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RESEARCH PAPER

Habitat preferences of European turtle dove *Streptopelia turtur* in the Czech Republic: implications for conservation of a rapidly declining farmland species

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Abstract. The European turtle dove (*Streptopelia turtur*) is an endangered IUCN Red List species impacted by agricultural intensification. Although its population has declined, there is limited knowledge of its habitat preferences in Eastern European countries. To address this gap, we conducted a study in the Czech Republic to investigate the environmental factors that affect the distribution of turtle doves. We used turtle dove presence data from countrywide monitoring efforts, as well as environmental variable datasets describing all natural and human-modified ecosystems making up the land cover of the country. We analysed the general effects of land cover on turtle dove distribution using generalised mixed-effects models. We performed a compositional analysis of habitat use to investigate detailed habitat preferences. A higher proportion of urban and wetland land cover was associated with a significant decrease in turtle dove presence. In contrast, a higher proportion of agricultural and forest land cover was associated with the increased presence of turtle doves. In addition, the compositional analysis revealed significant differences between the suitability of individual habitat types within each land cover type. For example, turtle doves preferred coniferous tree plantations and semi-natural beech and riparian forests, but oak forests, broadleaf, and mixed tree plantations were strongly avoided. In agricultural areas, turtle doves strongly preferred semi-natural grasslands and vineyards but avoided intensive agriculture. Overall, our study provides important insights into the habitat preferences of the endangered turtle dove in the Czech Republic, which can better inform conservation efforts for the species.

Key words: agricultural intensification, land cover, conservation, habitat preferences, declining species

Introduction

The populations of many European bird species have declined in recent decades (Inger et al. 2015). These declines are often emphasised for farmland birds endangered by agricultural intensification (Donald et al. 2001, 2006). Endangered groups include common grassland passerines (Reif et al. 2008) but also rare birds of meadows (Roodbergen et al. 2012) or ground-foraging granivores (Franklin et al. 2005). Population declines are linked to life strategies such as long-distance migration (Vickery et al. 2014),

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dietary specialisation, and ground-feeding (Bowler et al. 2019). All these strategies are combined in one species, the European turtle dove (*Streptopelia turtur* Linnaeus, 1758). It is an Afro-Palearctic migrant and ground-foraging granivore closely tied to human-modified cultural landscapes (Browne & Aebisher 2003). Its population has gone through a steep decline (PECBMS 2015), resulting in its classification as 'vulnerable' in the IUCN Red List of Threatened Species (Birdlife International 2021) and adoption of the EU single species action plan (Fisher et al. 2018). The decline of turtle dove populations was most dramatic in the UK, where its abundance dropped by 96% from 1970 to 2012 (Hayhow et al. 2014). Habitat loss due to agricultural intensification was reported as the primary cause (Browne & Aebisher 2005), although infections and disease have also played a role (Stockdale et al. 2014). Turtle dove distribution in the UK was associated with hedgerows, shrubs, and standing water and was negatively affected by grazing (Browne & Aebisher 2003). Nesting success was reported only to be around 35%, and the breeding season was significantly truncated (Browne & Aebisher 2003). Breeding success and post-fledgling survival were also affected by seed availability, which can be limited in intensively exploited landscapes (Dunn et al. 2017).

The decline in the population of turtle doves is severe in Western Europe as well (Browne & Aebisher 2005). For example, in the Netherlands, its numbers dropped by more than 90% between 1984 and 2015 (van Turnhout 2018) and in France by 48% between 1989 and 2015 (Jiguet 2016). The causes are similar to those in the UK; the loss of foraging habitat due to agricultural intensification, disease and consequently reduced breeding success (de Vries et al. 2022). Unsustainable hunting during migration is also a problem. The current levels of hunting pressure in France, Italy and the Iberian Peninsula were reported to be unsustainable, with the hunting pressure highest in northern Italy and Spain (Lormée et al. 2020). In Southern Europe, the turtle dove is an exceptionally valued game species, complicating conservation efforts (Moreno-Zarate et al. 2021). Simultaneously, the landscape-level effects on breeding populations in the area are not fully understood. In Spain, forests and shrublands reportedly harmed turtle dove abundance, as it most preferred complex cultivation areas (Moreno-Zarate et al. 2020). In contrast, coniferous forests were the most favourable breeding habitat in Portugal (Dias et al. 2013) and Greece (Bakaloudis et al. 2009). In Italy, turtle doves inhabited riparian forests and tree plantations and avoided areas of intensively cultivated croplands (Chiatante et al. 2021).

The turtle dove population has been explored the least in Central and Eastern European countries. Data from regional surveys and bird censuses show decreases in abundance in Ukraine and Belarus (Nakonechnaya et al. 2020), Poland (Orłowski & Ławniczak 2009) and the Czech Republic (Šťastný et al. 2006, 2021). A slight population increase was reported in Hungary (Bankovics 2001) and Austria (Teufelbauer & Frühauf 2010). The turtle dove population in these countries uses migration routes different from the western flyway (Marx et al. 2016), and the effects of hunting pressure along these migration paths have not been examined. The landscape characteristics also differ from those of Western Europe. Post-communist countries were particularly impacted by the agricultural collectivisation of the past century, which has effectively reduced the diversity of animals in farmland ecosystems by consolidating privately owned land into large state-owned crop fields (Šálek et al. 2014). In addition, inadequate environmental regulation by communist-era governments coupled with industrial development has caused massive environmental damage, negatively impacting many bird species (Cole 1998). Recently, the land cover in many countries of the former Eastern Bloc has gone through massive changes as part of the Common Agricultural Policy of the European Union. Agricultural intensification, including the heavy application of fertilisers, has transformed farmland areas to maximise crop yield (Reif & Vermouzek 2019). As a result, farmland bird populations have further declined (Reif et al. 2008). In some cases, this historical development leads to lower applicability of some conservation measures, e.g. agro-environment schemes, based on the data and knowledge from other European regions (Havlíček et al. 2021).

The Czech countryside is a typical example of post-communist conversion to intensive agriculture (Bičík et al. 2015). The decline of many farmland species has been accurately monitored by banding programmes and regular field surveys (Reif et al. 2011). Turtle dove occupancy is highest in the warm south-eastern region of the country, where it was reported to seek out vineyards and shrublands for breeding (Šťastný et al. 2021). As part of the Atlas of breeding bird distribution in the Czech Republic 2014-2017, correlation indices of turtle dove occurrence with different land cover types were presented (Šťastný et al. 2021). In addition, Floigl et al. (2022) conducted a study on the habitat overlaps of Columbidae species breeding in the Czech Republic. Although their findings expand existing knowledge about the species' ecology, they did not explore the impact of agricultural intensity or provide any new insights into habitat selection. While the turtle dove is generally known as a farmland species (Fisher 1953), recent research has shown that forests also play an essential role as their breeding habitat (Hanane 2018). However, the significance of forests for the regional turtle dove population in the Czech Republic remains to be investigated.

Our study aimed to be the first to examine the effects of landscape characteristics on the turtle dove population in the Czech Republic. To accomplish this, we focused on two primary research questions. Firstly, we sought to determine the primary environmental effects that contribute to the distribution of turtle doves. Secondly, we aimed to identify the most suitable habitats for the species during the breeding season. We used a robust dataset determining the presence and abundance of turtle doves during the breeding season (Šťastný et al. 2021) and combined it with land cover information from the Consolidated Layer of Ecosystems (CLE) provided by the National Conservation Agency of the Czech Republic (Hönigová & Chobot 2014). We performed statistical analyses that consider the confounding effects of spatial autocorrelation. Our findings lay the ground for future landscape-level conservation efforts to prevent further decline in the turtle dove population. In addition, we highlight the necessity of expanding the scope of scientific knowledge towards Eastern European bird populations, as it is often insufficient to prevent biodiversity loss.

Material and Methods

Data collection

The study was conducted in the Czech Republic, a middle-size central-European country (78,786 km^2) with a wide range of altitudes (115-1,603 m a.s.l.), diverse land cover (general land use: urbanised areas 6.7%, arable land 36.4%, grassland habitats 10.2%, vineyards, gardens, and other agricultural land 10.2%, forests 35.6%, waterbodies and wetlands

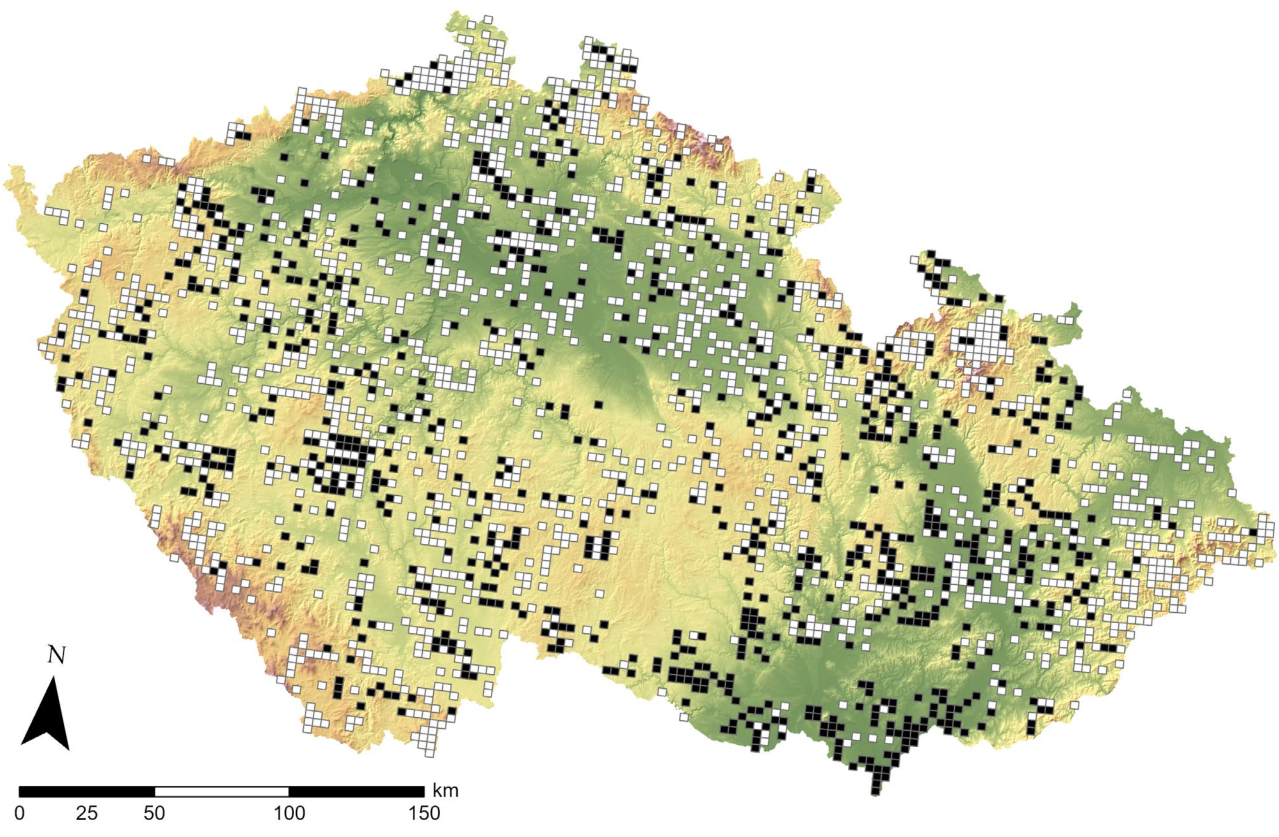

Fig. 1. Map of the Czech landscape with survey design. Black squares highlight sampled areas where turtle dove was found during at least one of the two visits. White squares highlight sampled areas where turtle dove was absent. The coloured shaded background refers to the elevation of the Czech landscape, with green areas being predominantly lowlands (up to 400 m a.s.l.), yellow areas being hills (400-700 m a.s.l.) and brown areas mountainous regions (above 700 m a.s.l.). The source of the elevation data is the WMS service of the National Office for Mapping and Cadastre (ČÚZK 2023).

0.9%; Grešlová et al. 2021), and a continental climate (mean temperature during whole year, summer and winter months, and mean precipitation in the last year of your study: 8.6 °C, –1.7 °C, 18.5 °C, and 683 mm; Czech Hydrometeorological Institute 2018). Data were collected during the works on the Atlas of breeding bird distribution in the Czech Republic in 2014-2017 in squares of size roughly 3 × 2.8 km, evenly covering the entire area of the country (Šťastný et al. 2021).

All data were collected by experienced volunteers who followed the uniform methodology of timed list modification for use within similar projects in central European conditions (Flousek et al. 2015). The timed-listed methods generally work under the assumption that the more common and abundant species are recorded sooner than the rare and less abundant ones (Bibby 2004). Walking slowly inside the mapping square, the volunteers counted all bird species heard or seen for 60 min. The goal was to visit most of the habitats in the mapping square, while the start of counting and most of the time should be spent in the most represented ones. The counting took place at the time of highest bird activity, i.e. early morning or late afternoon, which covered the voice activity of the turtle dove (Calladine et al. 1999), and under the appropriate climatic conditions without heavy rain, strong wind, or high temperatures. All data were written down in uniform form on the web pages or the mobile application designed for the project (Šťastný et al. 2021). The presence/absence of turtle doves was recorded for each mapping square. For this study, we used only the data collected from April 15 to July 5, the turtle dove breeding season, and consequently a period of highest voice activity of the turtle dove in the Czech Republic (Calladine et al. 1999).

In addition, we addressed an additional confounding effect stemming from volunteer sampling. During the field surveys, some squares with turtle doves were visited more often than others. It is plausible that turtle doves in these areas were more likely to be detected simply because more effort was put into their detection. To eliminate this issue, we only used a subset of mapping squares in our analyses, which were all visited twice during the breeding season. These squares represent 2,378 independent observations that cover roughly 25% of the area of the Czech Republic (Fig. 1). We suggest that trends influencing turtle dove distribution in this subset apply to the whole country, as it encapsulates all ecosystems that turtle dove occupies across all elevations.

Environmental data were obtained from CLE, a dataset of all natural and human-modified ecosystems making up the land cover of the Czech Republic (Hönigová & Chobot 2014). We identified four main categories of land cover describing general environmental characteristics: agricultural, forest, urban and wetland. Agricultural land cover included different grassland habitats, from semi-natural grasslands to crop fields on arable land, hop fields, orchards, vineyards, and gardens. Forest land cover included both commercial and semi-natural forests, as well as shrublands. Urban land cover described multiple human-modified habitats, from city and road infrastructure to public parks and recreational areas. Finally, wetland land cover included water bodies, bogs, marshes, and swamps. A detailed list of all habitats within each land cover is available in Table S1. The land cover proportion within each mapping square and the perimeter of individual land cover types per 1 km^2 inside each mapping square was computed in Arcgis Pro Desktop (ESRI 2023). The area of the four land cover categories within each mapping square was then used to describe the general environmental effects on turtle dove distribution in further analyses.

Statistical analyses

To calculate the effect of the main environmental gradients on turtle dove distribution, we used the glmmTMB function, package glmmTMB (Magnusson et al. 2017), for building generalised linear mixed-effect models (Bolker et al. 2009) in R 4.2.2 Software (R Core Team 2020). Turtle dove distribution was represented by its presence/absence (0/1) within each mapping square and used as the dependent variable. We performed stepwise forward selection for explanatory variables by AIC (Yamashita et al. 2007). We did this by first building a null model and then adding the explanatory variable that most improved model fit (represented by a decrease in AIC) for each step. We continued to include variables until none were left that decreased model AIC. In the final model, we only kept explanatory variables with a statistically significant effect (*P*-value) on the dependent variable.

We tested five explanatory variables as fixed effects: the area of agricultural, forest, urban and wetland land cover within each mapping square, as well as its median altitude. First-order interactions between altitude and land cover variables were also tested to account for the changing effects of land cover on turtle dove distribution at varying altitudes (Mansouri et al. 2020). The final model with the

Table 1. The effects of land cover (fixed effects) on the presence of turtle doves within sampled squares. Random effects were represented by the exponential spatial covariance structure (see Methods). The full formulation of the model and detailed information on fixed-effect variable transformation, residual diagnostics and multicollinearity test are available in Table S1-S3.

Independent variable	Estimate	Conf. int. (2.5/97.5%)	SE	Z	*P*
Agriculture	0.717	3.549/1.065	0.181	3.971	< 0.001
Altitude	0.025	0.286/0.003	0.009	2.790	0.005
Urban	–0.428	–0.655/–0.142	0.133	–3.226	< 0.001
Forest	0.848	0.576/1.193	0.157	5.393	< 0.001
Wetland	–0.175	–0.262/–0.09	0.007	–2.166	0.030
Altitude: agriculture	–0.001	–0.001/–0.001	0.002	–2.447	0.014
Altitude: urban	0.001	0.001/0.001	0.002	2.149	0.032
Altitude: forest	–0.001	–0.001/–0.001	0.001	–2.721	0.007

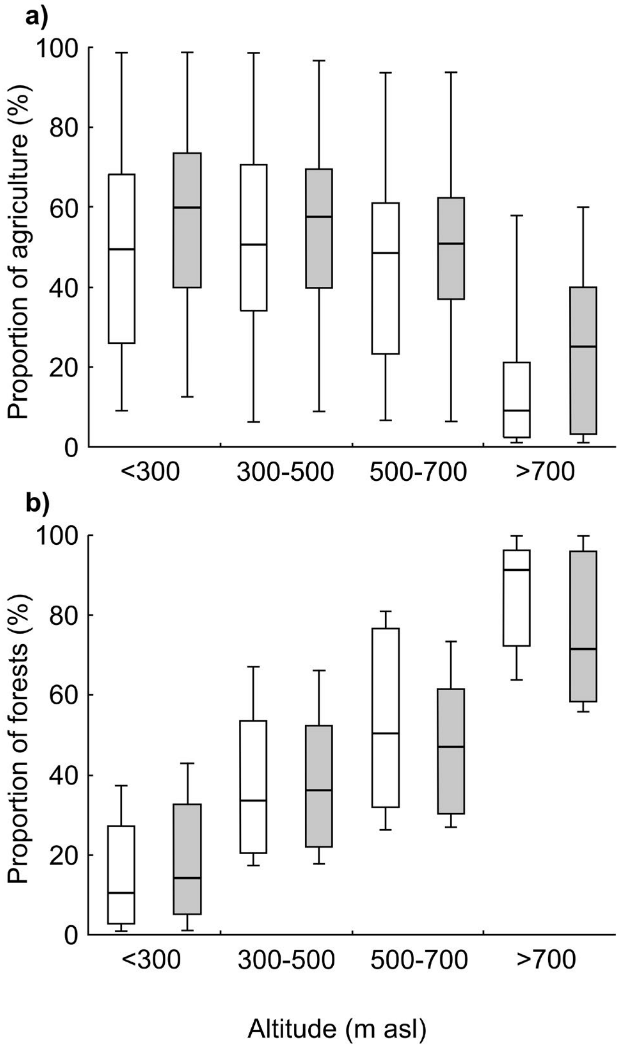

Fig. 2. Proportion of a) agriculture and b) forest land cover in squares across all four elevation categories, with empty boxes describing the absence of turtle doves and shaded boxes describing the presence of turtle doves. Whiskers – non-outlier range, boxes – 25-75% of data, thick lines – median.

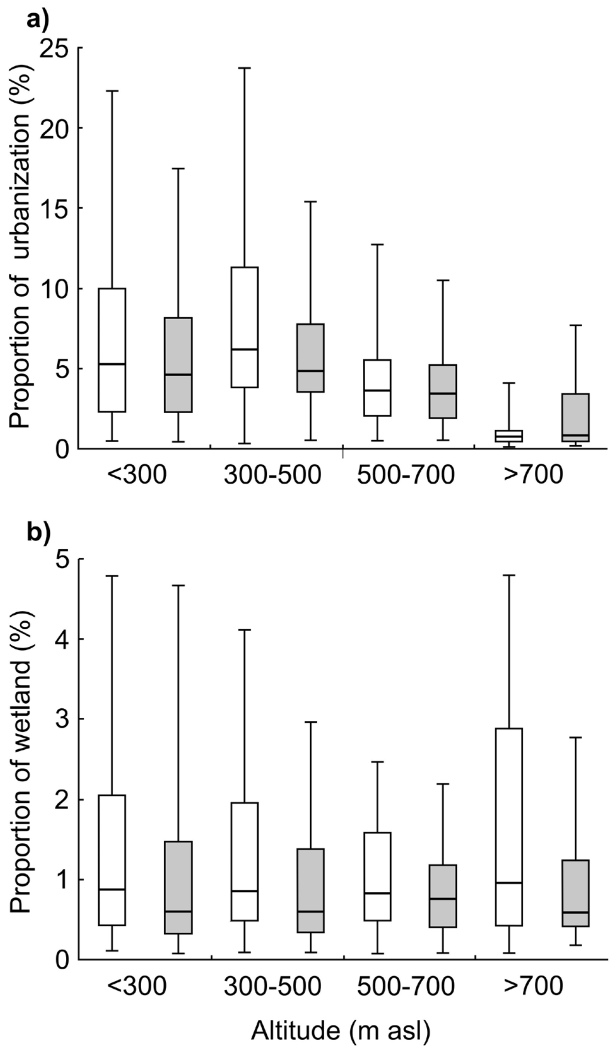

Fig. 3. Proportion of a) urban b) wetland land cover in squares across all four elevation categories, with empty boxes describing the absence of turtle doves and shaded boxes describing the presence of turtle doves. Whiskers – non-outlier range, boxes – 25-75% of data, thick lines – median.

lowest AIC included all five explanatory variables and interactions between altitude and three land use types, except for wetland (the effect of this interaction was nonsignificant, $P > 0.1$, and did not improve model AIC). We tested the goodness of fit of the final model using the DHARMa package for model

Table 2. Results of compositional analysis of habitat use. The significant effect of habitat selection is highlighted in the first row. Habitat types are sorted by preference for turtle dove inhabitation in descending order, from the most preferred to the least preferred.

Wilk's lambda λ: 0.641	*P*: 0.002	
Rank	Habitat type	Mean $\log_2$ (used/available)
1	Coniferous tree plantations	0.61
2	Beech forests	0.41
3	Vineyards	0.30
4	Semi-natural grasslands	0.25
5	Riparian forests	0.10
6	Natural shrub vegetation	0.01
7	Hop fields	–0.04
8	Commercial meadows	–0.05
9	Orchards & gardens	–0.07
10	Introduced shrub vegetation	–0.09
11	Semi-natural coniferous forests	–0.13
12	Arable land	–0.14
13	Mixed tree plantations	–0.28
14	Wetlands	–0.32
15	Broadleaf tree plantations	–0.50
16	Mines	–0.55
17	Built-up areas	–0.64
18	Parks	–0.74
19	Roads	–0.77
20	Oak forests	–0.90
21	Recreational	–1.04
22	Industrial	–1.33

diagnostics (Hartig & Hartig 2021). To view these diagnostics, the specific form of the final model, as well as an abridged version of the forward selection process, see Table S2.

To address the effects of spatial autocorrelation, we created a numeric factor to record spatial coordinates from each counting point using the NumFactor function, package glmmTMB (Magnusson et al. 2017). Using an exponential covariance structure, the numeric factor was included in each model as a random effect variable. Covariance structures allow for reliable inclusion of spatial relationships as terms in statistical models (Bevilacqua et al. 2022). For the specific formulation of the covariance structure in each model, see Table S2. We used a binomial distribution as the family function to fit the model (Hardin & Hilbe 2007) and performed dependent variable transformations when necessary (Table S2). We also performed multicollinearity tests for each non-interaction variable in the final model (package performance, Lüdecke et al. 2019).

After describing the effects of general environmental trends, we moved on to examining the habitat preferences of turtle doves using a compositional analysis of habitat selection, package AdehabitatHS (Calenge 2011) in R 4.2.2 Software. Habitat types from the CLE dataset were used as habitat categories (Table S1). We used a randomisation test with 500 repetitions. Habitat that was not found within a particular square (zero values in the entry data matrix) was replaced by 0.01 (Aebischer et al. 1993). We computed the proportion of each habitat within each square from the total square area. The analysis was carried out in two steps. First, the significance of habitat use was tested (using a Wilks lambda). A ranking matrix was built, indicating whether the row habitat category is significantly used more or less than the habitat type in the columns. Furthermore, habitats were sorted from most preferred to non-preferred (Aebischer et al. 1993). The relationships between the overall proportion of habitat available (proportion of habitat area in unoccupied squares) and habitat used (proportion of habitat area in occupied squares) were expressed by a selectivity index, formula: $\log_2$ (used/available) after Sunde et al. (2001).

Results

In total, turtle doves occupied 64% out of the 2,378 analysed squares covering roughly 25% of the area of the Czech Republic (Fig. 1). Most occupied squares were below 500 meters altitude (72%), and only 15 occupied squares were above 800 meters, highlighting a preference of lower elevations. Turtle dove distribution was significantly impacted by land cover as well as altitude (Table 1). Turtle dove presence was significantly increased in squares with a higher proportion of agricultural land cover over all elevations (Fig. 2a). On the other hand, the effect of forest land cover on turtle dove presence differed between altitudes. While turtle dove presence increased with afforestation in lower altitudes (up to 500 m), it significantly decreased in more afforested areas in higher altitudes (above 500 m, Fig. 2b). Turtle dove presence was decreased in squares with a higher proportion of urban and wetland land cover at all altitudes (Fig. 3), with this difference becoming less apparent for urban land cover in higher elevations (above 700 m, Fig. 3a). We did not find any significant effects of multicollinearity in our final model (Table S3).

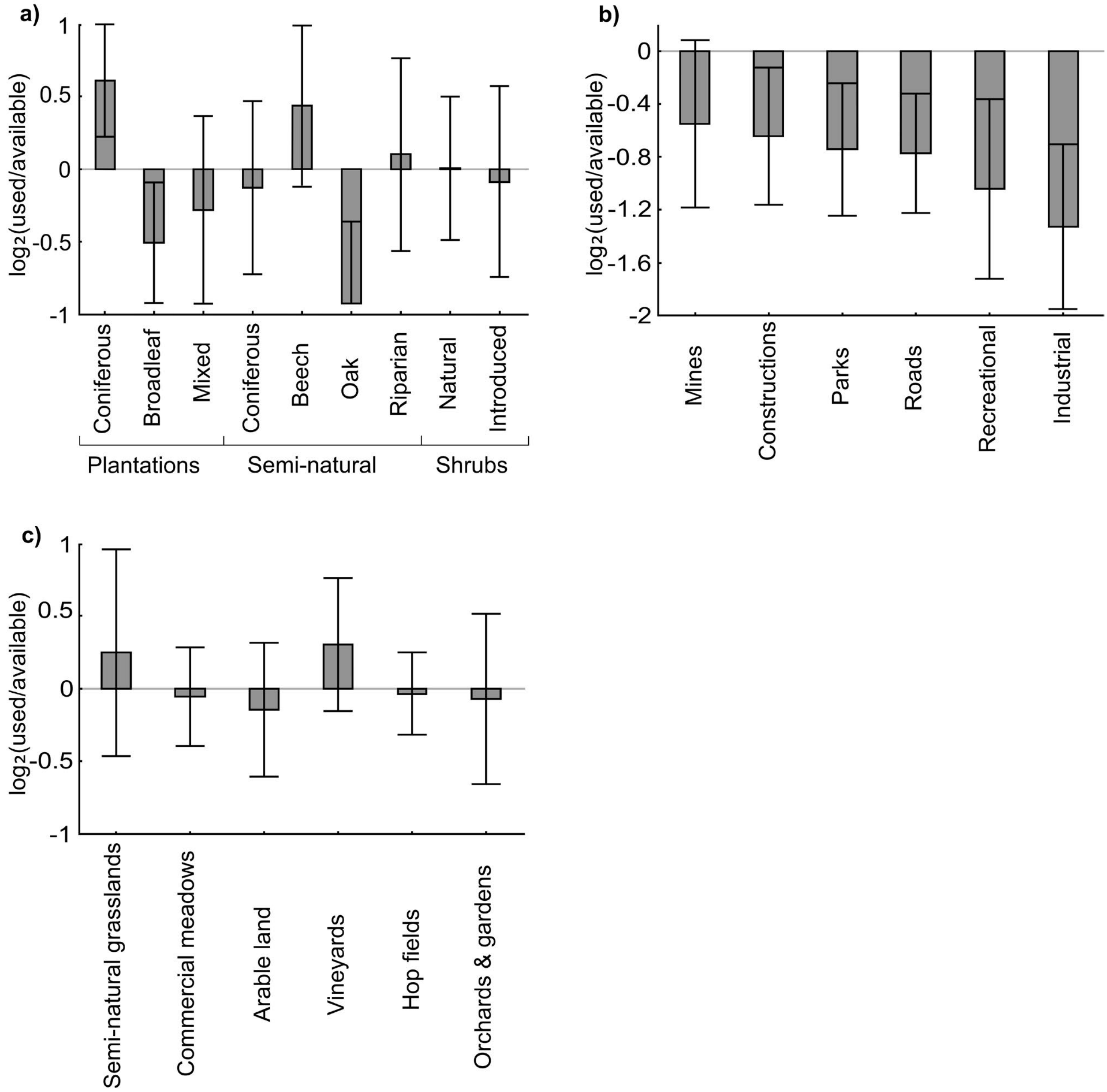

Fig. 4. Habitat selectivity index (± SD) of turtle dove for different habitat types: a) forests and shrub vegetation b) urban areas c) farmland, see Havlíček et al. (2021).

The compositional analysis found a significant effect of habitat selection (Wilk's lambda $\lambda = 0.641$, $P = 0.002$). Habitat ranking showed that coniferous tree plantations were the most preferred habitats, followed by beech forests, vineyards, semi-natural meadows, riparian forests, and natural shrub vegetation (Table 2). The remaining habitats were potentially unsuitable for turtle dove presence, as highlighted by their negative selectivity index values (Table 2). While coniferous tree plantations were the most preferred habitat, both broadleaf and mixed tree plantations showed a negative association with turtle dove presence (Fig. 4a). Similarly, while semi-natural beech and riparian forests were preferred, natural coniferous and oak forests were mostly unoccupied (Fig. 4a). Natural shrub vegetation was more suitable for turtle dove than introduced shrub vegetation (Fig. 4a). In sharp contrast to forests, urban habitats were all highly unsuitable for turtle dove occupancy, with industrial and recreational areas being the least suitable habitats in our dataset (Fig. 4b). Among farmland habitats, semi-natural grasslands were most preferred, followed by commercial meadows and arable land (Fig. 4c). Vineyards were strongly preferred, in contrast to hop fields, orchards and gardens (Fig. 4c).

Discussion

Our results on the general environmental effects on turtle dove distribution agree with similar studies. Turtle dove requires both forest land cover (Bakaloudis et al. 2009) and agriculture (Dunn et al. 2017, Sauser et al. 2022), while urbanisation was shown to have a negative effect on its presence (Floigl et al. 2022). Wetland land cover included a wide range of ecosystems, from littoral vegetation to bogs, peatlands, and water courses, none of which are typical habitats of turtle doves (Browne & Aebisher 2003), likely due to limited nesting opportunities (Mansouri et al. 2021). Our results also highlight the important relationship between altitude and land cover types, as higher elevations in the Czech landscape tend to favour forest land cover, while agriculture and urban infrastructure decrease its proportion (Chytrý 2017). As turtle dove requires a mix of farmland and forests for foraging and breeding (Browne & Aebisher 2003), the dominance of forests, together with the absence of agricultural land cover and a shorter vegetation season, negatively affects its distribution in higher elevations (Mansouri et al. 2020).

However, our analysis of habitat use has revealed more nuanced effects of land cover on turtle dove presence. We found that different forest types had varying levels of suitability for turtle doves. Semi-natural beech forests, coniferous tree plantations, and riparian forests were highly preferred habitats, while others were avoided. Beech forests are found in medium elevations in the Czech Republic (Chytrý 2017), have a high canopy closure, a medium to low-density understory, and are dominated by European beech (*Fagus sylvatica* Linnaeus, 1753; Chytrý et al. 2010). Similarly, coniferous tree plantations, which occur at similar altitudes, primarily consist of monocultures dominated by Norway spruce (*Picea abies* Linnaeus, 1753) or Scots pine (*Pinus silvestris* Linnaeus, 1753; Novák et al. 2012). These plantations share many characteristics with beech forests, including a low-density understory, intermediate shrub cover and higher canopy closure (Chytrý 2017). Such habitat features have been shown to positively affect turtle dove presence (Chiatante et al. 2021). In addition, recent logging of spruce forests infected by *Scolytinae* beetles has created many clearings (Hlásny et al. 2021). These can function as secondary foraging areas for turtle doves (Camprodon & Brotons 2006). Riparian forests also ranked highly among the preferred habitats for turtle doves. These forests consist of native tree species resistant to soil waterlogging (Chytrý et al. 2010). Previous research has suggested that water availability, herb layer productivity, and higher spacing between trees are the main drivers of turtle dove preference for riparian forests (De Buruaga et al. 2013, Gruychev & Mihaylov 2019, Gutierrez-Galan et al. 2019).

Avoided forest types included mixed and broadleaf tree plantations and semi-natural coniferous and oak forests. Mixed and broadleaf tree plantations are often made up of allochthonous species, such as Canadian poplar (*Populus × canadensis* Moench, 1794) or black locust (*Robinia pseudacacia* Linnaeus, 1753; Chytrý et al. 2010). Non-native tree plantations have a detrimental effect on bird species richness primarily due to a reduced food supply (Hanzelka & Reif 2016), which could also negatively impact turtle dove presence. Our results corroborate this, where natural shrub vegetation was preferred over non-natural. Turtle dove also mostly avoided semi-natural coniferous forests. Natural coniferous vegetation mainly occurs at higher altitudes (Chytrý 2017), where the short growing season and cold temperatures likely prevent successful breeding.

However, the forest habitat that was most avoided was the semi-natural oak forest. This result contrasts with other authors, who found that oak forests were associated with turtle dove occupancy (Gruychev & Mihaylov 2019). We offer several possible explanations. Firstly, some types of oak forests in the Czech Republic feature a dense understory and low spacing between trees (Chytrý et al. 2010), potentially impacting foraging conditions of turtle dove, which is known to require low understory density (Browne & Aebisher 2003). In addition, many types of oak forests grow in extreme environmental conditions (arid forest-steppes, highly acidic or basic soils, Chytrý et al. 2010), which can be unsuitable for turtle doves. Lastly, we cannot exclude the effects of spatial relationships, as oak forests mainly occur in lowland areas (Chytrý 2017), suggesting an association with urban habitats and wetlands, which turtle doves avoided.

In farmland areas, turtle dove followed the agricultural intensity gradient in its habitat preferences, with semi-natural grasslands being much more suitable than commercial meadows or arable land. In addition, a strong preference for vineyards was also found. This preference is known (Moreno-Zarate et al. 2020) and likely stems from the capacity of vineyards to function as both a heterogenous breeding and foraging habitat (Barbaro et al. 2017). Turtle dove is generally categorised as a farmland species (Browne & Aebisher 2005), though its dependence on forests has been emphasised (Dias et al. 2013, Hanane 2018). Adverse effects of agricultural intensification on farmland species were highlighted as the most critical issues for landscape-level conservation efforts (e.g. Donald et al. 2001, Reif et al. 2008).

One of the main strategies to prevent habitat losses of endangered farmland species is agro-environment schemes (AES, Vickery et al. 2004). These schemes can potentially create abundance strongholds for farmland birds but often achieve mixed results (Princé et al. 2012). This finding leads some researchers to suggest that AES management may not be sufficiently adapted to the ecological requirements of targeted species (Konvička et al. 2008). As not enough is known about the habitat preferences of the Eastern European turtle dove population, our results bring substantial baseline knowledge on the correct application of AES management. AES has been applied in the Czech Republic since 2004 to prevent land abandonment and agricultural intensification by funding the preservation of extensively managed grasslands, pastures, and wet meadows (Pražan & Theesfeld 2014). However, merely promoting low-intensity agriculture may prove insufficient for turtle dove conservation. Spatial ecosystem structure should also be considered. The conservation value of farmland in the Czech Republic has been impacted by collectivisation during the communist era (Lipský 1995). The resulting large homogenous blocks of fields are characterised by low biodiversity and a high risk of erosion and land degradation, causing further issues for ecological protection (Reif & Vermouzek 2019).

Recently applied AES, such as flower-rich strips, were introduced to increase the biodiversity of invertebrates and birds (Geppert et al. 2020), but the number of AES areas in the Czech landscape continues to be low, which leads to isolation and inaccessibility by foraging birds (Pražan & Theesfeld 2014). Some AES proposals highlighted the necessity of preserving both a breeding and foraging habitat in close adjacency (Fisher et al. 2018). A possible management regime to address this is presented in agroforestry. It effectively combines the cultivation of trees and crops (Nair 1993, Smith et al. 2013) and increases farmland capacity to improve ecosystem functioning while maintaining strong crop yields (Lojka et al. 2021). Agroforestry is prevalent in Southern Europe, and the resulting heterogenous cultivation areas are preferred habitats for turtle doves (Moreno-Zarate et al. 2020, Chiatante et al. 2021). As turtle doves prefer low-density beech forests and coniferous plantations, including them in agroforestry schemes could help create a sustainable breeding habitat without impacting crop yields. Integrating agroforestry in AES or government-funded agricultural subsidies could improve the suitability of the Czech landscape for turtle dove occupancy.

Conclusions

The current landscape-level conservation efforts appear insufficient in mitigating the decline of farmland birds, including turtle dove. In part, this is because they fail to consider the history and spatial structure of the landscape. In addition, the importance of forestry in farmland landscapes is often neglected. We offer a possible solution by promoting the agroforestry management that has dominated large parts of the Czech landscape pre-collectivisation. However, as the legislative framework for reintroducing agroforestry is lacking, its implementation is not expected soon. The protection of the turtle dove population will thus likely need to be improved at the landscape level, with further adverse effects associated with agricultural intensification and habitat loss exacerbated in the future.

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Author Contributions

J. Havlíček and K. Korejs were responsible for the study's conception and design. I. Mikuláš, J. Havlíček, J. Riegert, and many volunteers contributed to the data collection. J. Vrba and J. Havlíček performed GIS analysis. K. Korejs, J. Riegert, J. Havlíček, and I. Mikuláš performed the data analysis. K. Korejs and J. Havlíček wrote the first manuscript draft. All authors commented on previous versions and approved the final manuscript.

Data Availability Statement

The data and RScript supporting this study's findings are available in the FigShare Digital Repository: https://figshare.com/projects/Habitat_preferences_of_European_turtle_dove_Streptopelia_turtur_in_the_Czech_Republic_implications_for_conservation_of_a_rapidly_declining_farmland_species/198721.

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Supplementary online material

Table S1. Land cover data used in statistical analyses. The primary category (land cover group) joined similar types of land cover for the purposes of analysing the general environmental effects on turtle dove distribution. The secondary category (land cover type) was used as the input dataset in the compositional analysis of habitat use, effectively functioning as habitat types. The tertiary (CLE) category describes which ecosystems (as described by the Consolidated Layer of Ecosystems, AOPK ČR 2012) make up different land cover types in this study. The final category describes the source of information for establishing the CLE category, either Habitat Catalogue of the Czech Republic (VMP, see Chytrý et al. 2010) and its corresponding GIS layer (VMP, AOPK ČR 2012) or ZBG geographic layer (ČÚZK 2012) or EEA Urban atlas (EEA 2006) or Corine Land Cover data (CLC, EEA 2006). KVES categories were merged into land cover groups based on a preliminary computation of the selectivity index for turtle dove inhabitation, by formula recommended by Sunde et al. 2001: mean $\log_2$ (used/available), as well as based on their general characteristics as described in the CLE layer.

Table S2. Additional information on the final model to analyse turtle dove response to general land cover characteristics. The model was performed by the package glmmTMB (Magnusson et al. 2017). Forward selection by AIC was performed and is elaborated upon in the Table. Goodness of fit was tested with the DHARMa package; the test results are explained in the Table (Hartig & Hartig 2021).

Table S3. Collinearity levels of variables in the mixed-effects model, tested by the multicollinearity function, package performance (Lüdecke et al. 2019). The variance inflation factor (VIF) is a measure to analyse the magnitude of multicollinearity of model terms. A VIF of less than five indicates a low collinearity of that predictor with other predictors. A value between five and ten indicates moderate collinearity, while VIF values above ten indicate unacceptable collinearity of model predictors (James et al. 2013). The Table also displays the associated confidence intervals, the factor by which the standard error is increased due to possible correlation with other terms, and tolerance values (including confidence intervals), where tolerance = 1/VIF. The interaction terms from the model are not included in the multicollinearity tests, as they inflate the variance inflation factor due to being linear combinations of their parent predictors (Lüdecke et al. 2019).

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