



An evaluation of global LULC maps for the estimation of habitat use of a declining migratory waterbird along its flyway

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ABSTRACT

Global products of land use and land cover (LULC) provide maps with a consistent classification, thereby allowing for comparisons of resource and habitat use of species over large spatial scales. While global LULCs tend to be evaluated extensively, the distribution ranges of species can extend into remote areas that are hard to access for ground truthing. It is unclear how adequate global LULCs are for mapping habitat of long-distance migrants throughout their entire range. Here, we investigated whether different global LULCs could successfully capture the known preferences of a migratory wetland specialist, the Eurasian wigeon (*Mareca penelope*), along the East Atlantic flyway. We evaluated how well five different global LULC products captured known wigeon habitat preferences using remote tracking data, and tested whether a further classification based on wetland expert knowledge can improve on their performance. We found that average performance of global LULC products varied greatly, with ESA WorldCover performing best with a 94% correspondence to wigeon habitat. All products performed best in the Tundra biome, and worse in Boreal as well as Temperate forests. In the latter areas, our wetland expert LULC classification provided improved results by explicitly considering small and temporary wetlands, and wetlands underneath vegetation. Overall, habitat use of habitat specialists can inform us about habitat types that are currently not considered in large-scale LULC maps. We suggest LULC mapping methods integrate information from tracking of wetland specialists for a better detection of small and temporary wetlands on a global scale.

1. Introduction

Across the globe, populations of wild birds are in decline (World Wildlife Fund, 2016; Rosenberg et al., 2019), with obligate and long-distance migratory species appearing particularly affected (Wilcove and Wikelski, 2008; Gilroy et al., 2016). While the mechanisms are not always understood at the species level, the overall heating of the climate and associated changes to phenology, along with the anthropogenisation of suitable natural habitat, appear to be key drivers forcing populations into decline (Both et al., 2006; Bairlein, 2016; Zurell et al., 2018; Beresford et al., 2019). Long-distance migratory species are dependent on finding suitable conditions throughout their range, including at stopover sites used for refuelling during migration.

The implementation of range-spanning conservation plans to counteract population declines however presents unique challenges: not only do they require collaboration on an international level (Runge et al., 2014; Allen and Singh, 2016; Schmaljohann et al., 2022), but also an understanding of where conservation efforts should be prioritised in the first place. Unravelling how individuals use habitat at a fine spatial scale while being able to link local conditions, and change thereof, to large spatial scales matching the extent of migratory movements could directly inform conservation planning (Wiens et al., 2009; Nagendra et al., 2013).

Space-based animal telemetry is well known to provide information of fine-scale movement and behaviour of individuals (mostly) irrespective of where on the planet they are (Nathan et al. (2022), Watanabe and

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Papastamatiou (2023). In combination with consistent accounts of the environmental context of remotely sensed animal movement, such data make it possible to investigate behaviour and resource use throughout the entire annual cycle and distribution range of a species (Buchan et al., 2023; Tuia et al., 2022). While small-scale products providing environmental context have emerged as powerful tools for understanding animal decision-making (Strandburg-Peshkin et al., 2015; Remelgado et al., 2018; Budaev et al., 2019), until recently global-scale environmental data were available at a spatial resolution coarser than the processes at which most animal movement occurs (Pasetto et al., 2018). Such a mismatch in resolution has the potential to mislead if the behaviour of interest, such as habitat selection, happens at a finer scale than can be resolved by existing products, especially if the presence of small patchy habitats is masked by dominant habitat types. Adjusting the spatial (and temporal) scale of the environmental context to the spatial and temporal scale of habitat selection (see e.g. Kays et al., 2023), or other behaviours of interest, should thus be preferred if possible. Resolution mismatch is particularly pronounced for species covering long distances or those with large distribution ranges, and might have contributed to the limited use of animal movement data for conservation planning thus far (Katzner and Arlettaz, 2020). However, the spatial resolution of LULC maps and other remote sensing products has progressively increased from >1 km in the 1990s to approximately 10 m since 2019 (Feng and Li, 2020; Karra et al., 2021). Access to the data, and the processing thereof, has also eased through initiatives such as Google Earth Engine (Gorelick et al., 2017). The Copernicus Programme of the European Space Agency (ESA) and the European Union (EU) have also had a positive impact on LULC mapping using the Sentinel-1 and Sentinel-2 multi-spectral instruments, whose primary objectives include the monitoring of crops, forests, urban areas, and water resources (Drusch et al., 2012). The use of Sentinel-2 data produces classifications of high accuracy (>80%) using machine-learning algorithms such as support vector machines and random forests (Phiri et al., 2020).

From this follows that global remote sensing products, with resolution now at the same spatial scale as the accuracy of most GPS tags, can be used to contextualise animal movement data with the spatial scale matched to the scale of the behaviour of interest. Consequently, habitat use can now be investigated at high spatial resolution, across large spatial scales, or both (Kays et al., 2023). Less clear is how well these global algorithms reflect habitat as it is perceived by different species, and how consistent the quality is throughout a species' entire distribution range. Scarcer land cover types and small habitats such as temporary flooded areas, which are often of critical importance to habitat specialists, remain difficult to identify (Buchhorn et al., 2020; Karra et al., 2021) even though their importance for understanding ecological processes occurring from fine to global scales is well established (Calhoun et al., 2017). Products with a low update frequency, while trading off temporal resolution with the possibility of aggregating data over a longer period, likely fail to capture changes in availability of seasonal habitats. Even so, data coverage may vary in time and space, which can influence consistency and reliability of products derived from e.g. satellite imagery (Frantz et al., 2023). Consequently, LULC categories of existing LULC maps, or indeed other global products, might not always be reliable and/or relevant for describing a species' habitat use. The challenge is then to select the most useful data, whether continuous or categorical, for mapping relevant habitats to national and international conservation planning and policy making (Tomaselli et al., 2013).

Here, we put several global remote sensing products to the test, and investigate how accurate they are in capturing the habitat preferences of a species with known habitat preferences. We decided to conduct this study with Eurasian wigeon (*Mareca penelope*, hereafter wigeons) as a study species, for the following reasons: (a) Wigeons are long-distance migrants with a large distribution range spanning the Palaearctic extending into remote areas in the Arctic Tundra (Cramp and Simmons, 1977), though they can appear as vagrants in the Nearctic as well. (b)

They are habitat specialists whose habitat preferences and movements have previously been detailed extensively (Viksne et al., 2010; Pöysä et al., 2017; Arzel and Elmberg, 2015). (c) While the species is globally considered as Least Concern, the population in the European flyway is decreasing (Fox et al., 2016). Habitat changes in terms of quality and availability have been put forward as main drivers for this population decline (Pöysä et al., 2017). Nevertheless, our current knowledge of habitat and energetic requirements of the species prevent us from assessing potential bottlenecks at the flyway scale (e.g., Lonsdorf et al., 2016). Stopover sites are considered of particular importance here as conditions encountered en route during spring migration can carry over to the subsequent breeding season (Finch et al., 2014; Sedinger and Alisauskas, 2014). The loss and degradation of important resting and foraging sites along the flyway is an increasing threat to the European population, though gas and oil developments on the breeding grounds are of additional concern (Viksne et al., 2010). Taken together, this makes the wigeon a relevant as well as ideal species for which to evaluate the adequacy of global products for mapping suitable wigeon habitat. When it comes to the choice of products to include in a comparative study, several approaches are possible. Including only products that specifically map the availability of important habitat aspects, e.g. presence of water in the case of wigeons, would ensure a thematic match between species habitat preferences and the remote sensing products, whereas products with a less specific focus, such as discrete land cover classifications, while likely not optimised for the particular habitat preferred by the study species, can provide situational context for habitat of interest. We here chose the latter approach, focusing on global LULC products, to accommodate that according to available literature, wigeons appear to select for the interface between wetlands and the vegetation belt surrounding them.

Using GPS data from migratory individuals, we initially tested whether resource selection of wigeons derived from GPS locations reflected previously published reports on habitat preferences. We further investigated whether resource selection was consistent throughout the annual cycle and the flyway. We then tried to answer two main questions: (1) How well do openly available global LULCs capture wigeon habitat preferences? (2) Is there a benefit to integrating expert knowledge on wetland ecology in the process of LULC map development? We address these questions by estimating the proportion of wigeon locations that are observed in habitat preferred by wigeons for each of several global LULC products. We additionally developed a map based on expert wetland knowledge for select locations used by wigeons. The map was produced using a random forest classifier, with predictions evaluated using photointerpretation, which was then used as a baseline against which to compare the global LULC products.

2. Methods and materials

2.1. Land use and land cover products

We considered several global LULC products available in the Google Earth Engine catalogue (see Table 1), which differed to varying degrees in the underlying data used, their classification algorithm, spatial resolution, and update frequency. Spatial resolution ranged from 10 m (e.g. ESA WorldCover) to 500 m (MODIS MCD12Q1.061), where most products would be considered of a moderate resolution exceeding the commonly used assumption of GPS error of 20 m. The most common update frequency was annual, although we also included a near real-time product (Dynamic Worlds V1). Most products considered had a discrete classification into distinct LULC types, not all of which distinguished between different kind of aquatic environments. The Copernicus Global LandCover offers a discrete classification of 23 classes alongside cover fraction products indicating the percentage of a cell covered by a particular LULC type for ten LULC types.

Table 1

Global LULC products. Links provided are for the product on GEE, which provides a link for the original source of the data set. Details for the MWEK classification are provided for comparison.

LULC product	LULC type	Number of classes	Spatial resolution	Temporal resolution	Earth Engine snippet
Copernicus Global LandCover	Discrete classification	23	100 m	annual (2015–2019)	COPERNICUS/Landcover/100 m/Proba-V-C3/Global
Copernicus Cover Fractions	Percentage of cover	10	100 m	annual (2015–2019)	COPERNICUS/Landcover/100 m/Proba-V-C3/Global
ESA WorldCover	Discrete classification	11	10 m	annual (2020–2021)	ESA/WorldCover/v100
MODIS MCD12Q1.061 (Land Cover Type 1)	Discrete classification	17	500 m	annual (2001–2022)	MODIS/061/MCD12Q1
Dynamic World V1	Discrete classification	9	10 m	2–5 days	GOOGLE/DYNAMICWORLD/V1
MWEK	Discrete classification	28	10 m	see Table S6	–

2.2. Study species

2.2.1. Habitat preferences of Eurasian wigeons

Wigeons aggregate in large flocks during winter (Tamisier and Dehorter, 1999), and breed at low densities in the boreal zone and remote locations in the Arctic (Viksne et al., 2010). As income breeders, they need to forage along their migratory routes for the subsequent breeding season (Arzel et al., 2006). The quality of stopover sites used by wigeons during spring migration is therefore important, especially with regard to the availability of high-quality foraging conditions, usually considered to be vegetation at intermediate biomass (Merkle et al., 2016), during migration and on the breeding grounds (Holopainen et al., 2015; van Toor et al., 2021b). Along the European flyway, wigeons are typically found in coastal seagrass meadows, floodplains, banks of rivers, deltas, streams, small shallow lakes with vegetation belt made up of bushes, tundra wetlands and taiga forest wetlands (Viksne et al., 2010). They usually forage in shallow areas with vegetation such as short *Carex* and Poaceae, or on land by grazing (Arzel and Elmberg, 2004, 2015), and typically feed on inland pastures, mudflats, and agricultural fields in proximity to lakes (Owen and Williams, 1976; Jacobsen, 1993; Boscutti et al., 2019). Overall, wigeons are considered specialists for emergent vegetation, and are frequently found in rich/complex habitat structures (Holopainen et al., 2015), and often stay in close proximity to water (Jacobsen and Ugelvik, 1994).

2.2.2. Remote tracking data

We focused on the European wigeon population, a large part of which winters in the Netherlands and along the North Sea coast (Fox et al., 2016). The population is thought to breed predominantly in the Russian Arctic, but the breeding distribution stretches all the way to the Baltic region (Viksne et al., 2010). Tracking data from 39 wigeons captured in the Netherlands and Lithuania (2018–2020) with hourly relocations were available from a previous study (see van Toor et al., 2021b and Appendix A for details). A curated data set of the tracking data is available from the Movebank Data Repository (van Toor et al., 2021a). We censored active migration, retaining only data from periods when wigeons were stationary, including wintering, stopover, and breeding (see Appendix A for details). After censoring, the data set contained 119,999 locations from 32 individuals (mean \pm s.d.: 3750.0 \pm 2039.5 locations; range: 970–9062 locations), and a total of 7019 tracking days (mean \pm s.d.: 219.3 \pm 134.0 days; range: 42–545 days). We assigned each stationary period to the respective biome and ecoregion using the RESOLVE Ecoregions product on Google Earth Engine (Dinerstein et al., 2017).

We estimated the space use of wigeons during stationary periods using auto-correlated kernel density estimators (aKDE, Fleming and Calabrese, 2017; Silva et al., 2022), and used integrated resource selection functions (hereafter iRSF, Alston et al., 2023) to determine

resource selection based on the Copernicus Global LandCover map. A detailed description of these steps is available in Appendix A.

For evaluating LULC products at wigeon locations, we considered only points that could be considered as non-flight locations. We filtered out all locations for which instantaneous ground speed was greater than the $v_t = \text{mean} - 5 \times \text{s.d.}$ of the airspeed reported for Eurasian wigeons. We used the estimates from Pennycuick et al. (2013), which resulted in a speed cut-off of $v_t = 6.85$ m/s. The remaining data set (hereafter stationary points) contained 90,919 locations from 32 individuals, spread over 290 stationary periods (median number of stationary periods per individual: 7.5; IQR: [4 – 11]).

2.3. Do global LULC maps reflect habitat used by wigeons?

We used Google Earth Engine (hereafter GEE) to annotate wigeon stationary points with relevant information for each of the global LULC products listed in Table 1. The code we used for annotating wigeon stationary locations with global LULCs is available in Appendix B. For the discrete classification of Copernicus Global LandCover, ESA WorldCover, and MODIS MCD12Q1.061, this involved extracting for each wigeon stationary point the discrete LULC class at that location, as well as the distance of the point to the nearest grid cell considered water or wetland habitat. For every point, we chose the dataset that corresponded to the year of observation where available, or the layer was closest to the year of observation otherwise. For the cover fractions available as part of the Copernicus Global LandCover product, we instead extracted the cover fraction for crops and grass corresponding to the wigeon location, and calculating the distance to the nearest cell where cover fraction of either permanent or seasonal water was >10%. Finally, for the Dynamic World V1 product, we collected all available images collected within one month in time from a wigeon stationary point and computed the mode of the discrete classification. Again, we extracted the respective LULC class at wigeon locations, and calculated distance to the nearest cell considered water or flooded vegetation. In all cases, distances to the nearest water was only considered for a maximum distance of 5000 m to reduce computation time.

We subsequently used the information from each global LULC product to determine whether the conditions at wigeon stationary points corresponded to their expected habitat use (outcome is 1) or not (outcome is 0). As the classifications differed among products, this re-classification was done on a case-by-case basis (see Tables S1–S5 for details). Generally, any class describing aquatic environments (marine, permanent water, open water, herbaceous wetland, etc.) were considered wigeon habitat, as well as non-woody vegetation (grassland, meadow, cropland, herbaceous vegetation, etc.) within 500 metres of the nearest waterbody. For the cover fractions in the Copernicus Global LandCover product, we applied a threshold of at least 10% cover of either grass or crops. A table providing details on the re-classification for each LULC product are included in Appendix A (see Tables S1–S5).

We estimated how the average probability of wigeons being recorded in wigeon habitat (“success”) varied with LULC and biome using a mixed-effects logistic regression model. The success/failure of the LULC to reflect wigeon habitat preferences at individual wigeon locations was included as the dependent response variable. We included the LULC product and biome as fixed categorical covariates, and allowed the effect of LULC to vary with biome by including an interaction term between the two. Ring number of the individual (ID) and a unique identifier for the respective stationary period, nested within ID, were included as random effect terms to account for repeated observations for the same individual. This model took the form:

$$\text{logit}(p_{ijk}) = \beta_0 + \beta_1 \text{LULC}_i + \beta_2 \text{biome}_j + \beta_3 (\text{LULC}_i \times \text{biome}_j) + u_k + v_{k(\text{ID})}$$

where p_{ijk} is the probability of points being recorded in wigeon habitat for the i th LULC, j th biome, and k th ID, β_0 stands for the intercept, and β_1 and β_2 correspond to the effect coefficients for LULC and biome, respectively. The interaction term between LULC and biome is included as β_3 . The term u_k represents the random effect for individual, and $v_{k(\text{ID})}$ is the random effect for the respective stationary period nested within individual. The model was evaluated visually and using scaled residuals simulated using DHARMA (Hartig, 2022) to ensure that the data, and residuals of the model, did not violate the assumptions of the model. We predicted mean probability of success and 95% confidence intervals (CI) for each LULC and biome at the population level (i.e. setting all random effects to zero).

2.4. Map based on wetland expert knowledge

We derived a map based on wetland expert knowledge (hereafter MWEK) to provide a point of comparison for the habitat use derived from global LULC maps. While products mapping the occurrence of water on a global scale exist (Global Surface Water, see Pekel et al., 2016), in our own experience they can underestimate the presence and extent of small and temporary wetlands used by wigeons (see Appendix C). Instead, we decided to use wetland expert knowledge to derive thematic maps for the areas used by wigeons. As our approach included visual photointerpretation for the delimitation of the regions of interest, this was very time intensive. We thus had to limit the analysis to a selection of core home ranges that either exhibited forests on more than 50% of their total surface on the Copernicus Global LandCover map (discrete classification), or had less than 50% permanent open water and/or herbaceous wetland. Subsequent comparisons between MWEK and global LULC maps are based on the same subset of stationary periods (see Figure S1 for a comparison between full dataset and subset).

We created a sample of 5630 regions of interest (3403 for training and 2227 for validation) as outlined by wigeon core home ranges (contour of the 50% utilisation distributions). We used archives of Google Earth, ESRI, and BING images, and an application of the water in wetland index (Lefebvre et al., 2019) on image timelapses in the Earth Observation (EO) browser for the photointerpretation of the land classes. A list of satellite images used are available in Table S6, and a description of criteria used to identify the land classes can be found in Table S7 in the Appendix. Archive satellite imagery allowed us to visualise the vegetation coverage and the intra- and interannual moisture changes to detect temporary wetlands and small patches of water occurrence. The classification was performed with a Sentinel-2 MultiSpectral Instrument, Level-2 A image collection in GEE using the R-package Rgee. We selected images with a maximum of 3% cloud cover from the period of 01/06/2021 to 30/09/2021 (Table S6). We used the Rgee package to create a batch process to apply the GEE Random Forest classifier (Breiman et al., 1984; Breiman, 2001) with a 100 trees (chosen after testing for optimal tree number) to each selected core home range. We used the independent validation sample to assess the performance of the classification. We determined overall out-of-bag (OOB) error, considered a reliable measure of classification

accuracy (Lawrence et al., 2006; Zhong et al., 2014), of the resulting model as 14%. We further determined the overall accuracy on the independent validation sample; at 82%, we considered this as good. We further determined omission error and F1 scores for each thematic group of LULC classes (agriculture, shrubs, forest, wetland, meadow/grassland) using the independent validation sample. Among these groups, we found that the classification performed best for agriculture (omission error: 5%; F1-score: 0.93) and forest (omission error: 10%; F1-score: 0.93), and worst for areas covered in shrub (omission error: 25%; F1-score: 0.81), with performance for meadows/grassland (omission error: 10%; F1-score: 0.91) and wetlands (omission error: 18%; F1-score: 0.91) being intermediate. Errors in wetland classification were mainly due to confusions with meadows (see Table S7 for a detailed overview).

The resulting classified raster maps (see Davranche et al., 2024) were then used to investigate the proportion of stationary locations in each of the land classes. We identified the subset of wigeon stationary locations that intersected with the MWEK raster maps (52,318 out of 90,919 locations, from 290 stationary periods and 32 individuals). We annotated this subset as previously described for the global LULC products, and determined whether locations were recorded within wigeon habitat. Applying a model with the equivalent structure as described above to the subset of locations with MWEK and all global LULCs, we estimated how probability of points located within wigeon habitat varied among the different products. We further visualised the compositions of LULC classes for MWEK and the best-performing global LULC to be able to identify qualitative differences between products.

3. Results

3.1. Space use and resource selection

The analysis of wigeon space use using aKDEs revealed that the average core area, here defined as the contour of the 50% utilisation distribution (UD), was 2.64 km² (95% confidence intervals (CI): 1.20 – 5.09 km²). It was consistent across the different biomes, with the mean estimate for all biomes except for boreal forests/taiga being between two and three km² (see Fig. 1). The average full area, here defined as the contour of the 95% UD, was approximately five times as large, with a mean estimate of 15.8 km² (95% CI: 6.61–32.1 km²). As for the core areas, the mean full areas estimated for the different biomes were relatively similar, with mean estimates per biome ranging from 9.85 km² in temperate grasslands to 28.5 km² in boreal forests/taiga biome.

The integrated resource selection functions (based on the discrete classification available as part of the Copernicus Global LandCover product) showed that selection coefficients for forest, grassland, and cropland tended to be close to zero or negative irrespective of biome (see Fig. 2) or sex (Fig. 3), which was also reflected in the overall trend across all biomes and both sexes (Fig. 2, under totals). The interaction term with distance to water had negative estimates for all habitats and biomes except for the biome of temperate grasslands, savannas, and shrublands, where the models estimated an overall positive effect of distance to water on the selection coefficient for both cropland and herbaceous vegetation. When comparing sexes, the confidence intervals around mean estimates broadly overlapped. The only exception was forest, for which females exhibited a more strongly negative selection. However, the overall effects of distance to water on selection coefficients based on all stationary periods were negative for cropland (mean: -0.65, 95% CI: -1.47 - 0.17), grassland (mean: -0.91, 95% CI: -1.48 - -0.35), as well as forest (mean: -2.95, 95% CI: -3.90 - -2.00).

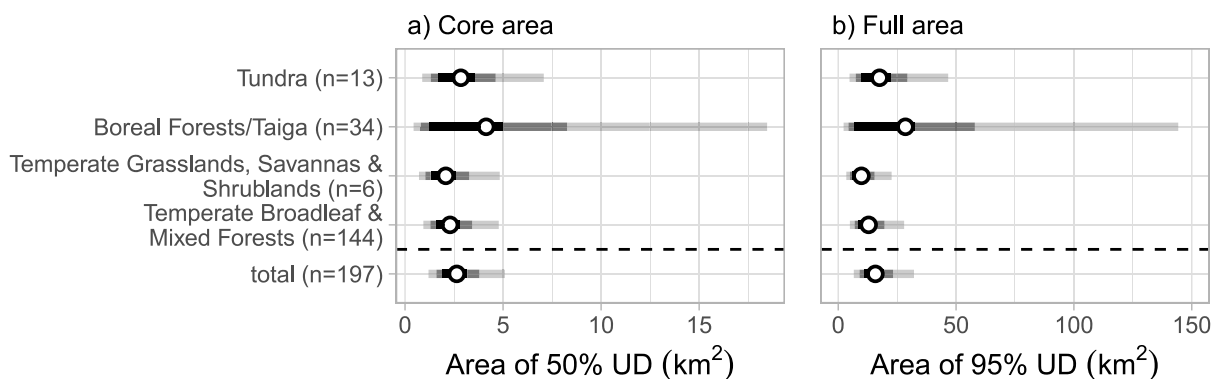


Fig. 1. Estimates for the space use of Eurasian wigeons during stationary periods (wintering, stopover, breeding). (a) shows the area estimates derived for core areas (contour of the 50% utilisation distribution) per biome and overall based on meta-analysis of autocorrelated kernel density estimators derived from 205 stationary periods. (b) shows the corresponding results for the full area occupied by wigeons during stationary periods (contour of the 95% utilisation distribution). Points correspond to the mean estimate, and the 50%, 75%, and 95% confidence intervals are shown as lines with decreasing intensity of shade.

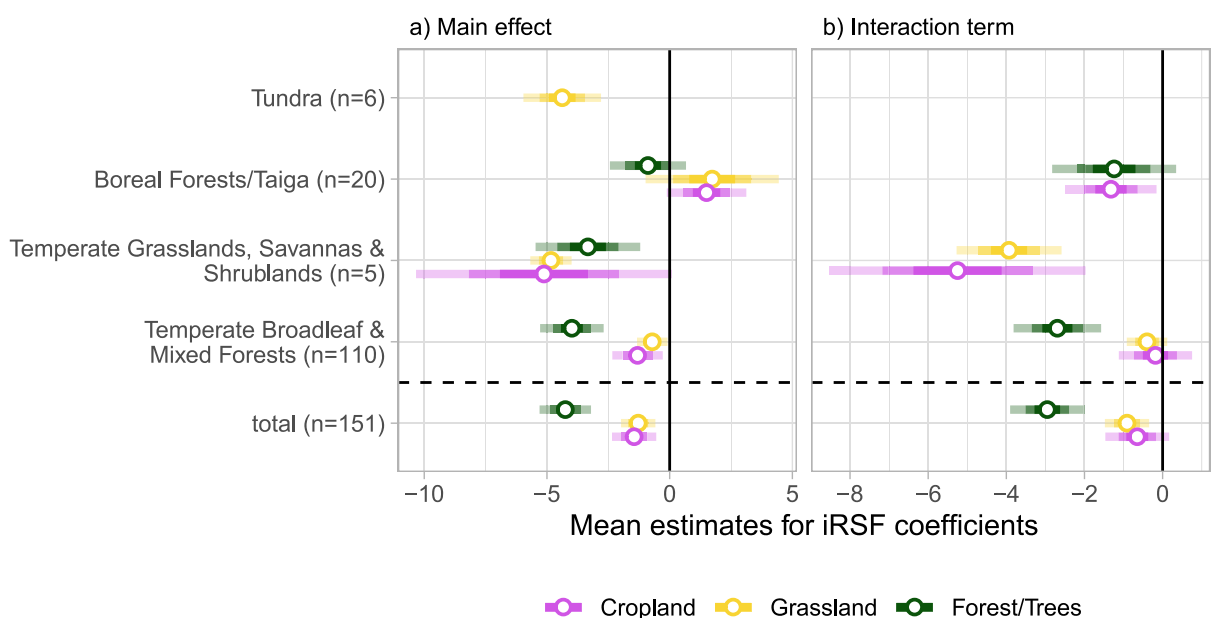


Fig. 2. Selection coefficients for Copernicus Global LandCover. The figure shows the average model iRSF coefficients per biome, and the total average. Resource selection functions were estimated based on the Copernicus Global LandCover product using the discrete classification. Shown are (a) the intercept term for each of the LULC categories considered as well as (b) the respective interaction terms with distance to water. Points correspond to the mean estimate, and the 50%, 75%, and 95% confidence intervals are shown as lines with decreasing intensity of shade. None of the iRSFs for the tundra biome included other terrestrial habitats than grassland and thus estimates for cropland and forest/trees are not available.

3.2. Evaluation of global LULC products (all wigeon stationary locations)

We found that the average probability of locations to be recorded in wigeon habitat differed greatly between global LULC products (see Fig. 4 and Table S8). The lowest overall probability was estimated for MCD12Q1.061 (mean: 0.24, 95%CI: 0.17, 0.31), whereas both the discrete classification (mean: 0.67, 95%CI: 0.58, 0.75) and cover fraction products (mean: 0.60, 95%CI: 0.60, 0.77) contained in the Copernicus Global LandCover product as well as Dynamic World V1 (mean: 0.72, 95% CI: 0.63, 0.79) were intermediate. The ESA WorldCover product was the best-performing global product, with an average probability of 0.94 (95% CI: 0.91, 0.96). Predicted probability also varied considerably with biome. While LULCs performed consistently best in the Tundra biome (mean across all products: 0.97, 95% CI: 0.90–0.99), response to biome otherwise differed between LULC products (see Fig. 4), and ranged for example for the “Temperate Grasslands, Savannas & Shrublands” biome from the worst overall performance with a mean of 0.12 (95% CI: 0.03, 0.40) in the MODIS MCD12Q1.061 product to the second-best performing biome in the ESA WorldCover product (mean:

0.83, 95% CI: 0.40–0.96). Estimates for model coefficients can be found in Table S8.

3.3. Comparison of MWEK with global LULC products (subset of wigeon stationary locations)

For the staging events selected for evaluation with the map based on wetland expert knowledge (forest cover >50% and/or water/wetland <50% in core areas), we found that the relative positions of global LULC products was the same as for the full data set, though uncertainty increased for some (see Fig. 5). Again, the ESA WorldCover had the highest overall success rate with a mean across biomes of 0.94 (95% CI: 0.92, 0.96). All other global products had a performance that was considerably lower (see Fig. 5), ranging from 0.19 (MODIS MCD12Q1.061, 95% CI: 0.00, 1.00) to 0.75 (Dynamic World V1, 95% CI: 0.69, 0.80). The overall performance of MWEK was similar to ESA WorldCover (mean: 0.90, 95%CI: 0.87, 0.93). When considering performance per biome, ESA WorldCover and MWEK were similar in their performance for the biomes “Temperate Grasslands, Savannas & Shrublands” (ESA

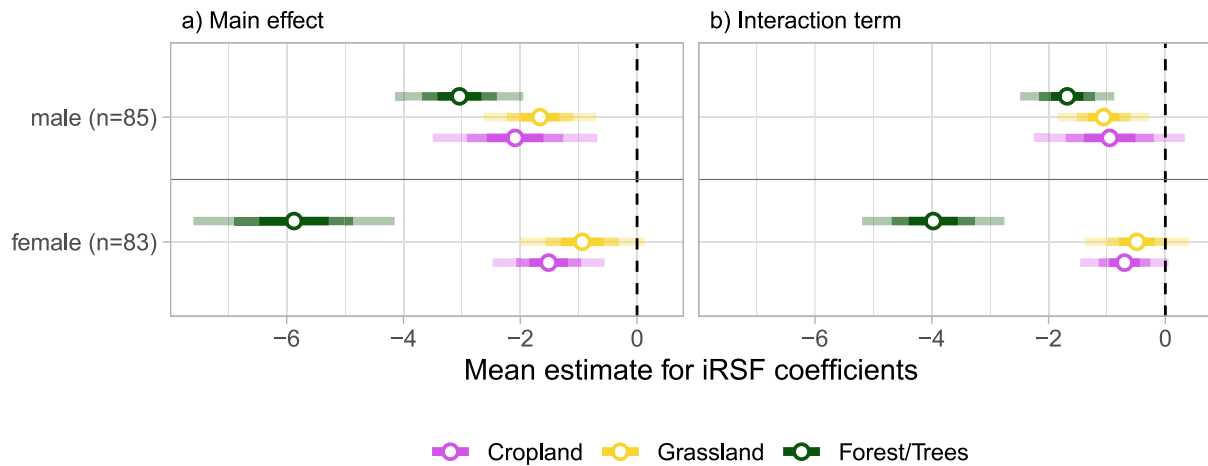


Fig. 3. Mean selection coefficients per sex. The figure shows selection coefficients estimated using iRSF models as in Fig. 2, albeit averaged for males and females rather than for biomes. Shown are (a) the intercept term for each of the LULC categories considered as well as (b) the respective interaction terms with distance to water. Points correspond to the mean estimate, and the 50%, 75%, and 95% confidence intervals are shown as lines with decreasing intensity of shade.

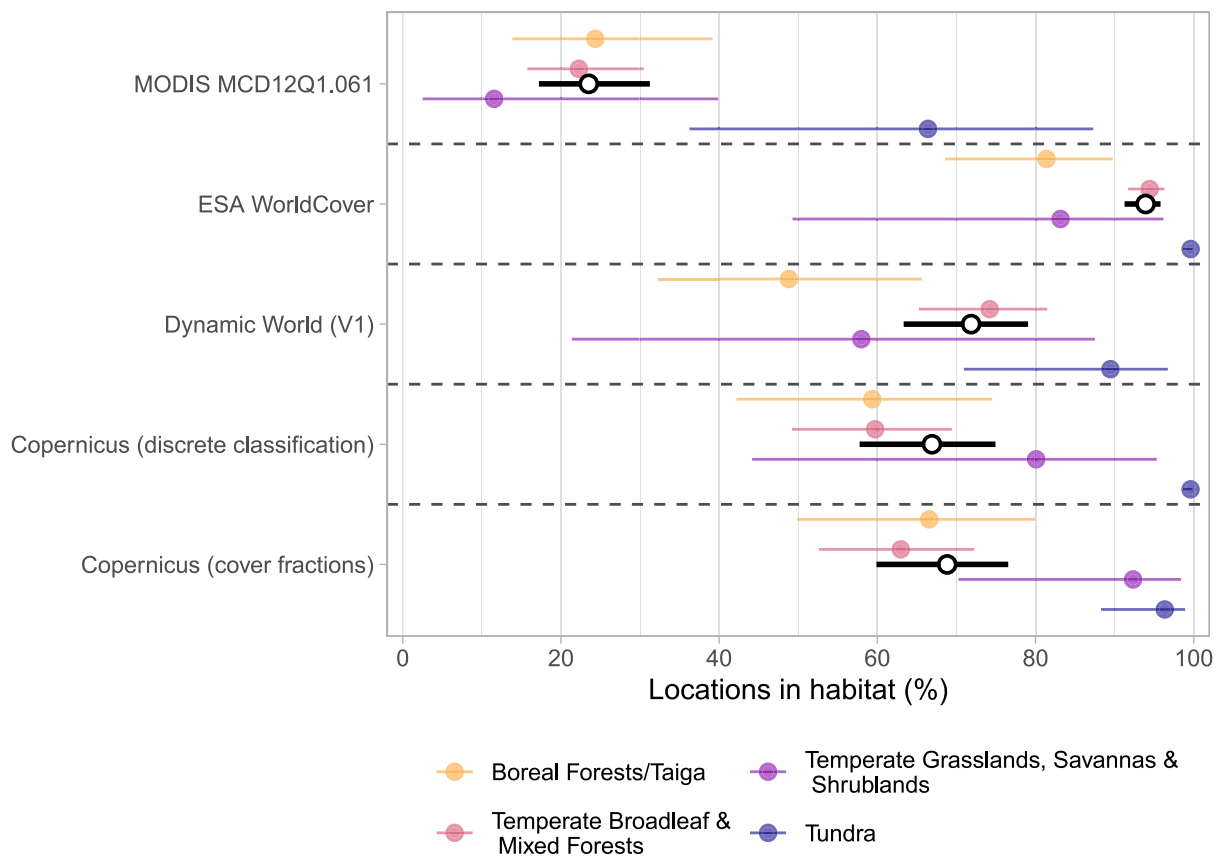


Fig. 4. Evaluation of global LULCs for all wigeon stationary locations. The figure shows the mean and 95% confidence intervals for the predicted probability of wigeon locations being detected in wigeon habitat. For each LULC product, we show mean estimates per biome as indicated in the legend, and the overall mean across biomes is shown in black.

WorldCover: 1.00, 95% CI: 0.89, 1.00; MWEK: 1.00, 95% CI: 0.89, 1.00) and “Tundra” (ESA WorldCover: 1.00, 95% CI: 0.98, 1.00; MWEK: 0.99, 95% CI: 0.94, 1.00). Whereas ESA WorldCover slightly outperformed MWEK in the biome “Temperate Broadleaf & Mixed Forests” (ESA WorldCover: 0.94, 95% CI: 0.92, 0.96; MWEK: 0.88, 95% CI: 0.84, 0.91), the reverse was the case for “Boreal forests and Taiga” (ESA WorldCover: 0.80, 95% CI: 0.67, 0.88; MWEK: 0.94, 95% CI: 0.90, 0.97). Estimates for model coefficients can be found in Table S9.

When comparing the two products within selected wigeon core home ranges, we found considerable differences in the composition of classes overall (Fig. 6). Overall, the proportion of points considered to be in herbaceous vegetation (grassland, cropland) was considerably lower in the MWEK (27.2%) than ESA WordlCover (45.8%), whereas the proportion in either water or wetland was considerably higher (MWEK: 65.9%; ESA WorldCover: 47.1%). Many locations considered by MWEK to be in wetlands were classified as trees, cropland, or

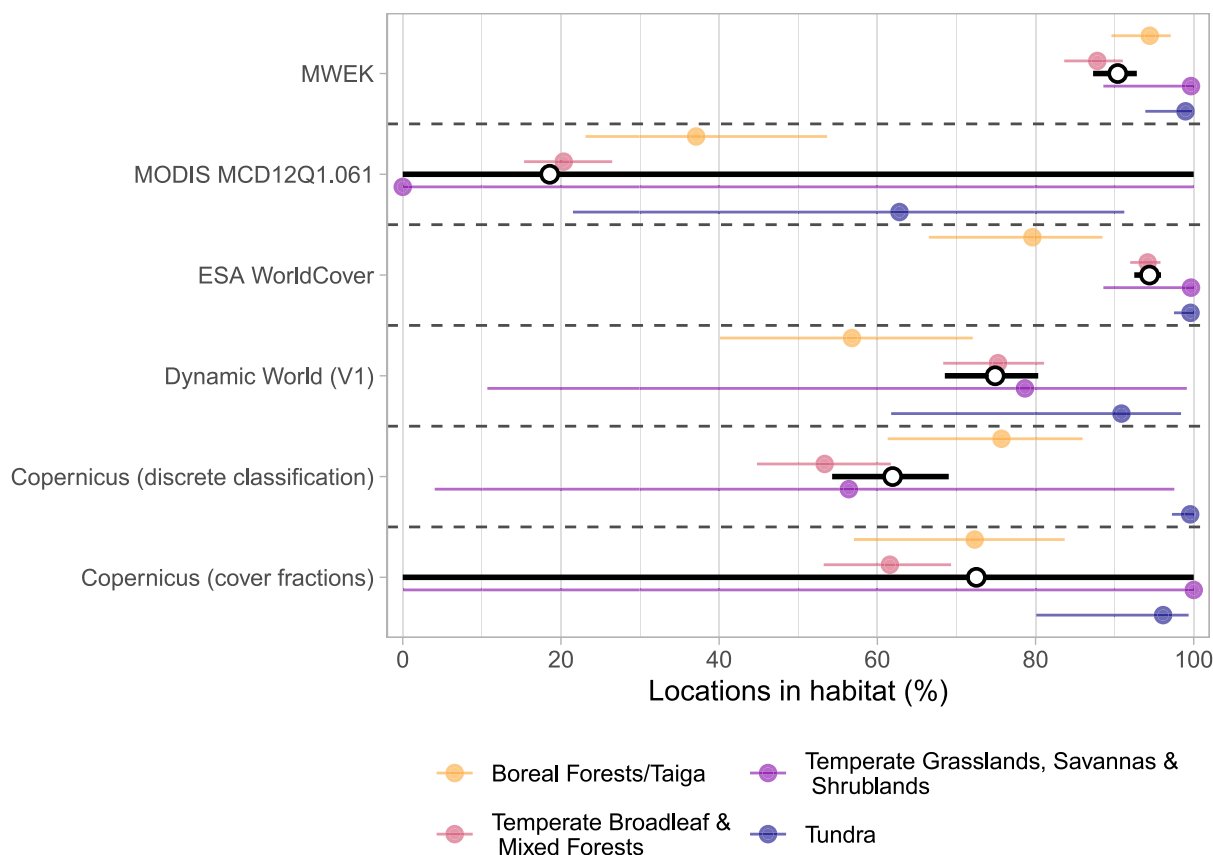


Fig. 5. Evaluation of global LULCs for subset of wigeon stationary locations. The figure shows the mean and 95% confidence intervals for the predicted probability of wigeon locations being detected in wigeon habitat. For each LULC product, we show mean estimates per biome as indicated in the legend, and the overall mean across biomes is shown in black.

grassland in the ESA WorldCover product, and the proportion of trees overall differed by a factor two when comparing MWEK (3.9%) with ESA WorldCover (6.9%).

4. Discussion

As a first step, we investigated whether habitat preferences reported for wigeons corresponded to quantitative estimates derived from the tracking data. We did find that wigeon habitat use in our study aligned to a large degree with prior expectations — with some caveats. As expected from published studies (Arzel and Elmberg, 2015; Pöysä et al., 2017; Holopainen et al., 2018), the majority of wigeon locations was considered to be on water, or in nearby herbaceous vegetation irrespective of the global LULC product used. Resource selection functions of wigeons further estimated that (a) wigeons consistently preferred herbaceous vegetation over shrubby vegetation, trees, and forest, though this difference was more pronounced in females than in male individuals (Fig. 3); and (b) increasing distance to any waterbody decreased the attractiveness of habitat, irrespective of the surrounding environmental context (Fig. 2). The iRSF also showed that the selection coefficients for herbaceous vegetation tended to be negative, even when directly next to water (i.e. estimates for the intercept). This finding suggests that wigeons spent less time in any of the considered vegetation types than expected given their availability within wigeon home ranges, despite nearly half of all wigeon locations being in either cropland or grassland (based on ESA WorldCover). Only for the boreal forest and taiga biome, where wigeons passing through the Baltic Sea region would have encountered a high overall forest cover, did we find positive selection for cropland and grassland. Consequently, it seems that in most biomes encountered by wigeons in this flyway, LULC classes indicating the presence of herbaceous vegetation were

common at sites used by wigeons during stationary periods. Given that most wigeons utilised mostly small core areas (58.1% of core home ranges were $<1 \text{ km}^2$), it appears that even relatively small suitable areas can provide sufficient habitat for a staging site. Computational limitations meant that our resource selection functions were limited to a single LULC product, and one with an intermediate resolution. Even though the performance of this product (Copernicus Global Land-Cover, discrete classification) was considerably lower than for the best-performing product (ESA WorldCover), the analysis could reproduce expected wigeon habitat preferences. We expect that this outcome would not change qualitatively when using products with a similar or higher performance, although the latter could potentially lead to better, more consistent estimates.

We assessed performance of different LULCs in capturing wigeon habitat by estimating the probability of any wigeon location being associated with wigeon habitat, here expressed as being either in water/wetland, or in herbaceous vegetation within 500 m from the nearest waterbody/wetland. Here, we found considerable differences in how well the global LULC products reflected wigeon habitat preferences, with the ESA WorldCover product outperforming other products significantly, and by a considerable margin. For all products, we found that performance varied considerably among biomes, with biomes characterised by the forests they support (Boreal forest/Taiga, and the Temperate Broadleaf & Mixed Forests biome) showing on average the lowest performance. While we had no prior expectation to which classification would best capture wigeon habitat preferences, we expected that performance would scale with both temporal and spatial resolution. For one, many wetland habitats are small and temporary (Calhoun et al., 2017; Schlesinger et al., 2024), and thus wetland habitat used by wigeons such as flooded meadows and vernal ponds might be ignored if classification algorithms do not specifically consider seasonal water

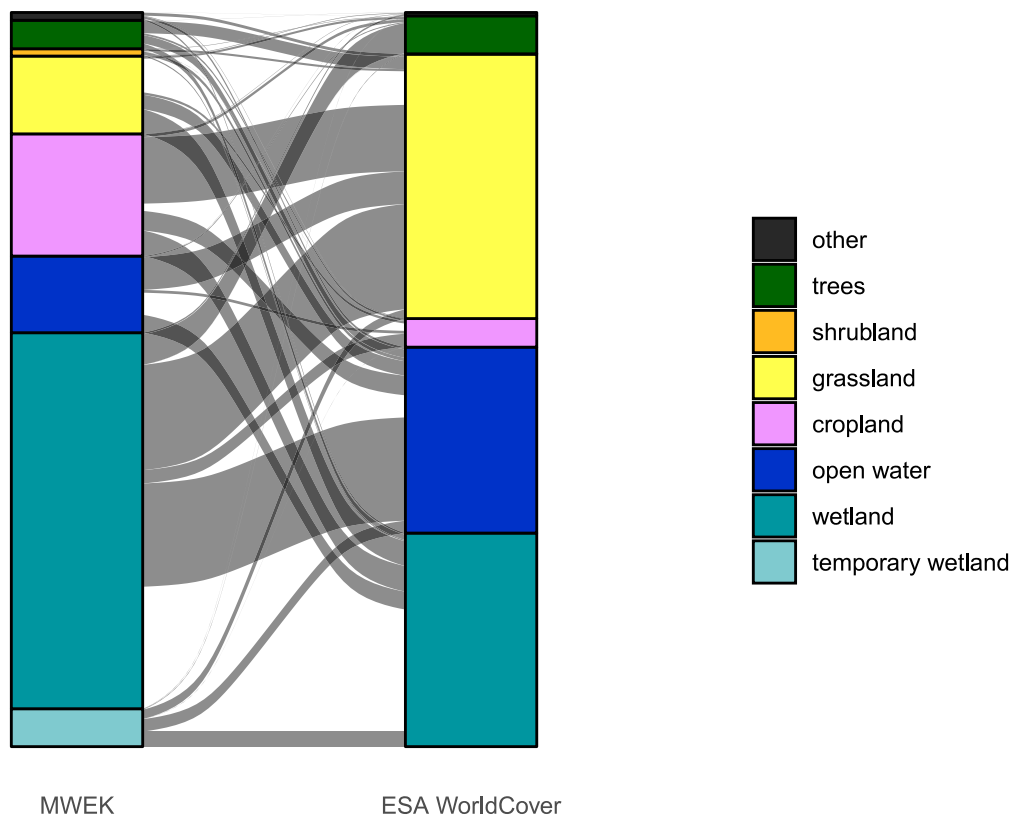


Fig. 6. Alluvial plot comparing ESA WorldCover and MWEK classification for subset of wigeon locations. The figure highlights the differences between classifications for selected wigeon stationary sites (forest cover >50%, and/or cover by wetland and water <50%). Eurasian wigeon locations were restricted to core areas (41.9% of all locations).

availability (e.g. Pekel et al., 2016). Even when water and wetlands are more persistent, small patches of wetlands can be hard to identify for LULC algorithms (Calhoun et al., 2017; Buchhorn et al., 2020; Karra et al., 2021), as are wetlands underneath a cover of vegetation (Adam et al., 2010; Gallant, 2015). Coarse spatial resolutions might thus be unable to detect small water bodies. The highest performing LULC product had the joint-highest spatial resolution of 10 m, and the lowest performance was observed for the product with the coarsest of the resolutions considered (MODIS MCD12Q1.061).

Similarly, LULC products with a relatively higher update frequency than e.g. annually should be able to capture changes in the availability of seasonally flooded habitat as used frequently by wigeons. By matching the time of observation with concurrent available imagery, one would expect to capture the environmental conditions experienced by wigeons at the time. However, despite temporal matching with the near real-time Dynamic World V1 product, which also had a high spatial resolution of 10 m, its performance was well below the annual ESA WorldCover, and on the same level as the annual Copernicus Global LandCover products at a coarser resolution. When comparing the Dynamic World V1 at wigeon stationary locations with ESA WorldCover, we found that it had classified a similar proportion of locations in water and/or wetlands, but proportionally more locations in trees leading to overall lower performance (see Figure S2).

The performance of ESA WorldCover was overall similar to our expert-derived maps, although the latter suggested that ESA WorldCover overestimated the use of herbaceous vegetation. MWEK revealed that the utilisation of water and wetland appeared to be considerably underestimated when relying on the global LULC products alone. While only based on a subset of the stationary periods, we found that all LULC products underestimated the use of water bodies, and the proximity of wigeons to water (Fig. 6). Even at the high resolution of ESA WorldCover, out of the 45.9% of stationary locations not recorded on water, 56.5% were within 500 m from the closest water body, whereas

this percentage rose to 93.5% in the MWEK. The proportion of locations on water (all water classes taken together) was also higher than for either of the global LULCs. The photointerpretation indicated that many of the wetlands that were not recognised as such in the global LULCs tended to be small, located under existing vegetation, and/or were only temporarily flooded.

Generally, a closer analysis of different classification algorithms might be required to understand why some global LULCs appear to be better suited at identifying habitat suitable for a wetland specialist such as the wigeon. MWEK was developed particularly to prioritise aquatic and wetland habitat, whereas available global LULC products might not prioritise wetland habitat to the same degree. Our own observations on the wintering grounds suggest that e.g. smaller ditches surrounding the polders frequented by wigeons were not recognised as water by any of the global LULCs, and instead classified as either agricultural land or herbaceous/grassy vegetation. The definition of classes for ESA WorldCover, for example, states that a cover of 10% or higher of trees would classify a given cell as trees, even if the area were inundated seasonally or permanently with the exception of mangroves (Zanaga et al., 2021). Prioritising trees over wetland habitat thus seems inherent to the classification algorithm, and likely at odds with how wigeons might perceive that same area. This apparent prioritisation might also have contributed to the discrepancy in ESA WorldCover performance between different biomes, with an average performance for boreal forests of 0.8 as opposed to 0.94 for MWEK. The boreal zone constitutes part of the breeding range of the European population and an important stopover area for the Arctic-breeding part of the population. In this biome, ESA WorldCover might fail to highlight suitable wigeon habitat, particularly small vernal wetlands among trees. Here, complementing or replacing existing LULC products with remote sensing products providing a closer thematic match for the habitat preferences of the species of interest can potentially improve performance of detecting suitable habitat, even if availability is non-permanent or limited to small patches.

From a conservation perspective, wetland habitat, including small and ephemeral wetlands, is crucial for wigeons during all life-history stages. While they can link distant habitats throughout their migration (van Toor et al., 2021b), the loss of wetland habitat could contribute to a fragmentation of stopover habitat (Patrick Donnelly et al., 2020; Xu et al., 2020), with potential ramifications for the overall population. The impact of wetland loss might not be limited to the local scale as loss of functional connectivity of stopover habitat along migratory corridors can contribute to population decline of migratory species (Xu et al., 2019). Over the past 400 years, a large proportion of wetlands has disappeared from the range of the East Atlantic population studied here (Fluet-Chouinard et al., 2023). This likely puts more importance on the suitable wetlands that remain, irrespective of size, while small and ephemeral wetlands in particular are threatened by environmental or land use changes, including climate change and society development needs. Despite these developments, they remain challenging to protect in an effective way (Calhoun et al., 2017; Reis et al., 2017). Larger wetlands, especially those supporting a considerable proportion of the population, receive protection under the bird or habitat directives (important bird areas etc.), while small and temporary wetlands are unlikely to qualify under these criteria. The [EU Water Framework Directive](#), for example, does not apply to water bodies and wetlands with an area of less than 50 ha, yet even in fragmented landscape small habitat patches can have an outsized effect for biodiversity (Fahrig et al., 2019; Wintle et al., 2019). In recognition of the importance of small wetlands for wigeons and other wetland-obligate migratory species, the RAMSAR Convention published the [Resolution XIII.21](#) in October 2018 (recall 2020) urging about the conservation and management of small wetlands. For wetland specialists and migratory species such as wigeons, then, including small and temporary wetlands in LULC classifications can help with the identification of potential spring stopover sites crucial for linking the wintering and the breeding grounds.

5. Conclusions

Nowadays, high resolution land use and land cover maps, along with other remotely sensed environmental information are available for conservation planners to use. LULC products in particular are widely used to assess available habitat, but the nomenclatures defined in these maps are in most cases not defined for purposes relevant to biodiversity and conservation practitioners. Here we showed that different classification schemes differ greatly in their ability to describe habitat preferred by wigeons and used by other wetland species, which could lead to a potential mismatch in habitat prioritisation and habitat preferences expressed by the study species. Here, we showed that for Eurasian wigeons, ESA WorldCover appears to consistently perform best among the products evaluated, albeit performance varied between biomes. We also showed that by using cloud-free SENTINEL data on platforms such as GEE, SENTINEL Hub, etc., it is possible to improve on existing classifications by prioritising preferred habitat, such as seasonal wetlands and wetlands under a vegetation cover, in the classification. This approach could be further refined by using time-stamped records from habitat specialists and help support the monitoring of habitat disturbance and decline in biodiversity conservation studies.

Research data for this article

Tracking data of Eurasian wigeons used in this article are available on the Movebank Data Repository under <https://doi.org/10.5441/001/1.dv5mm289.567> (van Toor et al., 2021a). A list of satellite imagery used in the map of wetland expert knowledge can be found in Table S6 in Appendix A. MWEK maps produced for the selection of staging sites can be found under <https://doi.org/10.5281/zenodo.10851798>. Documented R-code for the analysis of wigeon space use and resource selection are available in the Appendix and will be made available on github before publication.

CRediT authorship contribution statement

Mariëlle L. van Toor: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Aurélië Davranche:** Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Gabriel Delaunay:** Writing – review & editing, Formal analysis. **Clément Murgue:** Writing – review & editing, Data curation. **Jonas Waldenström:** Writing – review & editing, Funding acquisition. **Céline Arzel:** Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Conceptualization.

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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.

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Appendix A. Supplementary information

Appendix A - Supplementary information: pdf-document

containing additional details on tracking data collection, analysis of space use and fitting of resource selection functions. The document further contains the evaluation of the random forest classification for MWEK, as well as additional figures and tables.

Appendix B - Code: R-code for analysing wigeon space and habitat

use are included both as a quarto document and compiled html-file. Javascript files with documented code for accessing global LULC products and extracting information at wigeon stationary locations using GEE are also included.

Appendix C - Example of water occurrence in MWEK, WiW, and Global Water Surface:

Example of a small water body as portrayed in SENTINEL-2 imagery, Global Water Surface, and MWEK.

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.biocon.2025.111152>.

Data availability

Code and data used for this study are either shared as part of the appendix, or have been previously published and are cited accordingly.

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