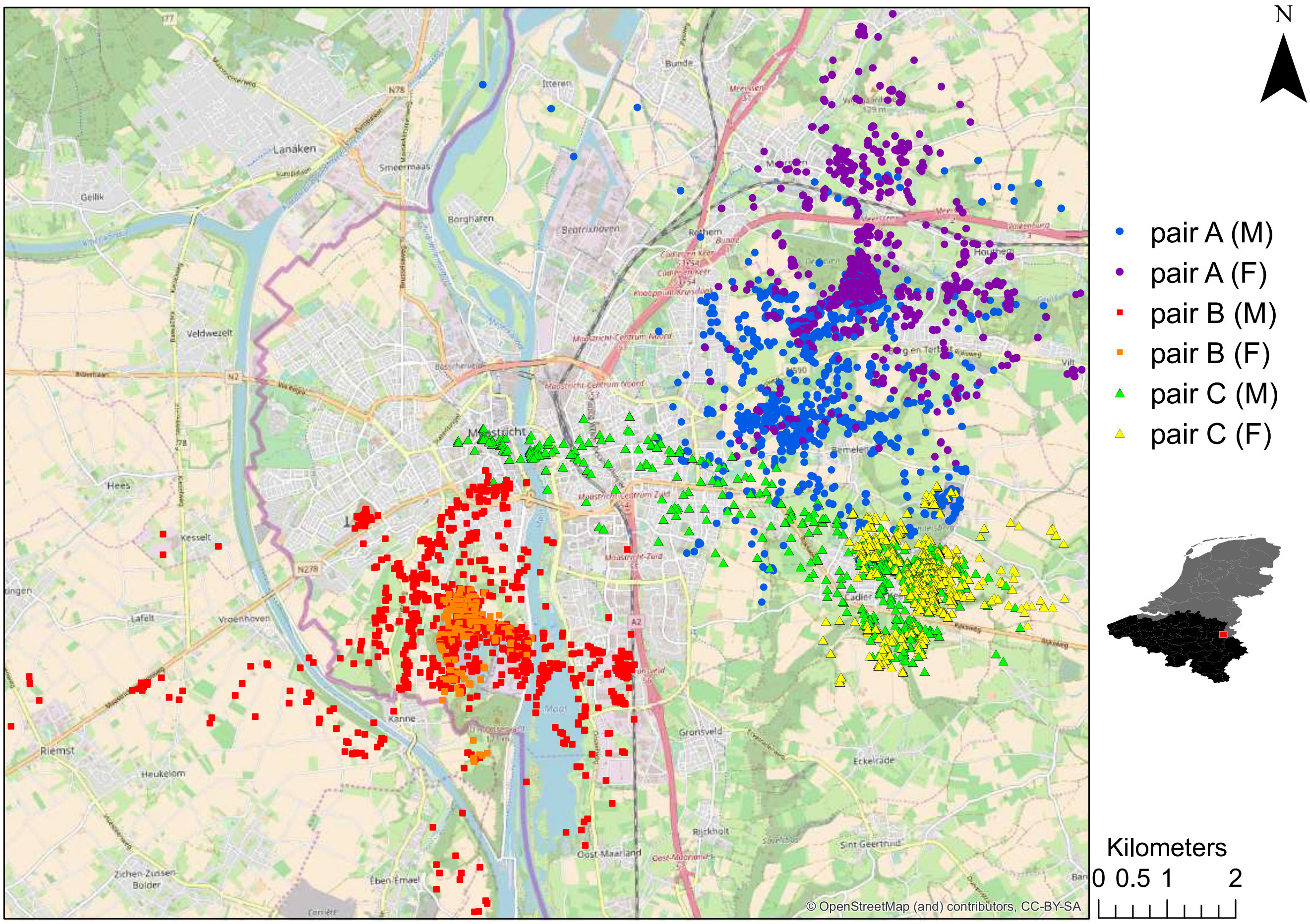


Fig. 1 Study area together with the GPS tracking data of the tracked eagle owls (source: OpenStreetMap contributors, UTM geographic coordinate system). The location of the study area is shown in the inset by a red rectangle

Eagle owls are at the top of the food chain and do not have natural enemies. Since the eagle owl preys on species from higher trophic levels, there is an increased health risk due to bioaccumulation (Lourenço et al. 2011). From 1960 onwards, strict protective EU legislation has saved the eagle owl from extinction. Besides, successful reintroductions

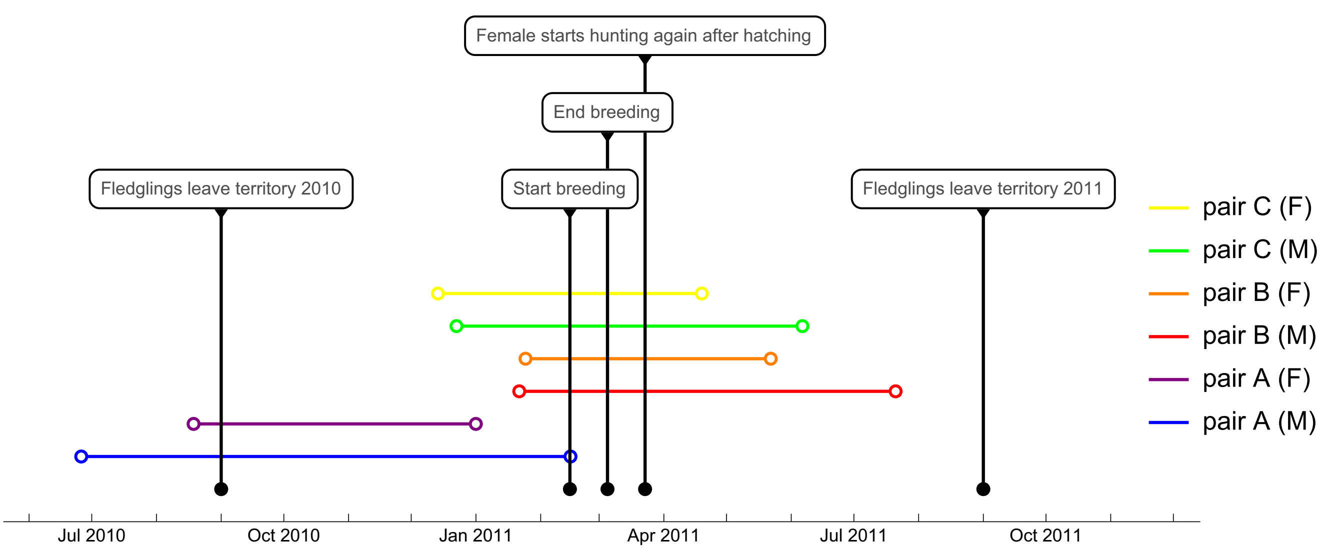


Fig. 2 Study period per owl

Table 1 Details on the extent of the tracking dataset

Individual	Number of time-stamped locations	Missing data (%)	Total number of fixes
A male	2306	2.73	2243
A female	1966	11.40	1741
B male	2412	9.87	2174
B female	1649	49.60	831
C male	2710	8.30	2484
C female	2048	37.20	1287

helped increase population sizes (Heintzenberg 2008). Currently, the IUCN lists the bird's conservation status as "being of least concern" (BirdLife International Downloaded in 2018).

An eagle owl kills its prey with its powerful talons and by biting their heads with its bill. Small animals are consumed at once, whereas larger ones are taken to a perch, where they are torn into pieces. Birds are first plucked before they are eaten (van den Brink and Jansman 2005; Heintzenberg 2008; König et al. 2010). Since owls are opportunistic predators, their space use is mainly determined by the presence of prey.

The most common prey species are the common wood pigeon (*Columba palumbus*) and the rock pigeon (*Columba livia*). The former's density is high in urban areas and half-open landscapes (Penteriani et al. 2002), which are characterized by pastures, arable land, trees, and hedgerows (Wassink 2014b). Wood pigeons often rest in those trees, hedgerows, or along the forest edges, whereas they are absent in treeless landscapes and rare inside large forests. Rock pigeons can be found year-round near urban areas (SOVON 2012). In addition to carrion crows (*Corvus corone*) and rook (*Corvus frugilegus*), which are generally present in large numbers (SOVON 2012), also rats (*Rattus* spp.), mice (*Mus* spp.), European hedgehogs (*Erinaceus europaeus*), Eurasian coots (*Fulica atra*), and European rabbits (*Oryctolagus cuniculus*) are, like many other species, preyed upon. Rats and mice are omnivores and can easily adapt to several habitats, but they prefer lush verge vegetation, and agricultural or urban areas (Marchesi et al. 2002; Strachan and Moorhouse 2006; Uhlenbroek 2008). In the Netherlands, hedgehogs are found near urban areas, such as gardens, parks, and orchards. They are known to avoid coniferous forests and humid areas (Young et al. 2006; Morris 2006; Uhlenbroek 2008; van de Poel et al. 2015). Rabbits also prefer dry areas to dig their holes, and areas with sufficient protection against predators, such as half-open landscapes, gardens, and edges of forests (Lombardi et al. 2003). To a lesser extent, also other raptors and owls are eaten.

Habitat suitability maps

Construction

The first step in the construction of an HS map usually consists of selecting the ECs that are determinants for the species' dynamics (Fish US and Wildlife Service 1981). These ECs are typically related to topography, human influence, land use, and landscape diversity (Hirzel et al. 2006). The tolerance of the species to an EC is represented by a function relating the EC to suitability, the so-called suitability index (SI). The SI and the spatial distribution of each EC lead to a pixel-based SI value in the unit interval. As such, each EC gives rise to a suitability map. Finally, the SI values of all ECs are aggregated per pixel into a single overall HSI value (Fish US and Wildlife Service 1981), on the basis of which an HS map can be generated. In this paper, we adopted a knowledge-based approach to design the HS map on the basis of literature and expert knowledge.

The resulting information typically describes the eagle owl's behavior in a qualitative way. To transform this into specific SI values, we considered each EC individually and chose 0.5 as a neutral SI value, meaning that a pixel having this SI value has no effect on the species, while it has a positive, respectively negative, effect if the SI value is higher, respectively lower, than 0.5. Depending on the intensity of influence exerted by a given EC, SI values are closer to 0 or to 1, in agreement with how they are typically interpreted (Fish US and Wildlife Service 1981). The details on the calculation of the SI values are shown in Appendix A.

There are several functions to aggregate n SI values of a pixel p into a single HSI value, which, for the same n SI values, leads to different HSI values, as they allow for a different degree of compensation between the different values to reach a given HSI value. Irrespective of the used aggregation function, it must lead to HSI values in the unit interval and it should reflect the relationship between the environmental characteristics (Fish US and Wildlife Service 1981; Van Horne and Wiens 1991). For instance, if any of the ECs is limiting, one may use the minimum as aggregation function. A weighted sum or average is taken if the combined effect of several SI values is considered, whereas the product allows individual ECs to have a large potential influence on lowering the overall HSI value. In this study, the so-called uninorm aggregation function is used. Its details can be found in Appendix A. Table 2 indicates that ECs with a positive influence compensate for ECs with a negative influence, and that synergistic effects occur when combining ECs having positive, respectively negative, influences.

Table 2 Some exemplary aggregations of SI values according to Eq. 4

$\mathscr{S}^{e1}_{a_e,r_e}(p)$	$\mathscr{S}^{e2}_{a_e,r_e}(p)$	$\mathscr{H}(p)$
0.9	0.5	0.9
0.2	0.9	0.69
0.2	0.8	0.5
0.9	0.7	0.95

Validation and interpretation

After constructing an HS map, validation is needed to confirm its credibility. If an HS map is well constructed, pixels with high HSI values are more likely to be visited by the species. Validation is preferably done by making use of an independent dataset on the sites where the species is present and where it is absent (Roloff and Kernohan 1999; Ottaviani et al. 2004; Hirzel et al. 2006). In this study, we used the available GPS tracking data for validation. GPS tracking studies lead to discrete observations of the continuous movement process and give no information on species absence, so one needs appropriate tools to deal with presence-only data (Ottaviani et al. 2004; Hirzel et al. 2006). Furthermore, GPS tracking data are auto-correlated. This means that common approaches focusing on hypothesis testing cannot be used (Boyce et al. 2002). Therefore, the HSI values of the pixels that were probably visited by the species were compared with those available in the landscape (Boyce et al. 2002). More specifically, we combined the methodologies presented in the papers by Reynolds-Hogland and Mitchell (2007) and Hirzel et al. (2006).

In the former, habitat selection is estimated on the basis of GPS tracking data, so we could use its underlying methodology to evaluate the preferential selection of high HSI values. First, fixes are transformed into a PDF reflecting the probability density that an individual visits a location in the study area, and this information is then summarized in terms of a home range, which may subsequently be used to analyze HSI selection and validate the HS map (Mitchell et al. 2002; Reynolds-Hogland and Mitchell 2007). Here, we used the Brownian bridge movement model (BBMM) to determine the PDF value in the center of each pixel (Bullard 1991; Horne et al. 2007; Van Nieuland et al. 2015), which served as a basis to define the home range. For that purpose, we calculated a threshold τ so that the subset of pixels having a PDF value in their center that is greater than or equal to τ represents 90% of the volume under the PDF. This subset represents the area with the highest possible PDF values, where the individuals are expected to be located during 90% of the studied time interval (Kie et al. 2010; Pop et al. 2018). In this way, the PDF itself and the home range could be used for validation.

On the basis of the PDF and the home range, two indices were calculated to compare the pixels that were probably visited with those available in the study area: Ivlev's electivity index (Ivlev 1960; Reynolds-Hogland and Mitchell 2007) and Manly's habitat selection index (Manly et al. 2002; Desbiez et al. 2009; Hirzel et al. 2006). For each of them, we considered a version based on the raw tracking data (I_c and M_c) and a version based on the PDF that reflects the probability density that an individual visits a certain pixel ($\widetilde{I}_c$ and $\widetilde{M}_c$). The details on their computation are given in Appendix B.

Ideally, both indices should increase linearly as a function of the average HSI value of each bin c, so that the average HSI value is proportional to the calculated indices (Hirzel et al. 2006), though the magnitude of the validation indices is sensitive to the extent and the shape of the study area.

Instead of choosing b HSI bins, Hirzel et al. (2006) used a moving window of width W that shifts from HSI value 0 to 1 in order to arrive at smoother graphs of the indices versus the average HSI value. As such, the shape of the graphs can be used, next to the index values themselves, to better evaluate and interpret the resulting HS map and to decide which pixels are suitable for the studied species and which are not (Hirzel et al. 2006).

Results

The habitat suitability map

As a first step in constructing the HS map, we inventoried the ECs that influence the behavior of the eagle owls. Then, for every EC, we defined the appropriate a_e and r_e, after which an SI value for every EC was assigned to every pixel. The 12 ECs that are assumed to influence the eagle owls in Limburg, the Netherlands, were selected on the basis of literature and expert knowledge (Table 3). The available geographical information corresponding to those ECs is shown in Fig. 9a–c (Appendix C). The importance of each selected EC can be assessed by means of a_e. The considered ECs and their corresponding SIs are subjective, though we relatively weighted our choices and motivated them as much as possible.

An important feature when selecting a habitat is the presence of potential nesting sites. In Limburg, so far, the eagle owls only nest in former quarries (EC1) (van Lierop and Janssen 2014; Wassink 2014c), whose presence may as such be designated as of utmost importance in our study area ($a_e = 1$). When the owls have to cover large distances to find their prey, this consumes a lot of energy and thereby makes locations farther away from quarries less suitable. The average distance between 28 territories of eagle owls

Table 3 Overview of the considered environmental characteristics (ECs), together with the SI value that typifies each EC e (a_e) and the radius of influence (r_e)

EC	Description	a_e	r_e (m)
EC1	Quarry	1	3500
EC2	Arable land or pasture	0.7	0
EC3	Forest edge	0.8	0
EC4	Agricultural land use related to trees	0.8	0
EC5	Town center	0.6	0
EC6	Industrial area	0.6	0
EC7	Vegetation structures	0.9	75
EC8	Difference in altitude	0.7	75
EC9	Water bodies	0.8	75
EC10	Minor roads	0.6	75
EC11	Major roads	0.2	1000
EC12	Buildings outside town center	0.7	75

nesting in the Netherlands, Belgium, and Northern Germany was found to be 6906 m (Wassink 2007). For that reason, we chose $r_e = 3500$ m as the maximal distance from the quarry edges up to which the quarry has a positive influence.

In the remainder of this section, we firstly study the ECs for which the influence radius is 0 ($r_e = 0$). These ECs are mainly related to land use. Secondly, we study the ECs for which $r_e > 0$ and that are related to physical elements in the landscape.

Pixels where arable land or pastures (EC2) are present were assigned a suitability of 0.7 ($a_e = 0.7$) since they do not only provide prey, but also bring along threats, such as barbwire and poisonous pesticides and herbicides. Forests are potential hunting grounds (Wassink 2014a, b). The center of a forest, however, is less suitable due to the higher vegetation density hindering hunting. This problem is much less of an issue along forest edges (EC3), which serve as ideal sleeping grounds for pigeons and habitats for rabbits (Wassink 2014a b). The extent of the positive influence of such edges depends on the area and shape of the forest, but typically ranges from 100 to 300 m inwards (Rusak 2003). In our study area, the forests are relatively small, so we chose the former as forest edge width. A suitability of 0.8 was assigned to pixels located in the forest edge ($a_e = 0.8$), whereas pixels corresponding to locations in the center of the forest or outside the forest were assigned a suitability of 0.5 for EC3. Pixels containing agricultural land uses related to trees (EC4), such as orchards, tree and fruit nurseries, and poplar plantations, were assigned an SI value of 0.8 since they are attractive for prey and consist of sparse vegetation serving as observation post ($a_e = 0.8$). In regions where the eagle owls can avoid contact with humans, they live in non-urban areas (Donázar 1989; Martínez and Calvo 2000). However, more and more breeding pairs can be found in major cities (such as Helsinki) (Alerstam et al. 2003). Likewise, in our study area, some prey are caught near urban areas (EC5) (Voskamp 2004; Wassink 2010a), so we set $a_e = 0.6$ for this EC. This SI value is lower than the one assigned to agricultural land use, because the more natural setting provided by the latter is an added value as compared to urban areas. Furthermore, industrial areas (EC6) are good hunting grounds for the species since, for example, pigeons often rest there (Wassink 2011b). In these areas, however, there is also human disturbance (König et al. 2010; Miosga et al. 2015; Wassink 2016), so we chose $a_e = 0.6$, which coincides with the value chosen for urban areas.

The first considered physical elements whose $r_e > 0$ are the isolated and linear vegetation structures (EC7) serving as observation posts for which we chose $a_e = 0.9$ and $r_e =$ 75 m. This radius was chosen based on an extrapolation of the findings reported in Mortenson (1971) for a related owl species. The same radius of influence is used for EC8, EC9, EC10, and EC12. Differences in altitude (EC8) also serve as observation posts, but do not necessarily imply an increased prey availability. They often occur together with EC7, so we set $a_e = 0.7$ and $r_e = 75$ m. Water bodies (EC9) positively impact the presence of eagle owls since their banks often provide shelter to prey (Martínez et al. 2003; Strachan and Moorhouse 2006; Wassink 2007; Heintzenberg 2008; König et al. 2010). Consequently, $a_e = 0.8$ and $r_e = 75$ m. However, pixels completely covered with water bodies were assigned a neutral SI value. For what concerns roads, it is clear that they might be avoided due to traffic, but their verges can contain prey. Moreover, it is easy to sit and wait in a tree along a road until a prey crosses so that it can be caught. Yet, this is unlikely to hold for busy roads. As such, we distinguished between minor roads (EC10) and major roads (EC11). The former are paved and more than 4 m wide, and have a negative effect on the species, so that $a_e = 0.2$ and $r_e = 1000$ m on either side of the road. This radius has been reported as the distance within which breeding birds are effected by roads (Reijnen and Foppen 2006). For what concerns minor roads (EC10), we assumed that only the ones located outside town centers have a positive effect, since there is less human disturbance and it has been reported that the species diversity in their verges is higher outside these centers (Centraal Bureau voor Statistiek 2015). Consequently, $a_e = 0.7$ and $r_e = 75$ m for minor roads outside town centers. Finally, buildings outside town centers (EC12) are considered because they are typically located relatively far from other human activities. These structures often relate to farms, which represent potential food sources (Tucker et al. 2018). Consequently, $a_e = 0.7$ and $r_e = 75$ m for this EC.

The resulting HS map for eagle owls in our study area is shown in Fig. 3, while the SI maps for the individual ECs can be found in Figs. 10 and 11 (Appendix D).

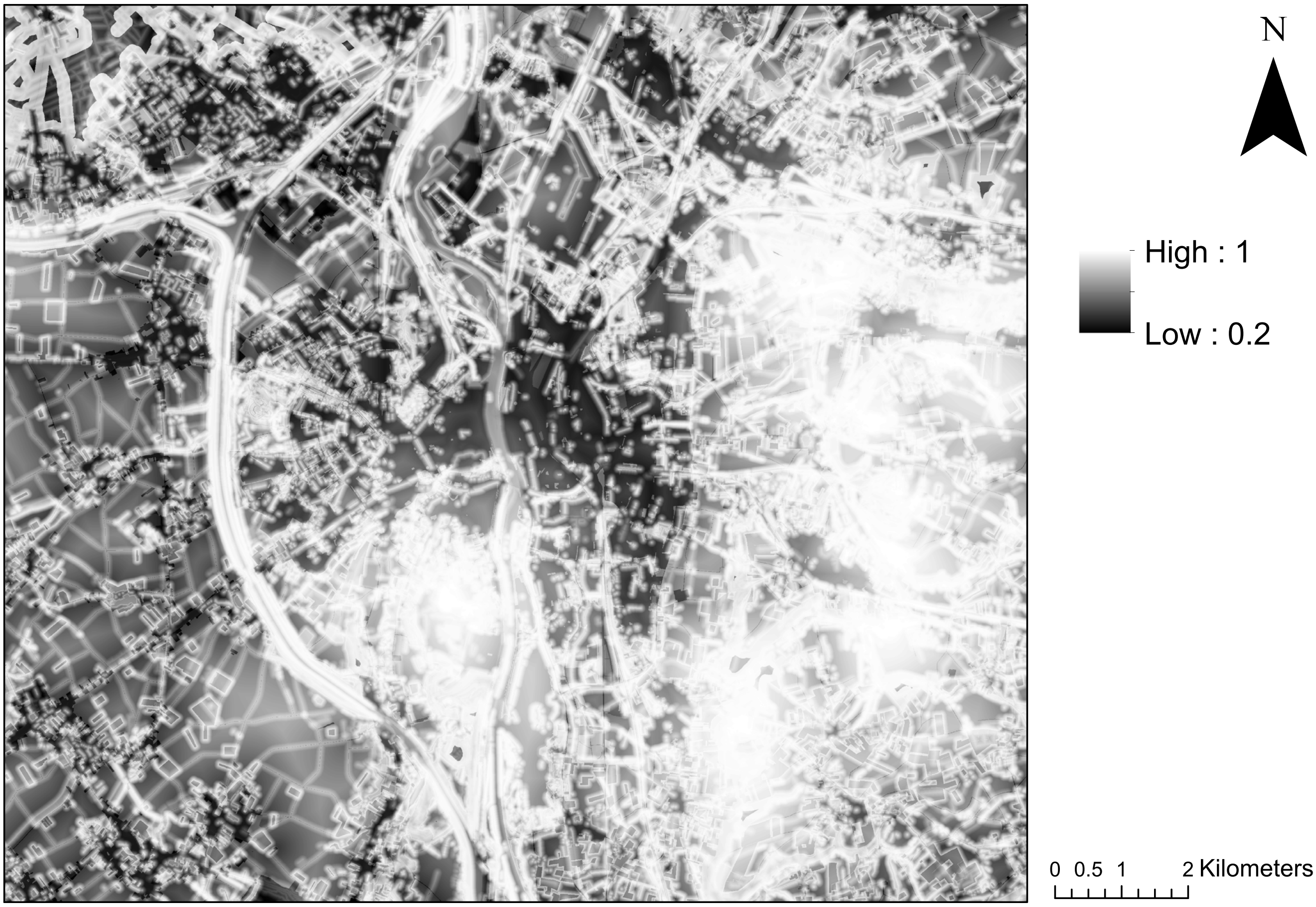


Fig. 3 The HS map for the eagle owls in the study area

The probability density of occurrence

The weighted average of the time-integrated Brownian bridges (TIBBs) defined in between each pair of consecutive fixes in the tracking data was calculated per individual owl to determine the probability density of occurrence of every individual at every location in the study area. Next, the average PDF of the six eagle owls in our study area was calculated and is shown in Fig. 4 by means of a contour plot. We determined 10 thresholds, one threshold τ per decile $\mathscr{D}$, so that the subset of pixels having a PDF value in their center that is greater than or equal to this threshold represents $(100 \times \mathscr{D})$% of the volume under the PDF. For each threshold, the pixels having PDF values equal to this threshold are connected, so that a contour is obtained that delineates the area having the highest possible PDF values where the individual is expected to be located during $(100 \times \mathscr{D})$% of the studied time interval. If the contour corresponding to the threshold of $\mathscr{D} = 1$, i.e., the contour enclosing the area where the individuals were certainly observed within the studied time interval, is not visible, then it corresponds to the boundary of the study area. The area enclosed by the contour corresponding to the threshold of, for example, $\mathscr{D} = 0.1$ is smaller than the area enclosed by the one corresponding to the threshold of $\mathscr{D} = 1$, but contains the most visited areas, with the highest probability densities.

Validation and interpretation

In Fig. 5, the probability mass function (PMF) of the HSI values assigned to the pixels in the study area (black) and those assigned to the fixes (gray) are shown (bin width = 0.05). The HSI values in the study area range from 0.2 to 1 with relatively more pixels with a higher suitability. However, this skewness is much more pronounced in the PMF for the fixes. The large majority of the pixels are located in highly suitable areas with an HSI value greater than 0.95. This probably stems from the fact that many fixes are located near the nesting sites. Nevertheless, also locations farther away from nesting sites are of interest since they can, for example, serve as hunting grounds.

Ivlev's electivity index (Ivlev 1960; Mitchell et al. 2002) and Manly's habitat selection index (Manly et al. 2002; Desbiez et al. 2009) were both calculated using a moving window of width $W = 0.1$ that was shifted along the HSI range in steps of 0.01. Plots of the average HSI value versus

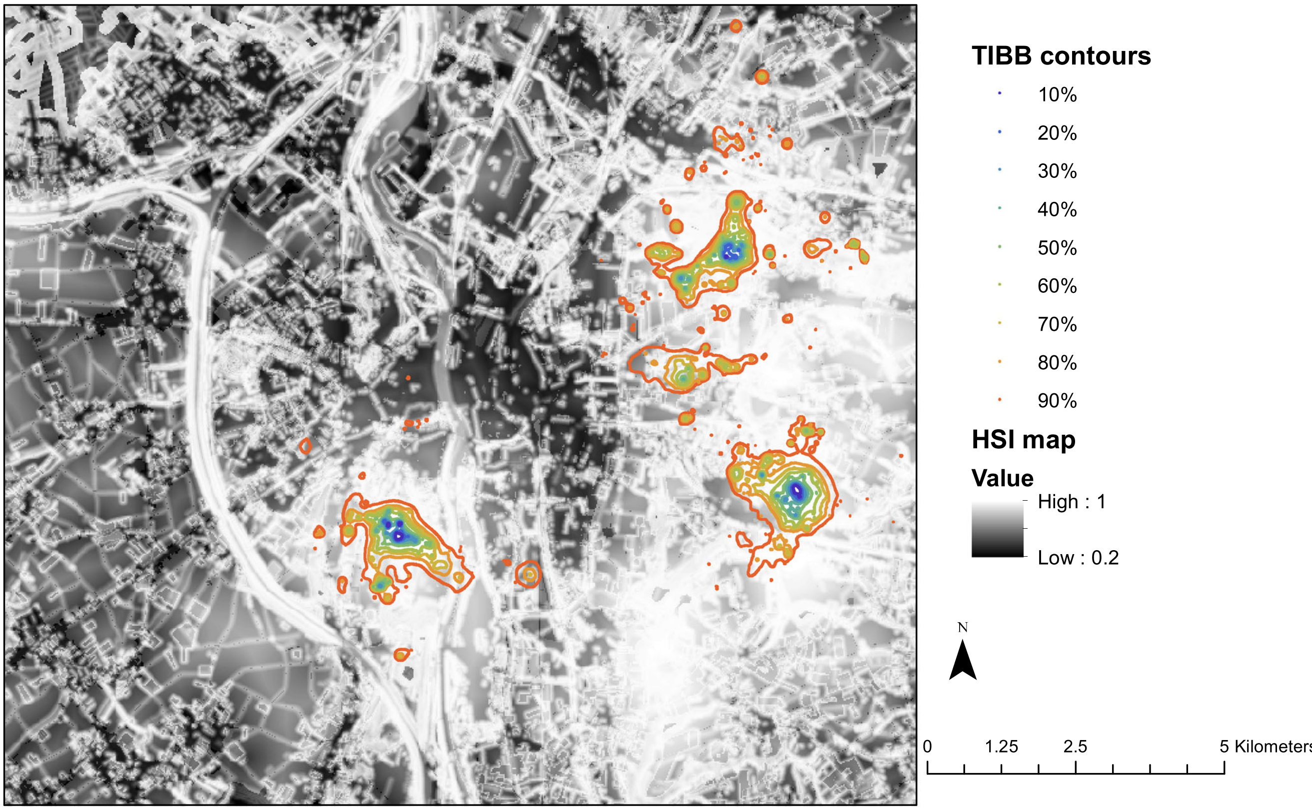
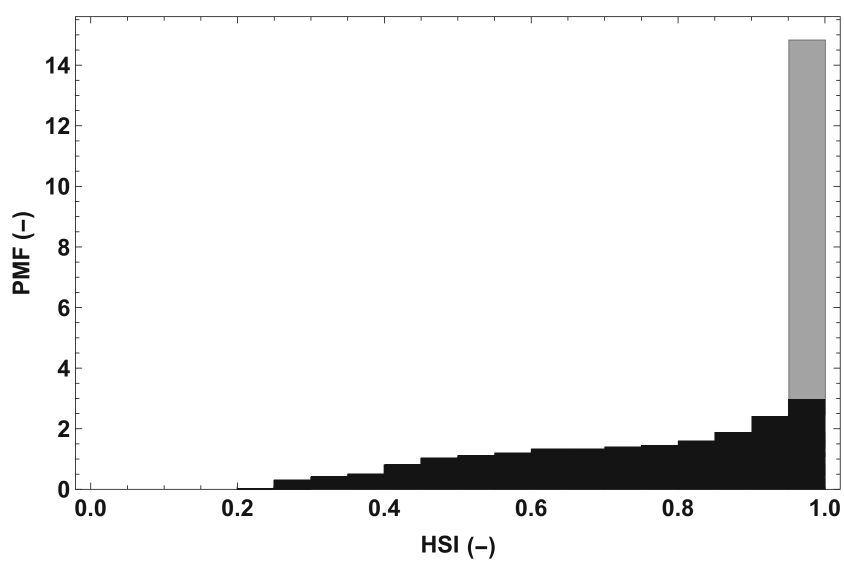


Fig. 4 The probability density of occurrence of the six eagle owls in the study area represented by means of a contour plot. The HS map is used as a base map

I_c (8) and $\widetilde{I}_c$ (9) are shown in Fig. 6, while plots of the average HSI value versus M_c (10) and $\widetilde{M}_c$ (11) are shown in Fig. 7. It can be seen that these indices do not increase linearly as a function of the HSI value, but that there is a sharp increase toward the end of the HSI range. This is due to the fact that many fixes in our dataset are located close to each other in a limited number of pixels, which consequently all have a very high probability of occurrence.

As can be seen in Fig. 6, the value of I_c is about −1 for HSI values lower than 0.55, while it is about −0.75 for HSI values between 0.6 and 0.7, after which it increases gradually. In contrast, $\widetilde{I}_c$ increases gradually, though from about 0.7 on it increases more rapidly, and this becomes even more

Fig. 5 The probability mass function of the HSI values assigned to the pixels in the entire study area (black) and those assigned to the fixes (gray) (bin width = 0.05)



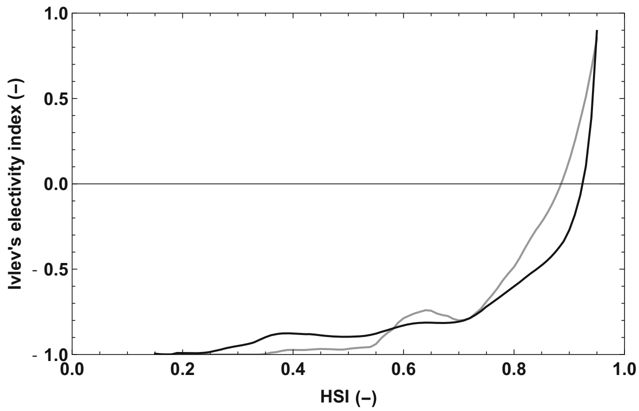


Fig. 6 The average HSI value versus I_c (gray) and versus $\widetilde{I}_c$ (black). In both cases, a moving window of width 0.1 that is shifted along the HSI range in steps of 0.01 was used

pronounced from about 0.9. If $I_c = 0$ would be chosen as a threshold to distinguish between suitable and non-suitable areas (according to Mitchell et al. 2002; Reynolds-Hogland and Mitchell 2007), then only areas with HSI values greater than 0.89 would be identified as suitable for the owls. For $\widetilde{I}_c$, this corresponds with HSI values greater than 0.93. These high HSI values result from the bias in the fixes' locations described earlier. Therefore, we had a look at the shape of the graphs to interpret the results in an alternative way. On the basis of I_c, we may conclude that pixels with an HSI value lower than 0.55 are unsuitable (where I_c is about -1), and pixels with an HSI value between 0.55 and 0.7 are suitable (just before the steep increase), while pixels with an HSI value greater than 0.7 are highly suitable. Alternatively, on the basis of $\widetilde{I}_c$, we may conclude that pixels with an HSI value lower than 0.7 are unsuitable (where $\widetilde{I}_c$ is low), and pixels having an HSI value between 0.7 and 0.9 are suitable (just before the steep increase), while pixels with an HSI value greater than 0.9 are highly suitable, and are probably located close to a possible nesting site.

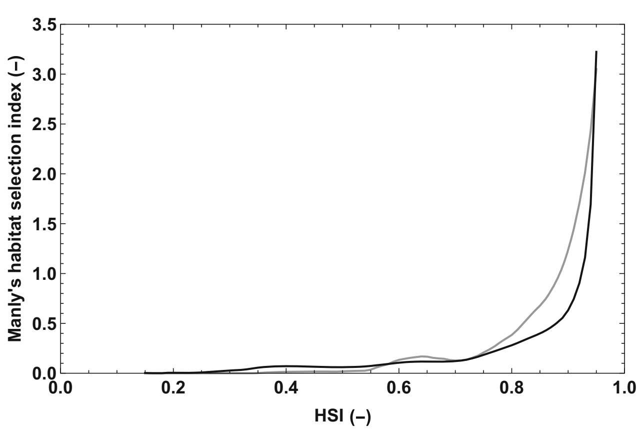


Fig. 7 The average HSI value versus M_c (gray) and versus $\widetilde{M}_c$ (black). In both cases, a moving window of width 0.1 that is shifted along the HSI range in steps of 0.01 was used

As can be seen in Fig. 7, M_c is about 0 for HSI values lower than 0.55, while it is about 0.15 for HSI values between 0.6 and 0.7 after which it increases gradually. For $\widetilde{M}_c$, which is computed on the basis of the probability of occurrence, the graph gradually increases from about 0.7 on, after which (at about 0.9) there is a steep increase. If $M_c = 1$ would be chosen as a threshold for distinguishing between suitable and non-suitable areas (according to Hirzel et al. (2006)), then only areas with HSI values greater than 0.89 would be labeled as suitable for the owls, i.e., then it holds that $U_c \geq A_c$. For $\widetilde{M}_c$, this corresponds with HSI values greater than 0.93. Given these HSI values and given that the slope of the graph of M_c, respectively of $\widetilde{M}_c$, changes at the same HSI values as the ones of I_c, respectively of $\widetilde{I}_c$, the same conclusions can be drawn from the shapes of the graphs when using Manly's habitat selection index instead of Ivlev's electivity index.

Given the fact that eagle owls almost exclusively use areas with HSI values greater than 0.7, and mostly areas with HSI values greater than 0.9, we may conclude that our HS map is well designed. It clearly reflects the suitability of the study area for the eagle owls. Since both indices lead to the same results, we cannot point toward the better one. However, we advise to use the indices based on Eq. 7, i.e., $\widetilde{I}_c$ and $\widetilde{M}_c$, since these assign higher weights to more frequently visited locations than to less frequently visited ones. As such, they better represent the species' preferences.

To conclude, HSI thresholds of 0.7 and 0.9 were used to reclassify the HS map (Fig. 3) into three suitability classes: very (highly) suitable, suitable, and less suitable (Fig. 8). Since suitable areas are more likely to be visited by the owls, they can be assigned as most important for the species.

Discussion

We selected 12 ECs that are important for the eagle owls in the study area and selected appropriate radii of influence (Table 3). Literature and expert knowledge are underpinning the resulting HS map. In order to consistently transform the qualitative information into SI values, we chose 0.5 as a neutral SI value and used a uninorm aggregation function to compute the resulting HSI value.

As can be seen in Table 3, 11 out of the 12 ECs can lead to SI values greater than 0.5, so we mainly accounted for positive impacts on the eagle owls. Given the available GIS data, only major roads could be assigned an SI value lower than 0.5. The highest a_e values were assigned to quarries and vegetation structures, followed by forest edges, agricultural land use related to trees and water bodies. It is important to note that one has to carefully select and motivate the considered ECs and their corresponding SIs, but a sound, objective underpinning of these choices is mostly not possible (Ray and Burgman 2006; Zajac et al. 2015).

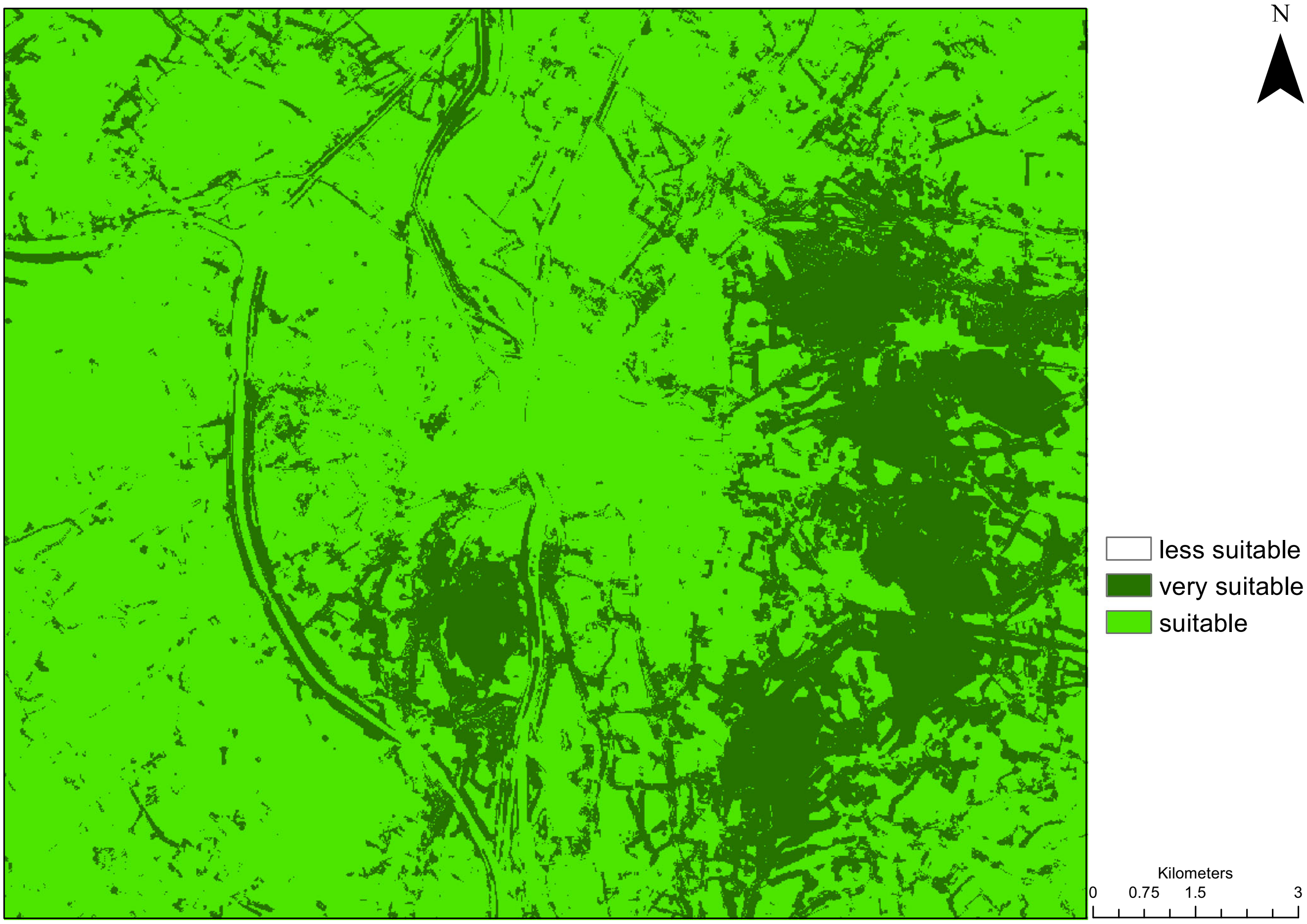


Fig. 8 Reclassified HS map using the graph of M_c based on the probability of occurrence (7) (HSI thresholds of 0.7 and 0.9)

Here, we motivated our choices as much as possible based on literature and expert knowledge. Consequently, even though the final choice of the ECs and their corresponding parameters a_e and r_e unavoidably depends on the study area at stake, the list in Table 3 may guide studies in other areas. Since every study area has its specifics, one ought not to expect that Table 3 can be adopted as is for other study areas, though its transferability could be assessed if independent occurrence datasets would be available.

GPS tracking data were used to evaluate the resulting HS map since an independent set of presence/absence data was not available for the study species in the region. Therefore, we combined two established methodologies. In Reynolds-Hogland and Mitchell (2007), habitat selection is estimated on the basis of GPS tracking data. For that purpose, the fixes need to be transformed into a PDF and a home range, after which the Ivlev's electivity index can be calculated to quantify the habitat selection. Since we wanted to evaluate the selection of pixels corresponding to each HSI bin, we could use this methodology. In Hirzel et al. (2006), validation of HS maps performed on the basis of (independent) presence-only data using the Manly's habitat selection index is considered. Therefore, we also considered this index in our analysis. Moreover, Hirzel et al. (2006) propose the use of a moving window instead of choosing a specific number of HSI bins to arrive at smoother graphs, which are eventually used to interpret and validate the obtained HS map. Consequently, by combining the approaches proposed by Reynolds-Hogland and Mitchell (2007) and Hirzel et al. (2006), we were able to validate the constructed HS map.

Many fixes in our dataset, however, are located close to each other in a limited number of pixels, which consequently all have a very high probability of occurrence. Furthermore, they are located in highly suitable pixels, close to a possible nesting site. As a consequence, the results are biased toward high HSI values so that we had to consider the shape of the graphs to interpret the results. Moreover, since we compared the pixels that were probably visited with those available in the landscape, the values of the indices depend on the definition of the study area. We defined our study area as the rectangular area enclosing all data points. If information on habitat suitability is needed in more detail, the study area might be limited to, for example, the neighborhood of the quarries. In this case, the interpretation of the HS map and the definition of (un)suitable can be done in function of the area of interest.

When considering the graphs of the average HSI value versus Ivlev's electivity index I_c and Manly's habitat selection index M_c (Figs. 6 and 7), we may conclude that pixels with an HSI value lower than 0.55 are unsuitable, and those with an HSI value between 0.55 and 0.7 are suitable, while those with an HSI value greater than 0.7 are very suitable. When considering the graphs of the average HSI value versus Ivlev's electivity index $\widetilde{I}_c$ and Manly's habitat selection index $\widetilde{M}_c$, which are directly based on the probability of occurrence of the species, we alternatively conclude that pixels with an HSI value lower than 0.7 are unsuitable, and those with an HSI value between 0.7 and 0.9 are suitable, while those with an HSI value greater than 0.9 are very suitable, and are probably located near a possible nesting site.

As such, both Ivlev's electivity index and Manly's habitat selection index lead to the same conclusions. Yet, one arrives at a different interpretation when using the probability of occurrence (7) instead of the home range (6) to describe the area used by the species. In the latter case, the influence of the individual fixes is more limited since all pixels in the home range are weighted equally, regardless of its frequency of visits. Consequently, the indices based on the home range increase more gradually. We believe, however, that the use of the probability of occurrence instead of the home range is more appropriate to deal with auto-correlated tracking data since it better accounts for the species' preferences. Given the fact that eagle owls almost exclusively use areas with HSI values greater than 0.7, and mostly areas with HSI values greater than 0.9, we may conclude that our HSI map is well designed. The HSI map clearly reflects the suitability of the study area for the eagle owls.

The HS map can first of all be used to guide field studies for locating possible sources of poisoning (PCBs) in the study area. More precisely, the HS map shown in Figure 8 can be used to select parcels in areas that were classified as very suitable for future field campaigns because they are those areas that are most frequently visited by the eagle owls and hence probably serve as their hunting grounds. Our analysis shows that such parcels are often located near quarries and/or covered by hedgerows, isolated trees, orchards, tree and fruit nurseries, and so on. As only a limited number of parcels can be visited due to budgetary constraints, it is probably most useful to rank the parcels in these very suitable areas according to their average HS, which can be computed on the basis of the HS map in Fig. 3. In this way, one arrives at a list of parcels ranked according to their suitability for the species at stake, and depending on the available resources, the first n parcels in this list could be visited.

Besides being of use for the considered study area, one could extrapolate our approach to a much wider spatial extent, which would be useful given the increasing number of breeding pairs that has been reported over the last years in the Netherlands, Belgium, and Germany (Natuurpunt 2016; SOVON consulted in 2017; Abo Wind 2017). Such an extrapolation would allow for a swift identification of potentially suitable regions for eagle owls residing in these countries. It should, however, be emphasized that the presented HS map is tailored to the land use and land cover occurring in the study area, so that the impact of potentially important ECs that are absent in the study area will not be accounted for in such an approach. Moreover, the presented HS map is tailored to the owls in the study area, who typically inhabit quarries and mainly prey on pigeons, crows, rats, mice, and hedgehogs. Although quarries serve as nesting sites in many regions, also other nesting sites can be exploited, such as old nests of buzzards (*Buteo buteo*), industrial buildings, and forests (Wassink 2011b). Furthermore, other prey, and, as such, other habitats, might be important for the species in other regions. Still, our study provides a well-founded basis to build HS maps for eagle owls, but adaptation might be needed for areas differing significantly from the one at stake in this paper. Especially the list of ECs and their corresponding parameters a_e and r_e will need to be reconsidered before the presented approach can be applied in other study areas.

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Appendix A: Calculating the HSI

The SI value of a pixel is either based on the presence or absence of a given EC in this pixel, or on the distance from this pixel to the nearest pixel where this EC is present. For the sake of simplicity, a linear relationship between distance and suitability is assumed. To mathematically define the function relating EC e to an SI value, we first define an indicator function $\mathscr{E}_e(p)$:

$$\mathscr{E}_e(p) = \begin{cases} 1 \text{ , if EC } e \text{ is present in pixel} p, \\ 0 \text{ , otherwise,} \end{cases} \tag{1}$$

where $p = 1, \ldots, N$, with N the number of pixels in the raster $\mathscr{R}$ covering our study area. Next, the set E_e is defined as the subset of pixels in $\mathscr{R}$ where EC e is present:

$$E_e = \{p \in \mathscr{R} | \, \mathscr{E}_e(p) = 1\}. \tag{2}$$

Furthermore, let $d(p, E_e)$ be the minimum Euclidean distance from a pixel p to E_e. The SI for EC e in pixel p is then given by:

$$\mathscr{S}^e_{a_e,r_e}(p) = \begin{cases} a_e - (a_e - 0.5), \frac{d(p, E_e)}{r_e} & \text{, if } 0 \leq d(p, E_e) \leq r_e, \\ 0.5 & \text{, otherwise,} \end{cases} \tag{3}$$

where r_e is the radius of influence of EC e and a_e is the numerical index that represents the suitability of EC e if $d(p, E_e) = 0$. The SI value is different from 0.5 only if $d(p, E_e) \leq r_e$. If $r_e = 0$, then the SI value only depends on the presence or absence of EC e in pixel p (Ortigosa et al. 2000).

In this study, the uninorm aggregation function given by De Baets and Fodor (1999):

$$\mathscr{H}(p) = \begin{cases} 0 & \text{, if } |\{e \mid \mathscr{S}^e_{a_e,r_e}(p) = 1\}| \geqslant 1 \text{and} |\{e \mid \mathscr{S}^e_{a_e,r_e}(p) = 0\}| \geqslant 1, \\ \dfrac{\prod_{e=1}^{n} \mathscr{S}^e_{a_e,r_e}(p)}{\prod_{e=1}^{n} \mathscr{S}^e_{a_e,r_e}(p) + \prod_{e=1}^{n} (1 - \mathscr{S}^e_{a_e,r_e}(p))} & \text{, otherwise,} \end{cases} \tag{4}$$

was used for the pixel-based aggregation of the SIs. This function has, to the best of our knowledge, not been used before in this context. It is symmetric and associative (Yager and Rybalov 1996; Grabisch et al. 2009), and has 0.5 as the neutral value (De Baets and Fodor 1999).

Appendix B: Validation indices

We used Ivlev's electivity index (Ivlev 1960; Reynolds-Hogland and Mitchell 2007) and Manly's habitat selection index (Manly et al. 2002; Desbiez et al. 2009; Hirzel et al. 2006) to validate the developed HS map. For that purpose, the HSI range is partitioned in b bins, after which two proportions are calculated for every bin $c = 1, \ldots, b$. The first one is the proportion of pixels in the study area that belong to HSI bin c and, as such, quantifies the area available for the species:

$$A_c = \frac{a_c}{N}, \tag{5}$$

with a_c the number of pixels in the study area belonging to HSI bin c and N the total number of pixels in the study area. The second one is the proportion of pixels in the home range that belong to HSI bin c and, as such, describes the area used by the species:

$$U_c = \frac{u_c}{\widetilde{N}}, \tag{6}$$

with $\widetilde{N} \leq N$ the number of pixels in the home range and u_c the number of pixels in the home range falling into HSI bin c.

In order to quantify the area used by the species more accurately, the PDF itself can be used (Reynolds-Hogland and Mitchell 2007):

$$\widetilde{U}_c = \sum_{i=1}^{a_c} t_i\, s^2, \tag{7}$$

with t_i the PDF value in the center of pixel p and s the size of a pixel. As such, $t_i\, s^2$ represents the volume under the PDF and, thus, the probability of occurrence in pixel p. Consequently, $\widetilde{U}_c$ embodies the probability of occurrence in HSI bin c.

Finally, these proportions can be used to define Ivlev's electivity index (Ivlev 1960; Mitchell et al. 2002; Reynolds-Hogland and Mitchell 2007):

$$I_c = \frac{U_c - A_c}{U_c + A_c} \tag{8}$$

for $c = 1, \ldots, b$. The values of this ratio range from -1 (avoidance) to 1 (strong selection). If the HS map is well designed, then it should hold that $I_c < 0$, resp. $I_c > 0$, in HSI bins corresponding to a lower, resp. higher, habitat suitability. By replacing U_c in Eq. 8 by $\widetilde{U}_c$, we obtain $\widetilde{I}_c$ (Reynolds-Hogland and Mitchell 2007):

$$\widetilde{I}_c = \frac{\widetilde{U}_c - A_c}{\widetilde{U}_c + A_c}. \tag{9}$$

The second validation index, Manly's habitat selection index (Manly et al. 2002; Desbiez et al. 2009), reads:

$$M_c = \frac{U_c}{A_c} \tag{10}$$

for $c = 1, \ldots, b$. This ratio is similar to the one underlying the Boyce index (Boyce et al. 2002; Hirzel et al. 2006). If the HS map is well designed, then U_c should be lower than A_c, and thus $M_c < 1$, in HSI bins corresponding to a lower habitat suitability. Again, U_c can also be replaced by $\widetilde{U}_c$ in Eq. 10 in order to calculate the ratio on the basis of the probability of occurrence of the species:

$$\widetilde{M}_c = \frac{\widetilde{U}_c}{A_c}. \tag{11}$$

Appendix C: The spatial distribution of the environmental characteristics

Fig. 9 The spatial distribution of quarries, arable land, pasture, forest, and agricultural land use related to trees and water bodies (**a**), of town centers, industrial areas, buildings outside town centers, and roads (**b**), and of linear and isolated vegetation and differences in altitude across the study area (**c**)

Appendix D: SI map for every EC

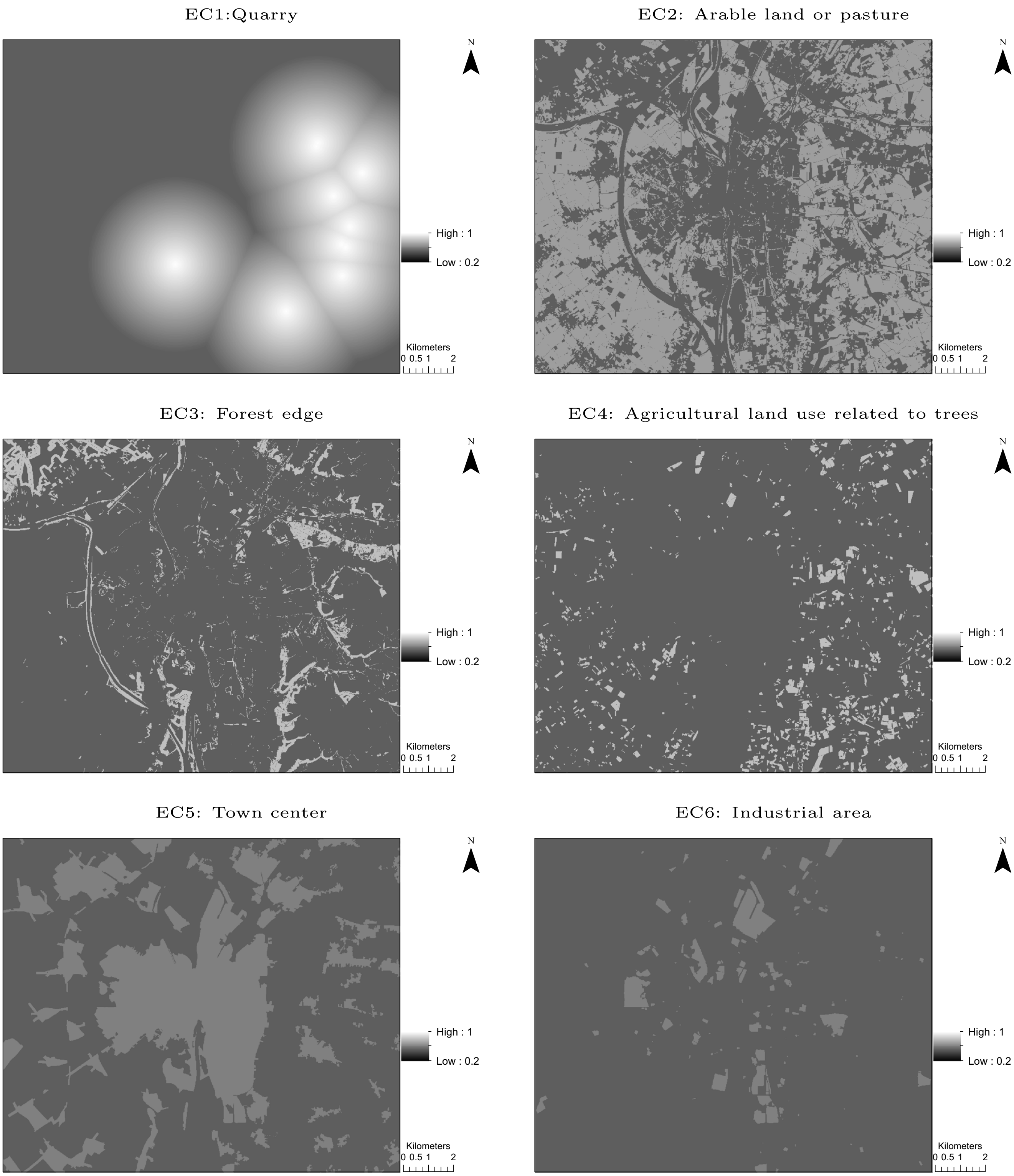

Fig. 10 The SI map covering the study area for environmental characteristics 1–6

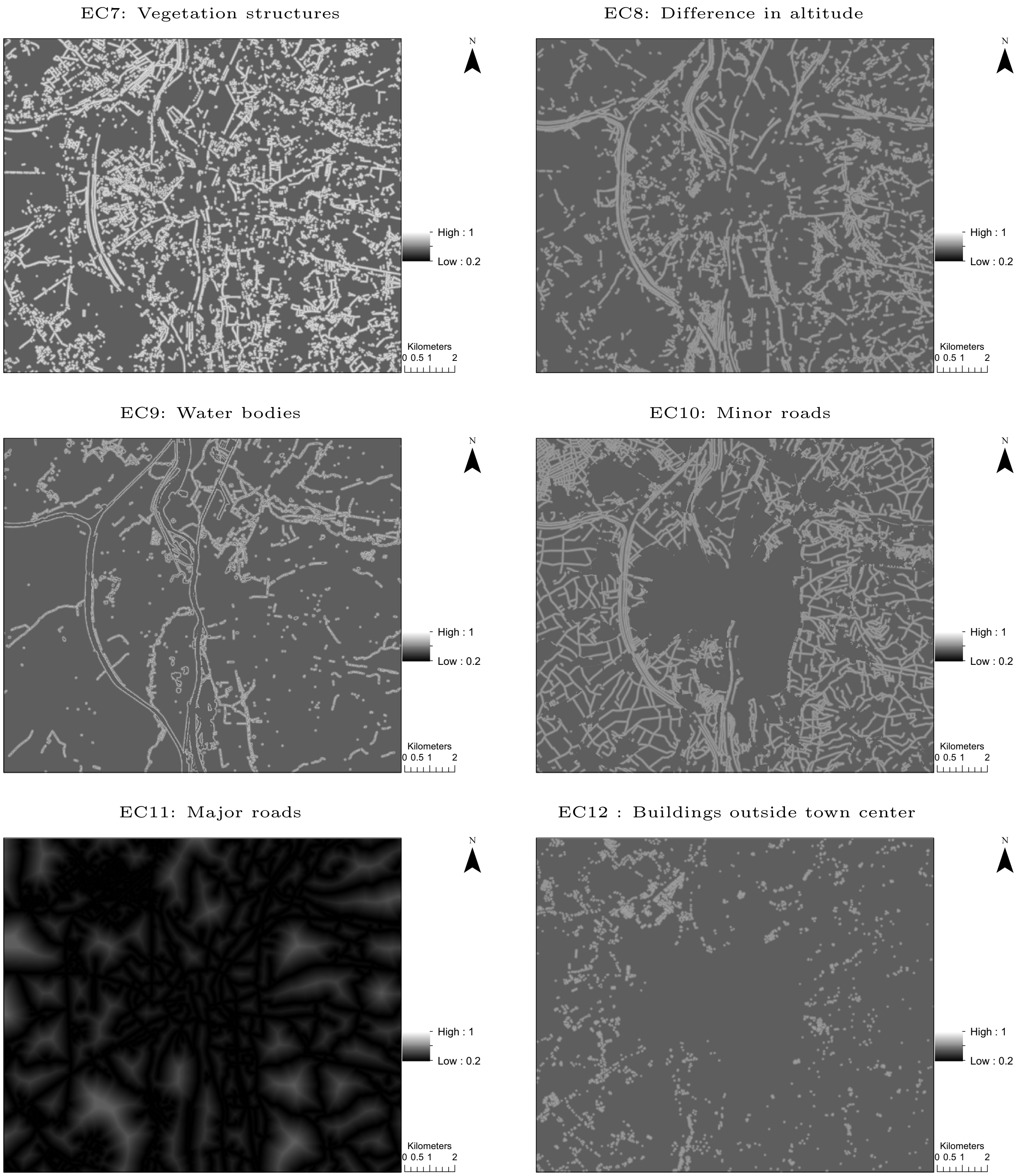

Fig. 11 The SI map covering the study area for environmental characteristics 9–12

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