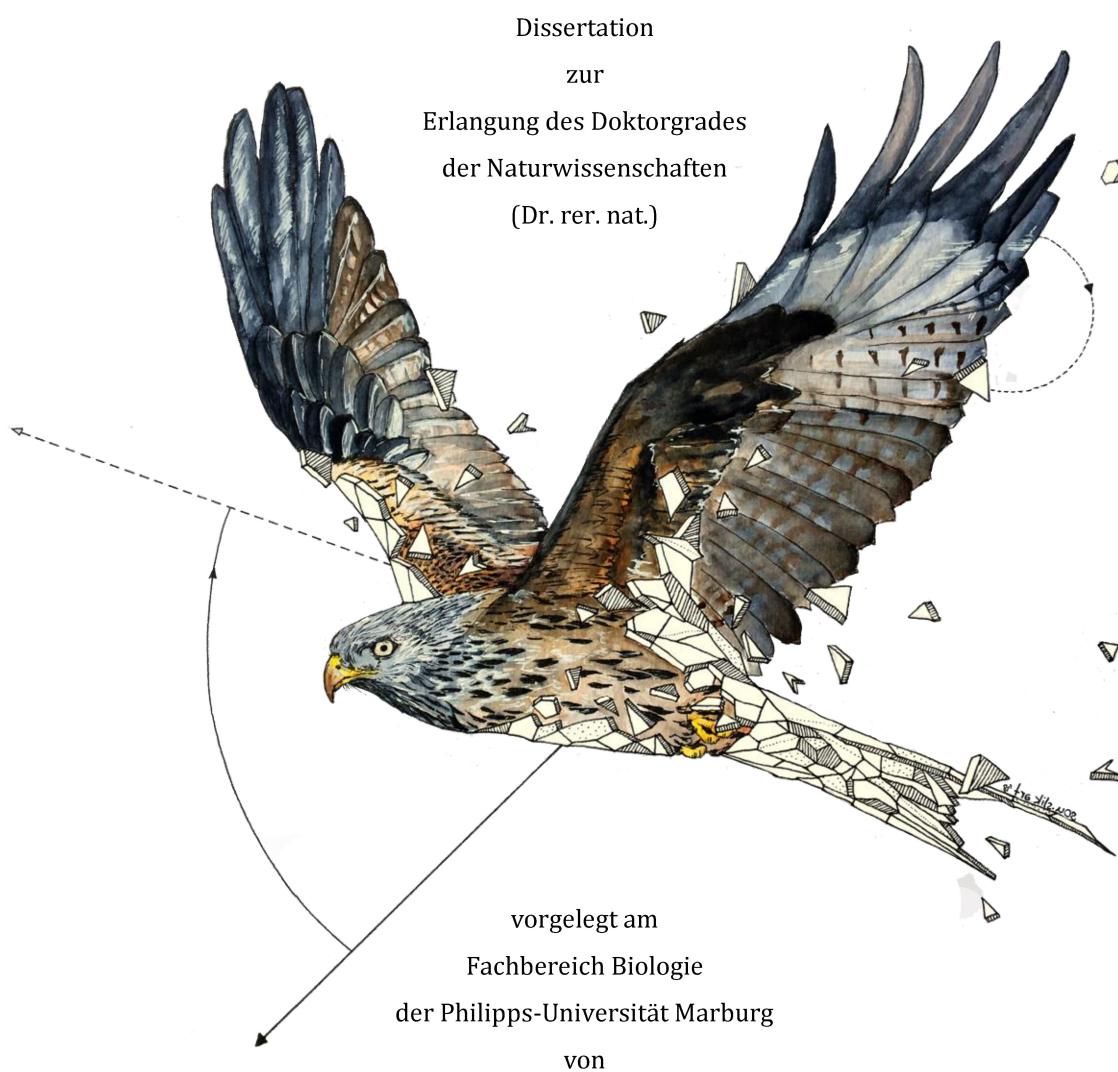


**What drives you?**

**Space and habitat use of Red Kites (*Milvus milvus*)**

**across different temporal and spatial scales**



Theresa Spatz  
aus Aschaffenburg

Marburg an der Lahn, März 2022

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zur  
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der Philipps-Universität Marburg  
von

Theresa Doris Spatz  
aus Aschaffenburg

Marburg an der Lahn, März 2022



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## Declaration of author's contributions

The studies for my PhD thesis entitled "What drives you? Space and habitat use of Red Kites across different temporal and spatial scales" were carried out at the Philipps-University of Marburg under the supervision of Prof. Dr. Nina Farwig

Chapter I, II, III and IV contain independent scientific manuscripts, which I published, submitted, or prepared for submission as lead author. The contributions of me and my co-authors for each of these manuscripts are given as follows:

### Chapter I

(published in German language)

**Theresa Spatz**, Sascha Rösner, Dana G. Schabo, Christian Gelpke, Nina Farwig (2019). Zwischen Revierbildung, Brutphase und Jungenaufzucht: Aktionsräume und Habitatnutzung adulter Rotmilane *Milvus milvus* in Hessen. Ornithologische Mitteilungen 71 (9/10), 1-8.

TS, SR, DS and NF conceived the study and applied for the necessary permits for the GPS-tracking of the Red Kites. TS organized and prepared field work and conducted it together with all co-authors. CG gave the expertise to capture adult Red Kites. TS programmed the transmitters, prepared, and analysed the data and wrote the manuscript. SR, DS, and NF supported the statistical analysis and improved the manuscript. All

authors contributed substantially to the study and gave final approval for publication.

### Chapter II

(published in German language)

**Theresa Spatz**, Dana G. Schabo, Nina Farwig, Sascha Rösner (2019). Raumnutzung des Rotmilans *Milvus milvus* im Verlauf der Brutzeit: Eine Analyse mittels GPS-basierter Bewegungsdaten. Vogelwelt 139, 161-169.

All authors conceived the study and applied for the necessary permits for the GPS-tracking of the Red Kites. TS, DS, and SR prepared and conducted field work. TS and SR programmed the transmitters. TS prepared and analysed the data with DS, NF, and SR giving advice for the statistical approach. TS wrote the manuscript, which was revised and improved by DS, NF and SR. SR improved the figures in the manuscript. All authors contributed substantially to the study and gave final approval for publication.

### Chapter III

(not published)

**Theresa Spatz**, Nina Farwig, Sascha Rösner, Dana G. Schabo. High collision risk of Red Kites across the entire range of occurring wind speeds.

All authors conceived the study and applied for the necessary permits for the GPS-tracking of the Red Kites. TS, DS, and SR prepared and conducted field work. TS and SR programmed the transmitters. TS prepared and analysed the data with DS, NF, and SR giving advice for the statistical approach. TS wrote the manuscript, which was revised and improved by DS, NF and SR.

#### **Chapter IV**

(submitted and under review: Journal of Avian Biology)

**Theresa Spatz**, Jakob Katzenberger, Nicolas Friess, Christian Gelpke, Eckhardt Gottschalk, Martin Hormann, Steffen Koschkar, Thomas Pfeiffer, Christoph Sudfeldt, Sascha Rösner, Dana G. Schabo, Nina Farwig. (2021 submitted to Journal of Avian Biology) Sex, landscape diversity and primary productivity shape the seasonal space use of a migratory European raptor.

TS, JK, EG, CS, SR, DS and NF conceived the study. TS, CG, EG, SK, TP, SR and DS conducted field work and provided data. TS and JK managed and prepared data. TS analysed the data and conducted statistics with support of JK, NFr, DS and NF. TS wrote the manuscript with support of JK, SR, DS and NF. An earlier version of the manuscript was revised and improved by TS, JK, NFr, EG, TP, CS, SR, DS and NF. NF and CS were the PIs of the research projects providing the data. All authors contributed substantially to the study and gave final approval for publication.

## Zusammenfassung

Landnutzungs- und Klimawandel sind die Hauptursachen für sich verändernde Umweltbedingungen, die weltweit zum Rückgang von Arten führen. Um die Auswirkungen des Klimawandels abzumildern, wurde die Nutzung erneuerbarer Energien, z. B. durch den Bau von Windkraftanlagen, in den letzten Jahrzehnten stark ausgeweitet. Windkraftanlagen stehen jedoch regelmäßig in der Kritik, weil sie unter anderem zu Lebensraumverlusten und Barriereeffekten führen und ein Kollisionsrisiko darstellen, insbesondere für hoch mobile, großräumig agierende Arten wie Vögel. Um die Auswirkungen der sich ändernden Umweltbedingungen und die zusätzlichen Risiken durch Windkraftanlagen beurteilen und effiziente Schutzmaßnahmen entwickeln zu können, ist es wichtig, die Raum- und Habitatnutzung von Vögeln zu verstehen. Daher habe ich mich in meiner Forschung auf die Raum- und Habitatnutzung von Rotmilanen (*Milvus milvus*) auf verschiedenen zeitlichen und räumlichen Skalen konzentriert. Da der Verbreitungsschwerpunkt dieser Greifvögel in Deutschland liegt, haben wir eine besondere Verantwortung für den Schutz und Erhalt dieser Art, die auch eine Leitart für den Vogelschutz in Deutschland ist.

In meiner **ersten Studie** (Kapitel I) untersuchte ich den Einfluss der intrinsischen Treiber Geschlecht und Reproduktionstrieb auf die Raum- und Habitatnutzung von Rotmilanen und

ob sich deren Einfluss im Verlauf von drei verschiedenen Phasen innerhalb der Brutsaison verändert. Die Raumnutzung der Rotmilane hing von ihrem Geschlecht und ihrem Reproduktionsstatus ab. Die Aktionsräume der Weibchen während der Brutzeit waren deutlich kleiner als die der Männchen oder die in den anderen Phasen der Brutzeit. Damit bestätigten diese Ergebnisse, dass Rotmilane während der Brutzeit geschlechtsspezifische Rollen haben: die Weibchen bebrüten die Eier, während die Männchen sie mit Nahrung versorgen. Die Habitatnutzung veränderte sich im Verlauf der Brutzeit nicht. Unabhängig von den Phasen wurden Wälder weniger und Ackerland mehr genutzt als aufgrund ihrer Verfügbarkeit zu erwarten gewesen wäre, was die Bindung der Rotmilane an Agrarlandschaften bestätigt.

**Zweitens** (Kapitel II) untersuchte ich Unterschiede in der Raumnutzung zwischen den Geschlechtern im Verlauf der gesamten Brutsaison und deren zugrunde liegenden intrinsischen Treiber. Auch hier waren die geschlechtsspezifischen Rollen der Rotmilane die Hauptursache für die Unterschiede zwischen den Geschlechtern in den Flugdistanzen und den mittleren Entfernungen zu den Nestern. Sowohl die Flugdistanzen als auch die mittleren Entfernungen zum Nest waren bei den Weibchen während der Brutphase am geringsten und um die Zeit des Ausfliegens der

Jungvögel am größten, also dann, wenn auch der Nahrungsbedarf der großen Jungvögel am höchsten ist. Die Rolle der Männchen als Versorger hingegen wurde im unimodalen Kurvenverlauf der Flugdistanzen mit Maximum in der frühen Phase der Jungtieraufzucht, wenn das Weibchen beginnt bei der Nahrungssuche zu unterstützen, deutlich. Insgesamt war die Raumnutzung der Männchen gleichbleibender als die der Weibchen, was sich in der sich kaum ändernden mittleren Entfernung zu den Nestern zeigte und darauf hin-deutet, dass die Territorialität während der gesamten Brutsaison gegeben, jedoch bei den Männchen stärker ausgeprägt ist als bei den Weibchen.

**Drittens** analysierte ich den Einfluss des extrinsischen Treibers Windgeschwindigkeit auf die dreidimensionale Raumnutzung der Rotmilane und die daraus resultierenden Konsequenzen für deren Kollisionsrisiko mit Windkraftanlagen. Flugaktivität und Flughöhen von Rotmilanen ändern sich nichtlinear mit den auftretenden Windgeschwindigkeiten. Während Rotmilane bei eher ruhigen Windgeschwindigkeiten bis zu 2 m/s auf 10 m über Grund am wenigsten aktiv waren, nahm ihre Aktivität mit zunehmender Windgeschwindigkeit zu, bis sie bei Windgeschwindigkeiten von 4,8 m/s - 6,8 m/s ihr Maximum erreichte. Bis zu Windgeschwindigkeiten von 4,4 m/s waren die Flughöhen der Rotmilane konstant knapp über 100 m über Grund und damit sowohl auf Rotorhöhe von Windenergieanlagen, die im Studiengebiet zurzeit betrieben werden, aber auch auf Rotorhöhe zurzeit geplanter, höherer Windenergieanlagen. Bei Windgeschwindigkeiten zwischen 4,4 m/s - 6,0 m/s sanken die Flughöhen der Rotmilane um ~ 1 m pro 0,1 m/s und lagen im Mittel bei 83 m ± 8 m (Mittelwert ± SD). Der prozentuale Anteil der Flüge auf Rotorhöhe der betriebenen Windenergieanlagen im

Untersuchungsgebiet lag, abhängig von der individuellen Anlagenhöhe zwischen 32 % und 57 %. Da die derzeit geplanten Windenergieanlagen größer sind, sinkt der Prozentsatz der Flüge auf Rotorhöhe zukünftiger Windenergieanlagen auf 31% - 37%, was noch immer kein vernachlässigbarer Anteil ist. Daher werden Maßnahmen zur Verringerung des Kollisionsrisikos von Rotmilanen auch in Zukunft unverzichtbar bleiben, für die meine Studie einige vielversprechende Ansatzpunkte lieferte.

**Viertens** untersuchte ich die Unterschiede in der Raum- und Habitatnutzung zwischen Sommer- (Brutzeit) und Winterhabitaten (Nichtbrutzeit) der Rotmilane sowie deren zugrunde liegenden intrinsischen und extrinsischen Treiber. Die Aktionsräume und täglichen Flugdistanzen waren im Winter deutlich größer als im Sommer, was vermutlich darauf zurückzuführen ist, dass Territorialität im Sommer eine größere Rolle spielt als im Winter. Im Winter zeigten die Weibchen einen geringeren Raumbedarf als die Männchen, während im Sommer das Gegenteil der Fall war. Im Sommer spielte jedoch der Bruterfolg eine entscheidende Rolle: Bei erfolgreich brütenden Rotmilanen gab es keinen Unterschied zwischen den Geschlechtern, während bei nicht erfolgreich brütenden Rotmilanen die Weibchen einen größeren Aktionsraum hatten als die Männchen. Dieses Ergebnis deutet erneut auf ein ausgeprägteres Territorialverhalten von männlichen als von weiblichen Rotmilanen hin. Unabhängig von der Jahreszeit nahmen die Aktionsraumgrößen und die täglichen Flugdistanzen mit zunehmender Primärproduktivität (NDVI) zu, die als Indikator für die Ressourcenverfügbarkeit diente und von der bekannt ist die Raumnutzung von Vögeln zum Beispiel während des Zuges zu beeinflussen. Die Größe der Aktionsräume und die täglichen Flugdistanzen nahmen jedoch mit

## Zusammenfassung

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zunehmender Landschaftsvielfalt ab, was höchstwahrscheinlich auf die grobe Auflösung der verwendeten Landnutzungsdaten zurückzuführen ist. Die Habitatverfügbarkeit innerhalb der Aktionsräume unterschied sich deutlich zwischen den Jahreszeiten und ist durch die unterschiedlichen Landschaftsausstattungen in den Winter- und Sommerhabitaten zu erklären. Die Nutzung der Habitate unterschied sich ebenfalls zwischen den Jahreszeiten: Agrarlandschaften wurden im Winter stärker genutzt als im Sommer. Insgesamt konnte ich mit dieser Studie zeigen, dass sowohl intrinsische als auch extrinsische Treiber die Raumnutzung in den beiden Jahreszeiten beeinflussen. Daraus entstehen Unterschiede in der Raum- und der Habitatnutzung bei wandernden Greifvögeln zwischen ihren Sommer- und Winterhabitaten. Die Ergebnisse unterstreichen, wie wichtig es ist des gesamten Jahreszyklus

wandernder Arten für das Naturschutzmanagement zu berücksichtigen.

Zusammenfassend konnte ich mit meinen Studien zur Raum- und Habitatnutzung von Rotmilanen in verschiedenen zeitlichen und räumlichen Maßstäben wichtige intrinsische und extrinsische Treiber für deren Bewegung identifizieren. Daraus konnte ich Schlussfolgerungen ziehen, die einen wichtigen Beitrag zur Bewertung bestehender und der Entwicklung weiterer effizienter Schutzmaßnahmen leisten können. Durch effiziente Schutzmaßnahmen und die Rolle des Rotmilans als Flaggschiffart für den Vogelschutz können wir nicht nur unserer besonderen Verantwortung für den Schutz und den Erhalt des Rotmilans gerecht werden, sondern gleichzeitig viele andere Arten schützen, die durch die veränderten Umweltbedingungen gefährdet sind.

## Summary

Land use and climate change are the main causes of changing environmental conditions that lead to the decline of species worldwide. To mitigate the effects of climate change, the use of renewable energies, e.g. through the construction of wind turbines, has been strongly expanded in recent decades. However, wind turbines are regularly criticised because, among other things, they lead to habitat loss, barrier effects and collision risks, especially for highly mobile animals such as birds. Among birds, raptors particularly have an expansive space use. To assess the impact of changing environmental conditions and the additional risks posed by wind turbines, it is important to understand the space and habitat use of raptors. I focused my research on the space and habitat use of Red Kites (*Milvus milvus*) on different temporal and spatial scales. As the distribution centre of Red Kites is in Germany, we have a special responsibility for the preservation and conservation of this species, which is also a flagship species for bird conservation in Germany.

In my first study (**Chapter I**), I investigated the influence of the intrinsic drivers sex and reproductive instinct on the space and habitat use of Red Kites and whether their influence changes over the course of three different periods within the breeding season. The Red Kites' space use depends on their sex and reproductive instinct, as the activity ranges of females during the

incubation period were significantly smaller than those of males or those in the other periods of the breeding season. Thus, these results confirmed that Red Kites show reproductive role specialisation during the breeding season: females incubate the eggs while males provide them with food. Habitat use did not change during the breeding season. Regardless of the period, forests were used less and arable land more than would have been expected due to their availability, which confirms the Red Kites' attachment to agricultural landscapes.

Secondly (**Chapter II**), I investigated differences in space use between the sexes throughout the entire breeding season and their underlying intrinsic drivers. Again, the reproductive role specialisation of Red Kites were the main drivers of differences between the sexes in flight distances and mean distances to nests. Both flight distances and mean distances to the nest were lowest for females during the incubation period and highest around the fledging of the juveniles, i.e. when the food requirements of the large fledglings are also highest. The role of the males as providers, on the other hand, became visible in the unimodal curve of the flight distances with a maximum in the early phase of fledgling rearing, when females start to support the search for food. Overall, the males' space use was more constant than that of the females, which was also reflected

in the hardly changing mean distance to the nests and indicates that territoriality is present throughout the breeding season, but more pronounced in the male than in the female Red Kites.

Thirdly (**Chapter III**), I analysed the influence of the extrinsic driver wind speed on the three-dimensional space use of Red Kites and the resulting consequences for their collision risk with wind turbines. Flight activity and flight altitudes of Red Kites changed non-linearly with the occurring wind speeds. While Red Kites were least active at rather calm wind speeds up to 2 m/s at 10 m above ground, their activity increased with increasing wind speed until it reached its maximum at wind speeds of 4.8 m/s - 6.8 m/s. Up to wind speeds of 4.4 m/s, the flight altitudes of the Red Kites were constantly just above 100 m above ground and thus at rotor height of both, wind turbines currently operating, and currently planned, taller wind turbines in the study area. At wind speeds between 4.4 m/s - 6.0 m/s, the flight altitudes of the Red Kites decreased by  $\sim 1$  m per 0.1 m/s and ranged around  $83 \text{ m} \pm 8 \text{ m}$  (mean  $\pm$  SD). The percentage of flights at rotor height of the operating wind turbines in the study area was between 32 % and 57 %, depending on the individual turbine height. As currently planned wind turbines are taller, the percentage of flights at rotor height of future wind turbines might decrease to 31% - 37%, which is still not a negligible amount. Therefore, mitigation measures to reduce the collision risk of Red Kites will remain indispensable in the future, for which my study provided some promising starting points.

Fourthly (**Chapter IV**), I investigated the differences in space and habitat use between summer (breeding season) and winter (non-breeding season) habitats of the migratory Red Kites and their underlying intrinsic and extrinsic

drivers. Activity ranges and daily flight distances were significantly larger in winter than in summer, probably due to territoriality being a more pronounced driver for space use in summer than in winter. In winter, females showed a more restricted space use than males, while the opposite was true in summer. In summer, however, breeding success played a decisive role: there was no difference between the sexes in successfully breeding Red Kites, while in unsuccessfully breeding Red Kites, females had larger activity ranges than males. This result again indicates a more pronounced territoriality of male than female Red Kites. Regardless of the season, activity ranges and daily flight distances increased with increasing primary productivity (NDVI), which served as proxy for resource availability, which is known to influence birds' space use, for example during migration. However, the activity range sizes and daily flight distances decreased with increasing landscape diversity, most likely due to the coarse resolution of the land use data used in the study. Habitat availability within the activity ranges differed significantly between seasons and can be explained by the different landscape features in winter (south-western Europe) and summer habitats (central Europe). Habitat use also differed between seasons: Agricultural landscapes were used more in winter than in summer. Overall, I was able to show with this study that both intrinsic and extrinsic drivers influence the space use in the two seasons, which results in differences in space and habitat use between their summer and winter habitats. The results underline the importance of considering the entire annual cycle of migratory species for conservation management.

To conclude, during my studies on the space and habitat use of Red Kites at different temporal and spatial scales I identified important

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intrinsic and extrinsic drivers for their movement. From these, I was able to draw conclusions that might contribute to the evaluation of existing and the development of further efficient conservation measures. Through efficient conservation measures and the role of the Red Kite as a flagship

species for bird conservation, we can not only fulfil our special responsibility for the protection and conservation of the Red Kite, but at the same time protect many other species that are threatened by changing environmental conditions.

## General Introduction

Intensification of land use and climate change are the main causes for changing environmental conditions with severe consequences for biodiversity (IPBES, 2019; Sala et al., 2000). Due to associated habitat modifications and losses, species declines have been observed worldwide over the past decades (IPBES, 2019). Particularly visible is the decline of farmland bird species all over Europe over the past decades, caused by the intensification in agriculture, with its rising crop yields and increasing use of fertilizers (Donald et al., 2001; Lemoine et al., 2007; Sauerbrei et al., 2014). At the same time, the expansion of renewable energy utilization, e.g., through the construction of wind turbines, has been strongly promoted to mitigate the effects of climate change, (Leung & Yang, 2012; Ridley & Hill, 2018; Tabasum-Abbas et al., 2014). But wind turbines are regularly criticised for noise emission, visual disturbance, deforestation, and land erosion, leading to habitat loss, building barrier effects and an increased collision risk, especially regarding highly mobile animals such as bats and birds (Drewitt & Langston, 2006b; Garvin et al., 2011; Lehnert et al., 2014; Nazir et al., 2020; Voigt et al., 2015).

To assess the impact of land use change and wind turbines on birds, it is crucial to understand the movement patterns of these highly mobile animals. Movement is a fundamental process in animal ecology and the key for the accessibility

of adequate breeding and foraging habitats as well as the connectivity and gene flow between populations (Blouin-Demers & Weatherhead, 2002; López-López et al., 2014; Mueller & Fagan, 2008; Nathan et al., 2008; Tucker et al., 2019). It can be influenced by numerous intrinsic drivers such as internal states (hunger, reproductive instinct) and extrinsic drivers such as local abiotic (topography, wind speed) and biotic conditions (landscape composition, distribution of resources) (La Sorte et al., 2014; Nathan et al., 2008; Reid et al., 2015; Safi et al., 2013; Tucker et al., 2019). By understanding such intrinsic and extrinsic drivers, it is possible to gain crucial insights into the ecology of birds and ultimately derive approaches for efficient conservation measures.

Among birds, raptors have a rather extensive space use, due to their relatively large body size and the circumstance that they are often top predators (Peery, 2000). Like other top predators, raptors are used as flagship species for conservation approaches, as they are charismatic and often threatened by e.g., persecution, poisoning, human disturbance, and habitat loss or modifications (Martínez-Abraín et al., 2012; McClure et al., 2018; Sergio et al., 2008). Most raptors occur in low densities and have a relatively low reproductive rate, so the loss of an individual during the breeding season is particularly critical, as

it often means the loss of the entire brood, which ultimately can cause negative impact on population level (Garvin et al., 2011; Grünkorn et al., 2016; Kikuchi, 2008; Langston & Pullan, 2003; Péron et al., 2017). Consequently, it is particularly important to mitigate threats during this sensitive season, hence, to understand space and habitat use in the breeding season.

The space and habitat use of raptors during the breeding season is considerably influenced by intrinsic drivers, such as their reproductive instinct. Successive periods, such as territorial occupation, incubation, and chick-rearing, characterize the space use of raptors during breeding season, although often in different ways between the sexes (Brodin et al., 2003; Fernández et al., 2009; Hernández-Pliego et al., 2017; Mirski et al., 2021; Negro & Grande, 2001). For example, the reproductive role specialisation shown by many raptors, with mostly females incubate the eggs and males provide them with food, leads to a more restricted space use of females than males during the incubation period (Brodin et al., 2003; Hernández-Pliego et al., 2017; Mirski et al., 2021; Pfeiffer & Meyburg, 2015; Wesolowski, 1994). On the other hand, territoriality is often more pronounced in males than in females, which becomes visible, e.g., in the display flights performed mostly of males during territory occupation period or in a more consistent space use of males than of females throughout the breeding season (Campioni et al., 2013; Mirski et al., 2021; Negro & Grande, 2001). Such sex-specific differences in space-use might weaken, e.g., during chick rearing period, when both parental birds provide food with increasing age of the nestlings, or even disappear completely in the post-breeding period (Brodin et al., 2003; Hernández-Pliego et al., 2017; Pfeiffer & Meyburg, 2015).

Beside such intrinsic drivers, also extrinsic drivers, like local abiotic and biotic conditions affect the space and habitat use of raptors. Abiotic conditions, such as wind and topography, e.g., influence the flight speed, flight direction and flight altitude of birds, as they cause tail and side winds but also contribute to the occurrence of thermal and orographic uplifts in the landscape (Péron et al., 2017; Reid et al., 2015; Safi et al., 2013). Those are used especially by soaring raptors to move in three-dimensional space with relatively low energetic costs (Hanssen et al., 2020; Hedenström & Bone, 1993; Péron et al., 2017). Furthermore, biotic conditions, like the availability of key habitats, the landscape diversity, or the availability of resources have been linked to the space and habitat use of raptors, in the way that favourable conditions led to a more restricted space use (Klaassen et al., 2014; La Sorte et al., 2014; Mirski et al., 2021; Tews et al., 2004; Tucker et al., 2019).

Local conditions, especially the availability of resources, are also the main drivers for bird migration, which is performed by approximately 25% of the raptor species occurring in Africa and Eurasia (Goriup & Tucker, 2007; Klaassen et al., 2014; La Sorte et al., 2014). However, living in such distinct habitats might result in differences in the space and habitat use, as e.g., the landscape composition and the inter- and intraspecific competition for food differs, but also because important drivers for space use in breeding season, such as the reproductive instinct and territoriality play no or only a subordinate role during winter (Brodin et al., 2003; Heredia et al., 1991; Hernández-Pliego et al., 2017; Klaassen et al., 2014; Mirski et al., 2021; Schlaich et al., 2017; Trierweiler et al., 2013). The conditions during migration and in the winter habitats influence survival, fitness and presumably also the breeding success of an individual (Harrison et al., 2011; Marra et

al., 1998). Hence, it is particularly important but challenging to consider the entire annual cycle of a species to develop effective conservation measures.

Conservation measures of raptors are based on conventions (e.g., United Nations Convention on the Conservation of Migratory Species of Wild Animals), directives (e.g., Annex I of the European Birds Directive) and laws (e.g., Federal Nature Conservation Act) at different spatial and legal levels and reach from the designation of protected areas to preserve crucial habitats, to supplementary feeding to provide a safe and reliable food source (Cortés-Avizanda et al., 2010; L. M. González et al., 2006; McClure et al., 2018). In context of wind energy expansion, EU and national legislation demand environmental risk assessments with focus on collision-prone raptors to minimize the impact of wind turbines (Directive 2001/42/EC of the European Parliament and of the Council of 27 June 2001 on the Assessment of the Effects of Certain Plans and Programmes on the Environment, 2001; Directive 2014/52/EU of the European Parliament and of the Council of 16 April 2014 Amending Directive 2011/92/EU on the Assessment of the Effects of Certain Public and Private Projects on the Environment Text with EEA Relevance, 2014; UPGV; Verot, 2007). Based on these assessments, pre- and post-construction mitigation measures, such as an informed micro-siting of wind turbines or shutdown algorithms that regulate the operation times of wind turbines are implemented (Allison et al., 2019; de Lucas et al., 2012; Hanssen et al., 2020; Watson et al., 2018). Although much is already being done to resolve the threats highly mobile animals such as raptors face in times of land-use and climate change, there is still room for improvement.

## The study species: The Red Kite

In my thesis, I studied the space and habitat use of Red Kites, a highly discussed species in context of the expansion of wind energy utilization in Germany. The Red Kite is a diurnal, migratory raptor that is protected under Annex I of the European Birds Directive and subject to the Convention on the Conservation of Migratory Species of Wild Animals (Convention on the Conservation of Migratory Species of Wild Animals, 1979; Directive 2009/147/EC of the European Parliament and of the Council of 30 November 2009 on the Conservation of Wild Birds, 2009; Lyster, 1989). The IUCN classifies the Red Kite as "near threatened" (BirdLife International, 2020). Its distribution range spans from Portugal to the Baltic States and southern Sweden, hence it is endemic to Europe (BirdLife International, 2020; Hagemeyer & Blair, 1997). The population size is estimated to consist of 32,200 – 37,700 breeding pairs of which about 37% – 50% breed within Germany (14,000 – 16,000 breeding pairs), which implies the nation's special responsibility for the protection and conservation of this species (BirdLife International, 2020; Grüneberg & Karthäuser, 2019). Consequently, the Red Kite is also used as a flagship species for bird conservation in Germany and other European countries (Katzenberger, 2021; Sergio et al., 2021; Soriano-Redondo et al., 2017). Due to its size and its noticeably forked tail, it is easy to spot even for interested amateurs and thus helps to raise public awareness and support for its conservation (Aebischer, 2009; Katzenberger, 2021; Mebs & Schmidt-Rothmund, 2014).

Red Kites forage in open, agricultural landscapes, feeding opportunistically on small mammals, smaller birds, fish, amphibians, insects, and

carrion (Aebischer, 2009; BirdLife International, 2020; Bischofberger et al., 2019). They nest near forest edges or in rows of single trees, showing a high breeding-site fidelity (Aebischer, 2009; Gelpke & Hormann, 2010; Heuck et al., 2013). During breeding season, Red Kites show reproductive role specialization, as females incubate the clutch, while males provide the food. Only when the nestlings are about two to three weeks old, females help with the search for food (Aebischer, 2009; Pfeiffer & Meyburg, 2015). Territoriality of Red Kites persists the entire breeding season but lessens shortly before the start of migration, when they often spend the nights at communal roosts (Aebischer, 2009; Spatz et al., 2019). Such communal roosts are also used in the wintering habitats, where at least some Red Kites show site fidelity over several years, too (Pfeiffer & Meyburg, 2015, Spatz et al., in review).

The main threats to Red Kites are predominantly anthropogenic, including intensification of land use and associated changes in the environment, specific and unspecific poisoning as well as illegal hunting and netting (Berny & Gaillet, 2008; Farfán et al., 2009; Hegemann & Knüwer, 2005; Knott et al., 2009; Smart et al., 2010; Villafuerte et al., 1998). The expansion of wind energy is an additional significant threat for Red Kites, as they do not show avoidance behaviour, but rather use the fallow areas at the base of the turbines for foraging (Bergen, 2001; Gelpke & Hormann, 2010; Langgemach & Dürr, 2018; Mammen et al., 2013; Mammen et al., 2009). In relation to its occurrence, it is one of the most frequent collision victims at wind turbines in Germany, which are meanwhile the main cause of loss for Red Kites in Brandenburg (Länderarbeitsgemeinschaft der staatlichen Vogelschutzwarten in Deutschland LAG VSW, 2015; Langgemach & Dürr, 2018). Therefore, Red Kites

must be considered in environmental risk assessments when planning wind turbines. In a radius of currently 4,000 m around a planned wind turbine, the space use by Red Kites must be mapped in order to exclude an increased collision risk. Moreover, it is recommended to keep a minimum distance of 1,500 m between a planned turbine and the nest site of a Red Kite to prevent disturbance and to minimize the collision risk (Länderarbeitsgemeinschaft der staatlichen Vogelschutzwarten in Deutschland LAG VSW, 2015). Moreover, post-construction mitigation measures such as the implementation of shutdown-algorithms are used locally to further reduce the collision risk. Various additionally mitigation measures, such as designing the base of the turbine unattractively or management regimes for the agricultural- and grasslands surrounding the wind turbines have been developed to minimize the risk, too (Lerch et al., 2014; K. Mammen et al., 2013).

## Methodological approach

By using modern GPS-GSM-transmitters (Ornitela® OrniTrack E-25-B) I tracked the three-dimensional space use of Red Kites in the federal state of Hesse, Germany. The 21,115 km<sup>2</sup> state area of Hesse are characterized by low mountain ranges that span from 75 to 950 m a.s.l. Besides large anthropogenically shaped areas such as the Rhine-Main area, the state area is covered by approximately 42% agriculturally used landscapes, like the Wetterau, and about 40% by forests (Schaldach et al., 2016). With approximately 3% of the globally existing breeding pairs and local breeding densities reaching up to eleven breeding pairs per 100 km<sup>2</sup>, Hesse is part

of the distribution centre of Red Kites (Gelpke & Hormann, 2010; Grüneberg & Karthäuser, 2019; Stübing et al., 2010).

During field work in the years 2017 – 2021 in total 38 adult and 39 juvenile Red Kites were equipped with GPS-GSM-transmitters. To capture adult Red Kites, we spanned an 8 m long and 4 m tall mist net with a mesh size of 70 mm between two poles in proximity to the nest during the chick rearing period. Behind this net we placed a stuffed Eagle Owl (*Bubo bubo*), which is a predator of Red Kites and its nestlings. As adult Red Kites attack their predator to protect their nestlings, they become entangled in the net. The capture was monitored from a safe distance, depending on the terrain, in order not to disturb the activity but also to allow for a quick intervention.

To equip juvenile Red Kites with transmitters, it was necessary to climb up to the nest using tree-friendly rope climbing techniques. As the juveniles needed to be of appropriate age, size, and weight, careful preparations were necessary. The optimal age was five to six weeks, as the juveniles have reached a weight  $> 800$  g and show akinesia, when the tree climbing person accesses the nest. After a first visual health check at the nest, the juveniles were lowered to the ground using cloth bags and a rope. The following procedure was the same as for adult individuals.

Regardless the age, all birds were banded with an individual ring from the Institute of Avian Research (IAR), Vogelwarte Helgoland. We measured wing length and body mass and determined the sex of the adults via the presence of a brood patch. Additionally, we took salvia samples for e.g., a genetic sexing of the study individuals. Then we fitted the transmitters on the birds' backs using a backpack harness made of Teflon ribbon. The weight of transmitter and harness was approximately 23 g, which is less than 3% of the

body weight of an adult Red Kite, as recommended by Kenward (2001). While the adults were released immediately afterwards, the juveniles were brought up back to their nest by a tree-climber.

All necessary permits for these minimally invasive animal experiments were granted by the Hessian regional councils and the Federal Institute for the Protection of Birds.

The GPS-GSM-transmitters are designed to collect data over several years. For this purpose, they are equipped with an elevated solar-panel to recharge the batteries, an internal memory to save several thousands of data points, an integrated barometer to determine the flight altitude with an accuracy of a few metres, and a GSM-antenna to automatically send the recorded data to a server. The frequency of the data collection depends on the battery level and varies between five-minute to up to eight-hour intervals during the day only. By intersecting the gained movement data with environmental data such as land cover or weather data, it is possible to gain important knowledge about the space and habitat use of such highly mobile animals and its drivers.

## The aims of the studies

In my thesis, I studied the space and habitat use of Red Kites on different temporal and spatial scales. By identifying the intrinsic and extrinsic drivers for movement of this flagship species, I aimed on contributing to the development and evaluation of efficient conservation measures for this and other highly mobile animals that are threatened by today's changing environmental conditions.

My thesis consists of four chapters, each containing one study that is structured like a journal publication, including an introduction, details of methodology, results, and a discussion. As all necessary background information is given, the chapters I, II, III, and IV and can be read independently. Chapters I and II have been published in scientific journals in German language with additional abstracts in English. Chapter III is currently being prepared for submission and chapter IV is under review in a scientific journal in English language.

The aim for Chapter I was to investigate the space and habitat use of reproductive Red Kites in different periods within the breeding season. I focused on the periods, territory occupation, incubation and chick rearing to study the influence of these periods and sex on the activity range sizes of twelve adult individuals (seven males and five females). Moreover, I compared the mean land use composition within their activity ranges in the different periods to the land use composition within the entire study region as reference area.

The aim of Chapter II was to identify differences in the space use of adult Red Kites between the sexes over the entire breeding season and to investigate the underlying intrinsic drivers. To do so, I calculated the flight distances and the mean distance to the nest of 13 adult Red Kites (eight males and five females) pentad-wise across the entire breeding season (March – September). After assigning these pentads to one of five periods within breeding season, I analysed the flight distances and the mean distances to the nests over time and in relation to sex.

The aim of Chapter III was to investigate how the three-dimensional space use of Red Kites during breeding season is influenced by local abiotic conditions, namely wind speed. Based on

data of 26 adult Red Kites over three years, I analysed flight activity and flight altitude of Red Kites in relation to the occurring wind speeds. I chose the space use variables flight activity and flight altitude, as they are important for assessing the collision risk of highly mobile animals with wind turbines. Thus, I also determined the proportion of flights that take place at critical heights regarding collisions with rotors of wind turbines.

As Red Kites are mostly migratory, the aim of Chapter IV was to compare the space and habitat use of Red Kites between summer and winter habitats and to assess the influence of intrinsic and extrinsic drivers in these two seasons. I calculated the activity range sizes and daily flight distances and linked them to the sex, the season, the primary productivity (NDVI, as proxy for resource availability) and the landscape diversity. Additionally, I assessed differences in the availability and in the use of five aggregated land use types within the activity ranges of the Red Kites between summer and winter habitats.

## **Chapter I – Zwischen Revierbildung, Brutphase und Jungenaufzucht: Aktionsräume und Habitatnutzung adulter Rotmilane *Milvus milvus* in Hessen**

Theresa Spatz, Sascha Rösner, Dana G. Schabo, Christian Gelpke, Nina Farwig (2019). Ornithologische Mitteilungen 71 (9/10), 1-8.

### **Zusammenfassung**

Die Habitatqualität ist einer der größten Einflussfaktoren für den Erfolg wildlebender Tierarten. Arten mit großen Aktionsräumen, wie etwa Greifvögel, sind durch die Veränderungen in der Qualität von Nahrungshabitaten und anderen Ressourcen stark in ihrer Reproduktion, ihrem Überleben und ihrer Verbreitung beeinflusst. Der Rotmilan *Milvus milvus* ist in seiner Verbreitung auf Europa begrenzt und nutzt bevorzugt halboffene und offene Landschaften. Zeitliche und räumliche Bewegungsdaten 12 telemetrierter und brütender Rotmilane wurden hinsichtlich der Habitatnutzung und der Aktionsräume in Hessen im Detail untersucht. Die vorliegende Arbeit vermittelt in einer ersten Analyse einen Überblick zu den genutzten Flächen und Landnutzungsformen von 12 adulten Rotmilanen. Die Ergebnisse basieren auf der Verwendung von räumlich und zeitlich hochauflösten Bewegungsdaten und erlauben Aussagen über (I) die Aktivitätsraumgrößen während drei verschiedener Brutzeitphasen: (a) der Revierbildung, (b) der Brutphase und (c) der Jungtieraufzucht. Zudem konnte mit Hilfe detaillierter Landnutzungsdaten (II) die Zusammensetzung der Aktionsräume während dieser drei Phasen analysiert werden. Die Aktionsräume reichten von minimal 0,07 km<sup>2</sup> bis 23,2 km<sup>2</sup> bei den Weibchen ( $n = 5$ ) und minimal 4,5 km<sup>2</sup> bis max. 19,8 km<sup>2</sup> bei den Männchen ( $n = 7$ ). Die Analyse ergab einen signifikanten Effekt der Interaktion von Geschlecht und Brutzeitphase auf die Aktionsraumgröße. Dieser Effekt ist auf die Brutphase der Weibchen, in der diese signifikant kleinere Aktionsräume nutzten als die Männchen bzw. als während der anderen Brutzeitphasen, zurückzuführen. Ursächlich hierfür ist das ausschließliche Bebrüten der Gelege durch die Weibchen. Im direkten Vergleich mit Hessen als Referenzgebiet wiesen die Aktionsräume der Rotmilane einen deutlich geringen Flächenanteil an Wald sowie dörflichen Strukturen, jedoch einen erhöhten Anteil an Agrarland auf. Dieses Ergebnis unterstreicht das Wissen um die Habitatpräferenz der Rotmilane für offene Kulturlandschaften.

## Abstract

The quality of breeding habitats is one of the main drivers for the distribution, the reproduction and the survival of wildlife. Due to their large activity ranges, highly mobile species like birds of prey are most likely affected by alteration of habitats, their composition and quality. In a survey focusing on the movement ecology of breeding Red Kites *Milvus milvus* in Hesse (Germany), we equipped 20 adult birds with GPS-GSM transmitters to unleash habitat use over the breeding season in more detail. In a first step, we used the movement data of twelve birds i) to investigate the size of the activity ranges of this European raptor in relation to three different periods of the breeding season (a) territory occupancy, b) incubation, c) chick rearing) and sexes. Furthermore, we used detailed land use data to ii) analyze the land use composition within these activity ranges. The activity range sizes ranged between 0.07 km<sup>2</sup> and 23.2 km<sup>2</sup> for females (n=5) and between 4.5 km<sup>2</sup> and 19.8 km<sup>2</sup> for male Red Kites (n=7). We found an interactive effect of sex and period of breeding seasons on the activity range size. This effect was driven by the incubation period of female Red Kites, during which they used significant smaller activity ranges (0.07 km<sup>2</sup> – 0.3 km<sup>2</sup>) than male birds or in any other period of the breeding season respectively. The analysis of the land use composition showed that the activity ranges of the twelve GPS-tagged birds consisted of significantly smaller amounts of forest and settlements but higher amounts of arable land. Our findings subscribe the broadly accepted knowledge about i) the very restricted movement of female birds during the incubation period as only she is breeding, and ii) that Red Kites prefer open cultivated landscapes.

## Einleitung

Die Intensivierung der Landnutzung ist einer der größten Treiber für den Verlust von Biodiversität (Sala et al., 2000). Insbesondere großräumig agierende Arten – wie etwa Greifvögel – sind durch die Veränderungen in der Qualität von Nahrungshabiten und anderer Ressourcen stark in ihrer Reproduktion, ihrem Überleben und ihrer Verbreitung beeinflusst. Die Bestände vieler Greifvögel, wie etwa dem Rotmilan, nehmen in durch den Menschen dominierten Lebensräumen ab (Aebischer, 2009; Mebs & Schmidt-Rothmund, 2014; Seoane et al., 2003). Etwa die Hälfte des weltweiten Rotmilanbestandes brütet in Deutschland (BirdLife International, 2018), sodass eine entsprechende Verantwortung zum europaweiten Erhalt der Population gegeben ist. Daher ist es essentiell zu verstehen, wie

Landnutzungsintensivierungen die Habitatnutzung des Rotmilans beeinträchtigen.

Diverse Arbeiten verweisen auf Bestandsrückgänge der Rotmilane anhand rückläufiger Reproduktionswerte (Gelpke & Hormann, 2010; Seoane et al., 2003). Die Identifizierung der Ursachen für die Bestandsrückgänge ist komplex. Die zur Verfügung stehenden Bruterfolgs- und Reproduktionsdaten hängen von vielfältigen Faktoren, etwa der umgebenden Landschaft, deren Zusammensetzung, oder den Bewirtschaftungsformen ab. Eine veränderte Raumnutzung und damit Hinweise auf potentiell veränderte Habitatqualitäten fehlen.

Herausfordernd ist bei der Analyse der kausalen Zusammenhänge zwischen Habitatqualität und Raumnutzung, dass sich die

Habitatnutzung durch die Rotmilane im Jahresverlauf ändert (Spatz et al., 2019). Der Rotmilan ist ein Zugvogel (Aebischer, 2009; Mebs & Schmidt-Rothmund, 2014), der unterschiedliche Landschaften und Ökosysteme im Sommer und Winterhalbjahr nutzt. Doch auch während des Sommerhalbjahres können unterschiedliche Brutzeitphasen abgegrenzt werden. Direkt nach der Rückkehr aus dem Überwinterungsgebiet findet die Balz und die Revierbildung statt, in der sich die Brutpaare wiederfinden oder neu bilden und einen Horst besetzen bzw. bauen (Mebs & Schmidt-Rothmund, 2014). Es folgt die Brutzeit, in der das Gelege vom weiblichen Tier bebrütet wird, während das Männchen dieses mit Nahrung versorgt. Zur Zeit der Jungtieraufzucht sind beide Elterntiere aktiv, um den Nachwuchs zu versorgen, der sich in der anschließenden Phase, der Bettelflugphase, meist noch im elterlichen Revier aufhält. Die letzte Phase vor dem Winterzug kann als „Nachbrutzeit“ bezeichnet werden. Während dieser halten sich Rotmilane noch immer in ihren Revieren auf, bis sie sich im Spätsommer abendlächlich an Gemeinschaftsschlafplätzen zusammenfinden (Aebischer, 2009; Mebs & Schmidt-Rothmund, 2014).

Um die komplexe Habitatnutzung im Jahresverlauf erfassen zu können, hat sich der Einsatz von GPS-GSM-Sendern bewährt. Diese ermöglichen eine zeitlich und räumlich hochaufgelöste Erfassung der Bewegungen. Mittels solarunterstützter Stromversorgung kann dies über mehrere Jahre erfolgen. Durch die Kombination von Bewegungs- und Landnutzungsdaten lassen sich Landnutzungstypen identifizieren, die von Rotmilanen während der verschiedenen Brutzeitphasen vorrangig genutzt oder etwa gemieden werden. Dieses Wissen ist essentiell, um etwa Managementmaßnahmen in Form von

verbesserten Habitatqualitäten zielsicher in Schutzstrategien für die Greifvögel zu integrieren.

Daher wurden in der vorliegenden Arbeit zur Bewegungsökologie der Rotmilane in einem ersten Ansatz GPS-basierte räumliche und zeitliche Bewegungsdaten mit den entsprechenden Landnutzungsformen verschnitten. Dabei standen Fragen zu den vorrangig genutzten Habitattypen und die Größe der Aktionsräume beider Geschlechter im Vordergrund. Werden bestimmte Landnutzungstypen im Vergleich zu der mittleren Ausstattung in Hessen von den Rotmilanen bevorzugt genutzt? Unterscheiden sich die Aktionsräume der Geschlechter zwischen den Phasen der Brutzeit?

## **Material, Methoden und Datengrundlage**

### **Untersuchungsgebiet**

Die vorliegende Studie erstreckt sich über das Bundesland Hessen (Abb. 1). Mit Ausnahme der menschlichen Ballungszentren im Rhein-Main-Gebiet (Frankfurt, Darmstadt, Wiesbaden) besiedeln Rotmilane Hessen nahezu flächendeckend (Stübing et al., 2010). Für den Zeitraum von 2010 - 2014 geht man in diesem Bundesland von 1.000 - 1.300 Brutpaaren aus (Grüneberg & Karthäuser, 2019; Stübing et al., 2010). Dabei wurden in Nordhessen regionale Bruttoden von acht bis elf Brutpaaren pro 100 km<sup>2</sup> erreicht (Gelpke & Hormann, 2010). Hessen ist großflächig von Wäldern, aber auch von stark agrarwirtschaftlich genutzten Offenländern geprägt. Beides sind wichtige Landnutzungstypen für Rotmilane für die Brut bzw. die Jagd (Aebischer, 2009;

Heuck et al., 2013). Die Zusammensetzung der gesamten Landesfläche Hessens aus acht verschiedenen Landnutzungstypen (siehe Kap. 2.2) diente in dieser Studie als Referenz für die vergleichenden Analysen der Aktionsraum-Zusammensetzung brütender Rotmilane.

Die untersuchten Brutpaare wurden aus einem Datensatz aller hessenweit bekannten Brutstandorte ausgewählt, um die diverse Ausstattung der hessischen Naturräume mit u.a. unterschiedlichen Anteilen von geeigneten und nicht-geeigneten Jagdhabitaten möglichst repräsentativ abzubilden.

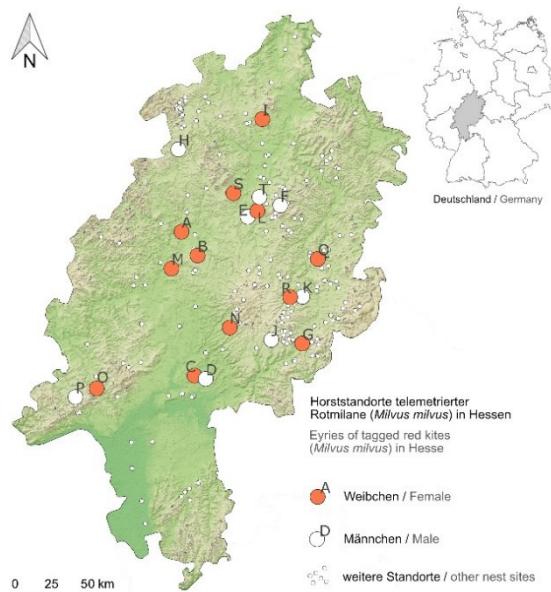
### Landnutzungsdaten

Die Zusammensetzung der Landnutzung in den Aktionsräumen der Rotmilane sowie der Referenzfläche Hessen wurde anhand des Digitalen Basis-Landschaftsmodells (ATKIS® Basis-DLM) der Hessischen Verwaltung für Bodenmanagement und Geoinformation analysiert. Dieses basiert auf der Klassifizierung der Geländeoberfläche mittels Orthophotos (1:5.000) in 64 verschiedene Landnutzungstypen (Hessische Verwaltung für Bodenmanagement und Geoinformation, 2016). Für die vorliegende Analyse wurden diese in acht übergeordnete Landnutzungstypen zusammen-gefasst: Wald, Ackerland, Grünland, anderes Offenland, Gehölze, Dörfer, Gewässer, und „übrige Landnutzungstypen“.

### Besonderung

Während der Jungtieraufzucht 2017 wurde an insgesamt 20 verschiedenen Rotmilanhorsten je einer der beiden Brutvögel in Horstnähe mittels der Dho-Gaza Methode (Bloom et al., 2007) gefangen. Jeder dieser Vögel wurde be ringt, vermessen und dessen Geschlecht anhand der Größe, des Gewichts sowie des

**Abb. 1:** Übersichtskarte (Relief) Hessens mit



Standorten der 20 untersuchten Rotmilan *Milvus milvus* – Brutpaare (A-T). Die telemetrierten Tiere ( $N=20$ ) sind nach Geschlecht differenziert (orange = Weibchen, weiß = Männchen).

*Distribution of Red Kite Milvus milvus nests of birds equipped with GPS-GSM devices ( $N=20$ ) in the federal state of Hesse, Germany. Positions and sex of the tagged birds of each breeding pair (orange = females, white = male) are given.*

Reliefkarte: © OpenStreetMap.

Vorhandenseins eines Brutflecks bestimmt. Im Anschluss wurde mit Hilfe eines Rucksack-Geschirrs aus Teflon-Band ein solarbetriebener GPS-GSM-Sender der Firma Ornitela® angebracht. Dieser Sender wog - inklusive des Geschirrs - etwa 23 g, womit die Kenward (2001) (2001) maximal empfohlenen 3% des Körpergewichts nicht überschritten wurden. Abhängig vom Akkustand der Sender wurde nach einem automatisierten Algorithmus die Position des Vogels alle fünf, 20 oder 60 Minuten erfasst. So konnte die Raumnutzung der Tiere über den gesamten Jahresverlauf mit relativ hoher räumlicher Auflösung erfasst werden. Die

Datenübertragung auf einen Server erfolgte täglich über das GSM-Mobilfunknetz.

### Auswertung der Bewegungsdaten

Die mittels GPS-GSM-Sendern erfassten Bewegungsdaten wurden vor der Analyse bereinigt. Aus dem Datensatz entfernt wurden Doppelungen (gleiche Zeitstempel und gleiche Position), alle Null-Koordinaten (kein GPS-Signal empfangen) sowie alle Positionen, an denen Geschwindigkeiten über 50 km/h gemessen wurden (fehlerhafte GPS-Erfassung; Ausreißer). In die Ergebnisse dieser Studie flossen somit insgesamt 237.629 Datenpunkte von 12 adulten Rotmilanen (5 Männchen, 7 Weibchen) aus den Monaten März 2018 bis Juli 2018 ein. Aus diesen wurden die Aktionsräume der einzelnen Tiere während drei verschiedener Brutzeitphasen berechnet: (a) der Revierbildung, (b) der Brutzeit und der (c) Jungtieraufzucht. Die zeitliche Abgrenzung dieser Phasen erfolgte mithilfe von Jungtier-Daten, die im Rahmen eines erweiterten Projektes erhoben wurden. Die Jungtiere der telemetrierten Altvögel wurden während Nestlingsphase im Juni 2018 im Horst beringt und besendert. Anhand der gemessenen Flügellänge und der Formel nach U. Mammen & Stubbe, 1995 wurde das Alter der Jungtiere bestimmt. Mit diesen Daten wurden der Schlupftermin sowie der Brutbeginn, ausgehend von einer durchschnittlichen Bruttärtige von 34 Tagen bestimmt (Mammen & Stubbe, 1995). Lagen keine Jungtierdaten zu einem Altvogel vor, wurde der mittlere Brutbeginn (14.04.2018) bzw. mittlere Schlupftermin (18.05.2018) über alle erhobenen Jungtierdaten der anderen Brutpaare verwendet. Insbesondere bei den fünf weiblichen Tieren konnte der Brutbeginn anhand der Bewegungsdaten zusätzlich verifiziert werden. Die Phase der Jungtieraufzucht endete zum Zeitpunkt des Ausfliegens der

Jungtiere, was aus den erfassten Jungtierbewegungsdaten abgelesen werden konnte, oder zum Zeitpunkt des Verlusts der Brut (Ursache in allen Fällen Prädation).

Zur Berechnung der Aktionsräume wurden autokorrelierte Kernel-Dichte-Schätzungen (AKDE) mit dem Paket ‚ctmm‘ (Calabrese et al., 2016) der Statistiksoftware R (R Core Team, 2013) durchgeführt. Diese Methode berücksichtigt die inhärente Autokorrelation der Bewegungsdaten. Die Anteile der Landnutzungstypen innerhalb der Rotmilan-Aktionsräume wurden in Relation zur Referenzfläche Hessen gesetzt, um z.B. etwaig präferierte Landnutzungstypen zu identifizieren. Die Ermittlung der Landnutzungstypen aus den ATKIS-Daten erfolgte mit Hilfe des ‚raster‘-Pakets (Hijmans, 2016) in R. Zur Ermittlung etwaiger signifikanter Unterschiede zwischen mehreren gepaarten Parametern wurden Friedman-Tests benutzt. Alle Abbildungen wurden ebenfalls mittels R und dem Paket ‚ggplot2‘ (Wickham, 2016) erstellt.

### Ergebnisse

Von den während der Jungtieraufzucht 2017 ursprünglich besenderten 20 Rotmilanen sind im Frühjahr 2018 insgesamt 19 aus dem Überwinterungsgebiet nach Hessen zurückgekehrt. Durch Verluste (Verkehrsunfall, natürliche Todesursachen, Senderausfall) oder frühzeitigen Brutabbruch lagen nur von zwölf Tieren vollständige Datensätze über alle drei Brutphasen (März bis Juli) vor. Dabei entfielen fünf Datensätze auf weibliche und sieben auf männliche Tiere, deren Brutreviere über diverse Naturräume Hessens verteilt sind (Abb. 1).

Die Größe, der mittels AKDE berechneten Aktionsräume schwankte über alle Phasen der Brutzeit stark; bei den weiblichen Rotmilanen schwankte die Größe zwischen 0,07 km<sup>2</sup> und 23,2 km<sup>2</sup> und bei den männlichen zwischen 4,5 km<sup>2</sup> und 19,8 km<sup>2</sup> (Tab. 1).

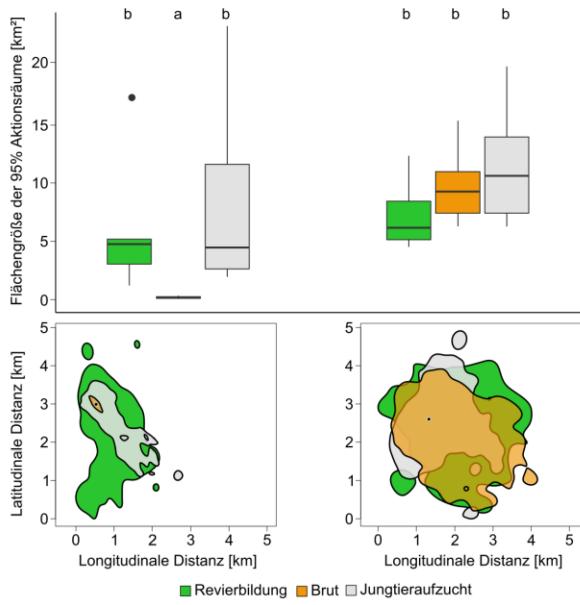
**Tab. 1:** Aktionsraumgrößen [km<sup>2</sup>] von zwölf adulten Rotmilanen *Milvus milvus* während drei verschiedener Brutzeitphasen (Revierbildung: grün, Brutzeit: orange und Jungtieraufzucht: grau) und nach Geschlechtern getrennt. Die Flächenberechnungen basieren auf autokorrelierten Kernel-Dichte Schätzungen (AKDE) aus über 200.000 Datenpunkten.

*Activity range sizes of female (left, n=5) and male (right, n=7) GPS-tagged Red Kites Milvus milvus. Data are provided from the three breeding periods: Territory occupancy (green), breeding (orange) and rearing of chicks (grey).*

	Aktionsraumgrößen [km <sup>2</sup> ] Weibchen (n=5)	Aktionsraumgrößen [km <sup>2</sup> ] Männchen (n=7)
Revierbildung	1,2 – 16,9	4,5 – 12,2
Brutzeit	0,07 – 0,3	6,2 – 15,2
Jungentieraufzucht	1,9 – 23,2	6,2 – 19,8

Die Varianzanalyse der Aktionsraumgrößen ergab einen signifikanten Effekt der Interaktion von Geschlecht und Brutzeitphase auf die Aktionsraumgrößen ( $F_{5,30}=8.66$ ,  $p<0.001$ ,  $R^2=0.52$ ). Ein Post-hoc Tukey-Test identifizierte die Brutphase der Weibchen als Treiber für diesen Zusammenhang, da sich nur diese Phase signifikant von allen Phasen der Männchen und den anderen

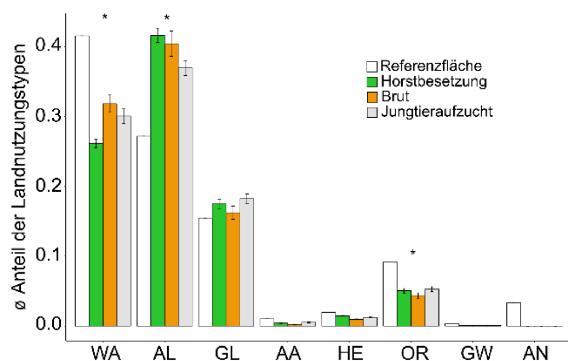
Brutzeitphasen (Revierbildung und Jungtieraufzucht) der Weibchen unterschied (Abb. 2).



**Abb. 2:** Oben: Signifikanter Effekt der Interaktion von Geschlecht und der Brutphase auf die Aktionsraumgrößen ( $F_{5,30}=8.66$ ,  $p<0.001$ ,  $R^2=0.52$ ): Die Aktionsraumgrößen (in km<sup>2</sup>) unterschieden sich signifikant zwischen den Brutphasen bei den Weibchen, aber nicht bei den Männchen (Friedman-Tests: ♀♀:  $X^2=7.60$ ,  $df=2$ ,  $p<0.05$ ; ♂♂:  $X^2=4.57$ ,  $df=2$ ,  $p=0.10$ ). Unten: Aktionsraum-Muster je eines repräsentativen weiblichen (links) und männlichen (rechts) Rotmilans während der drei Brutphasen: Die Aktionsraumgrößen unterschieden sich stärker bei den Weibchen als bei den Männchen.

*Top: Significant interactive effect between sex and breeding period: Activity range (AR) sizes differed significantly between phases in females but not in males (Friedman-Tests: ♀♀:  $X^2=7.60$ ,  $df=2$ ,  $p<0.05$ ; ♂♂:  $X^2=4.57$ ,  $df=2$ ,  $p=0.10$ ). Bottom: AR patterns of a representative female (left) and male (right) Red Kite during three breeding periods: Their sizes changed stronger for females than for males.*

Die Habitatzusammensetzung innerhalb der Aktionsräume der telemetrierten Rotmilane wurde mit den Daten der Habitatzusammensetzung über die Gesamtfläche Hessens als Referenzfläche verglichen. Die Aktionsräume der Rotmilane wiesen während allen drei Phasen signifikant geringere Waldanteile (WA, Abb. 3) sowie geringere Anteile dörflicher Strukturen (OR, Abb. 3), aber einen erhöhten Anteil Ackerland (AL, Abb. 3) auf ( $F_{8,280}=144.4$ ,  $p<0.001$ ,  $R^2=0.80$ , s. Abb. 3).



**Abb. 3:** Die Landnutzungsformen innerhalb der Aktionsräume der Rotmilane unterschieden sich von der Referenzfläche ( $F_{8,280}=144.4$ ,  $p<0.001$ ,  $R^2=0.80$ ): Sie zeigten geringere Anteile an Wald- und Dorfstrukturen sowie höhere Anteile von Agrarland. WA = Wald, AL = Agrarland, GL = Grünland, AA = anderes Agrarland, HE = Hecken/Gehölze, OR = Ortschaften, GW = Gewässer, AN = andere Landnutzungstypen.

*The land use composition within the Red Kites' AR differed from that in the reference area, showing lower amounts of forest and villages and higher amounts of arable land. WA = forest, AL = arable land, GL = grassland, AA = other arable land, HE = groves, OR = villages, GW = water bodies, AN = other land use types.*

## Diskussion

Zwölf der ursprünglich 20 telemetrierten Rotmilane haben im Jahr 2018 gebrütet. Mit Hilfe der GPS-GSM Sender wurden umfangreiche und hoch aufgelöste Daten zur Bewegungsökologie geliefert. Erste Analysen der Aktionsräume hinsichtlich deren Größe und deren Zusammensetzung aus acht verschiedenen Landnutzungsklassen (ATKIS-Daten) zeigten grundlegende Unterschiede im Vergleich zu den landesweiten Landnutzungsräumen bzw. zwischen den Geschlechtern.

Weibliche Rotmilane zeigten während der Brutzeit signifikant kleinere Aktionsräume als männliche Individuen. Abgesehen davon gab es keinen Unterschied in der Größe der genutzten Fläche zwischen den Geschlechtern oder den drei Brutzeitphasen Revierbildung, Brutzeit und Jungtieraufzucht. Ursache hierfür ist vermutlich, dass beim Rotmilan ausschließlich die weiblichen Tiere das Ausbrüten des Geleges übernehmen (Aebischer, 2009; Mebs & Schmidt-Rothmund, 2014). Auch entsprechen unsere Ergebnisse weitgehend denen von Nachtigall (2008), der mittels des Minimum Convex Polygon Ansatzes (MCP) und einer Kombination aus Bodentelemetrie und Sichtbeobachtungen zeigte, dass Weibchen tendenziell kleinere Aktionsräume nutzen als Männchen. Ein signifikanter Unterschied zwischen den Brutphasen konnte in unserer Studie jedoch nicht festgestellt werden (Walz, 2008) hingegen verweist durch reine Sichtbeobachtungen auf kleinere Aktionsräume der Weibchen während der Balzzeit. Im Gegensatz dazu konnte in unserer Studie trotz zeitlich und räumlich hochauflöster Daten in der Revierbildungsphase kein Geschlechterunterschied in der Größe der Aktionsräume nachgewiesen werden.

Hinsichtlich der Zusammensetzung von Landnutzungsklassen innerhalb der real genutzten Aktionsräume ergaben sich geringere Anteile an Wald sowie an dörflichen Strukturen als im Mittel in Hessen zu erwarten wäre. Zwar brüten Rotmilane in Hessen bevorzugt im Wald (oder in Baumreihen), nutzen aber die Offenländer als Jagdhabitat, welches sich in einem signifikant erhöhten Flächenanteilen von Agrarland in den Aktionsräumen zeigte. Dies entspricht der Bedeutung dieser Landnutzungstypen für den Rotmilan, der als typische Art des Offenlandes gilt und dort entsprechend der Nahrungssuche nachgeht (z.B. Aebischer, 2009).

Unsere Ergebnisse tragen dazu bei die zeitlich und räumlich komplexen Habitatnutzungsmuster dieser hochmobilen Tiere zu unterschiedlichen Phasen im Brutgebiet zu verstehen. Da juvenile Rotmilane in Mitteleuropa nicht unmittelbar nach dem Ausfliegen ihre elterlichen Reviere verlassen (siehe u.a. Mebs & Schmidt-Rothmund, 2014), soll in einem erweiterten Ansatz die Analyse um eine vierte Phase, die Bettelflugphase, ergänzt werden. Die Habitatemignung und -nutzung in dieser Zeit ist für die Fitness der Altvögel sowie das Überleben der Jungtiere essentiell. Eine veränderte Habitatqualität kann hierbei für die Regeneration der adulten Tiere nach der Brutphase essentiell sein und den physischen Zustand für die anschließende Zugzeit beeinflussen. Auch die Überlebenswahrscheinlichkeit der Jungtiere wird durch die Verfügbarkeit und Qualität geeigneter Habitate beeinflusst.

Zusätzlich werden derzeit Bewegungsmuster analysiert, um den Einfluss diverser Landnutzungstypen bspw. auf den Bruterfolg zu untersuchen sowie um essentielle Nahrungs- oder Bruthabitate zu identifizieren und zu charakterisieren. Auf diese Art werden wir dazu beitragen den Schutz und das Management von

Brut- und Jagdhabitaten der Rotmilane zu verbessern und der besonderen Verantwortung für den Erhalt dieser Greifvogelart gerecht zu werden.

## Danksagung

Die vorliegende Studie ist Teil eines Forschungsprojektes an der Philipps-Universität Marburg. Die Arbeiten werden durch ein Promotionsstipendium der Deutschen Bundesstiftung Umwelt (DBU) für Theresa Spatz gefördert. Die Genehmigung zur Besenderung der Tiere gemäß §8 Abs. 1 des Tierschutzgesetzes (TierSchG) wurde durch das Regierungspräsidium Gießen (gültig auch für RP Kassel, RP Darmstadt) ausgestellt. Das Projekt genießt die breite fachliche Unterstützung des Institutes für Vogelforschung (IfV) (O. Geiter), sowie der Staatlichen Vogelschutzwarte für Hessen, Rheinland-Pfalz und das Saarland (G. Bauschmann, M. Hormann). Die intensiven Feldarbeiten werden durch HessenForst, die Hessische Gesellschaft für Ornithologie und Naturschutz (HGON e.V.), dem NABU Hessen (M. Sommerhage), sowie zahlreiche Einzelpersonen unterstützt.

In Vorbereitung für ein Folgeprojekt u.a. zu Mortalitätsursachen juveniler Rotmilane haben wir im Sommer 2018 Jungtiere der hier untersuchten Altvögel beringt und besendert. Vielen Dank an R. Raab, P. Spakovszky für die Kooperation und die gemeinsamen Feld- und Kletterarbeiten.

Danke an T. Pfeiffer für die gemeinschaftlichen Kletteraktionen und die angeregten Diskussionen rund um die Bettelflugphase der Milane.

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Ohne die engagierte Hilfe der o.g. Institutionen und Personen wäre ein effizientes Arbeiten auf einer derart großen Untersuchungsfläche nicht möglich. Vielen Dank dafür.



## **Chapter II – Raumnutzung des Rotmilans *Milvus milvus* im Verlauf der Brutzeit: Eine Analyse mittels GPS-basierter Bewegungsdaten**

Theresa Spatz, Dana G. Schabo, Nina Farwig, Sascha Rösner (2019). Vogelwelt 139, 161-169.

### **Zusammenfassung**

Die Raumnutzung zahlreicher Vogelarten variiert auf unterschiedlichen räumlichen Skalen über den gesamten Jahresverlauf. Das Wissen um die realen Raumnutzungs- und Bewegungsmuster in Relation zum Brutplatz stellt dabei essentielle Informationen zum Verständnis über die Verteilung von Arten in Raum und Zeit. Kleine, leichte und hochauflösende Geräte zur GPS-Telemetrie erlauben es heute auch während der Brutzeit die komplexen Bewegungsmuster wildlebender Vögel zu bestimmen und zu analysieren. In der vorliegenden Studie haben wir die Raumnutzung von 13 mittels GPS-GSM-Einheiten telemetrierten adulten Rotmilanen in Relation zum Brutplatz von März bis September in Hessen analysiert. Dabei war die Evaluation folgender Inhalte von Bedeutung: Etwaige geschlechtsspezifische Unterschiede in der Raumnutzung, saisonale Variation der Bewegungsmuster sowie die Raumnutzung über die gesamte Spanne der Brutzeit. Unsere Ergebnisse zeigten signifikante Unterschiede sowohl in den zurückgelegten Distanzen als auch den mittleren Entfernungen zum Horststandort zwischen beiden Geschlechtern und entlang der zeitlichen Achse auf. Die Flugmuster der weiblichen Rotmilane zeigte einen phasischen Verlauf. Auf der Zeitachse von Mitte März an war zunächst die starke Abnahme der geflogenen Distanzen der Weibchen auffällig. Das Minimum wurde zwischen Mitte April bis Mitte Mai erreicht ( $Md_{P7-P14} = 6,2 \text{ km}$ ,  $Q^{0.25}_{P7-P14} = 4,4 \text{ km}$ ,  $Q^{0.75}_{P7-P14} = 8,0 \text{ km}$ ). Ab Ende Mai nahmen dann die Flugdistanzen wieder zu, bis schließlich in der ersten Juli-Hälfte das Maximum erreicht wurde ( $Md_{P23-P26} = 83,5 \text{ km}$ ,  $Q^{0.25}_{P23-P26} = 46,5 \text{ km}$ ,  $Q^{0.75}_{P23-P26} = 134,1 \text{ km}$ ). Der Kurvenverlauf der mittleren Entfernung zum Nest zeigte einen ähnlichen Verlauf über die Pentaden. Die Flugmuster der männlichen Rotmilane zeigte einen unimodalen Verlauf mit einem Maximum zwischen Mitte Mai und Mitte Juni ( $Md_{P13-P21} = 60,0 \text{ km}$ ,  $Q^{0.25}_{P13-P21} = 50,4 \text{ km}$ ,  $Q^{0.75}_{P13-P21} = 70,5 \text{ km}$ ). Die Flugdistanzen zum Horst blieben über den Jahresverlauf jedoch auf einem konstanten Wert mit einem Median von 0,88 km ( $Q^{0.25}_{P1-P39} = 0,59 \text{ km}$ ,  $Q^{0.75}_{P1-P39} = 1,24 \text{ km}$ ). Mit dem hier gewählten Ansatz konnten wir die räumlichen Änderungen der Bewegungsmuster über alle fünf Brutzeitphasen und einem Zeitfenster von sieben Monaten dokumentieren. Durch die Analyse der mittleren Entfernung zum Horst konnte eine klare Horstbindung beider Geschlechter über die gesamte Brutzeit bis in die späte Nachbrutzeit im September gezeigt werden. Für

nachhaltige Schutz- und Managementmaßnahmen sollte daher insbesondere bei gefährdeten Vogelarten die räumlich und zeitlich differenzierten Bewegungsmustern Berücksichtigung finden. Diese Eckdaten und Zeitskalen zur Bewegungsökologie brütender Rotmilane sollten somit zwingend in die planerische Relevanz dieser Greifvögel einfließen. Aus diesem Grund sollte man sich nicht nur auf die reine Brutphase vom Rotmilan konzentrieren, sondern auch die Nachbrutphasen bis in den September hinein berücksichtigen.

## Abstract

Space use of birds is driven by manifold factors and changes in scale and intensity over the year. Investigating actual space use and movements during the breeding season with modern satellite technology can provide important information on how individuals use the landscape. In the current study, we analysed the movement data of 13 GPS-GSM tagged adult Red Kites focussing on space use in relation to their nesting sites from March until September in Hesse, Germany. The main aim of the study was to evaluate sex differences in flight distances as well as seasonal variation in movement patterns during the breeding season. Both, the summed flight distance and the mean distance to the nest were clearly different between sexes and through the breeding season. For the female Red Kites, the flight distance showed a phase pattern during the breeding season. Initially flight distances decreased and reached their minimum between mid of April to mid of May, with a median distance of 6.2 km ( $Q^{0.25} = 4.4$  km,  $Q^{0.75} = 8.0$  km). Later in May, the flight distance of the females increased again till a maximum was reached from the beginning of July till mid of July ( $Md = 83.5$  km,  $Q^{0.25} = 46.5$  km,  $Q^{0.75} = 134.1$  km). The curve of the mean distance to the nest of female Red Kites showed a similar course. For the male Red Kites, the flight distance showed a shallow hump-shaped pattern during the breeding season. Flight distances reached their maximum mid of May to mid of June ( $Md = 60.0$  km,  $Q^{0.25} = 50.4$  km,  $Q^{0.75} = 70.5$  km). The mean distance to the nest stayed rather on a constant level throughout the breeding season ( $Md = 0.88$  km,  $Q^{0.25} = 0.59$  km,  $Q^{0.75} = 1.24$  km). Overall, the course of the curves of the flight distance and the mean distance to the nest from March to September could be linked to five different periods of the breeding season. For example, the flight distances of males and females diverged in the middle of the territory occupancy period and levelled back to the same order of size just when the period of begging flights started. In the post-breeding period in the first pentads of August, both sexes levelled back to the original flight distances of the initial phase of territory occupancy in March. Further, the local minimum of the flight distance of female Red Kites marked the incubation period during which female Red Kites incubate the eggs. By analysing the mean distance to the nest, we could also show that the bonding to the nest persists across all periods into the post breeding period. Therefore, conservation and management should be aware of seasonality of habitat use particularly in threatened species. For this reason, conservation assessments should not only focus on the mere breeding phase of the Red Kite but also consider post-breeding period into September.

## Einleitung

Die Raumnutzung von Vögeln unterliegt starken saisonalen und räumlichen Änderungen. Die maximale Ausdehnung dieser Änderungen findet sich im Zuggeschehen zwischen den Brut- und Überwinterungsgebieten. Aber auch innerhalb der Brutgebiete verändern sich die räumlichen Skalen der Raumnutzung im zeitlichen Verlauf (z.B. Odum & Kuenzler, 1955). Ursächlich hierfür sind unter anderem die Verteilung von Ressourcen im Raum bzw. die unterschiedlich intensive Nutzung von Habitaten während der verschiedenen Brutzeitphasen, z.B. während der Revierbesetzung, Eiablage und Brut sowie der Jungtieraufzucht (z.B. Roth et al., 2004). So reduziert etwa eine Vielzahl von Arten ihre Aktionsräume und ihre Flugstrecken vom Nest während des Bebrütens der Eier oder der Jungenaufzucht (Marzluff et al., 1997). Nachdem die Jungvögel flügge sind, folgen Brutzeitphasen, in denen die Jungtiere entweder schnell eigenständig werden oder von den Elternvögeln geführt werden und andere Habitate aufsuchen. Manche Arten, wie etwa Kolkkrabben *Corvus corax*, sind während dieser Phasen an ein enges Territorium gebunden, verändern aber ihre Bewegungsmuster zusammen mit dem Nachwuchs (Roth et al., 2004). Auch bei Rotmilanen halten sich die bereits frei fliegenden Jungtiere während der sogenannten Bettelflugphase noch im elterlichen Revier auf und werden zum Teil noch gefüttert (Aebischer, 2009). Die Dauer dieser letzten Brutzeitphase wird, je nach Quelle, mit zwei bis vier Wochen angegeben (Aebischer, 2009; U. Mammen et al., 2014; Mebs & Schmidt-Rothmund, 2014).

Mit den Übergängen zwischen den chronologisch aufeinander folgenden Brutzeitphasen ändern sich auch die Bewegungsmuster der

Rotmilane, und dies vermutlich auch in Abhängigkeit des Geschlechtes. So ist bekannt, dass nur die weiblichen Tiere brüten (Aebischer, 2009; Ortlib, 1989) und sich zu dieser Zeit nur wenig im Revier bewegen. Die Männchen übernehmen indes die Nahrungsversorgung für die Weibchen (Aebischer, 2009; Ortlib, 1989). Nach dem Schlupf der Jungtiere hudert das Weibchen die Küken. Erst mit zunehmendem Alter der Jungtiere entfernt es sich weiter vom Brutplatz und hilft bei der Nahrungsversorgung (Pfeiffer & Meyburg, 2015). Solche geschlechtsspezifischen Bewegungsmuster sind auch für andere europäische Greifvogelarten wie etwa den Rötelkalken *Falco naumanni* (Hernández-Pliego et al., 2017) oder den Spanischen Kaiseradler *Aquila adalberti* (Fernández et al., 2009) belegt.

Derart komplexe, sich verändernde Bewegungsmuster machen ein zielgerichtetes Management von Artenschutzmaßnahmen sehr aufwändig. Bedingt durch seinen Schutzstatus und die damit verbundenen artenschutzrechtlichen Verbote (§44 (1) BNatSchG) ist der Rotmilan Gegenstand zahlreicher Planungsverfahren. Dabei sind oft sehr umfangreiche Untersuchungen notwendig, um den nachhaltigen Schutz dieser bedrohten Greifvogelart sowohl am Brutplatz als auch in den Nahrungshabitaten zu gewährleisten. Auf Basis fachlicher Empfehlungen, wie etwa Abstandsempfehlungen zu bedeutsamen Vogellebensräumen, sollen artenschutzrechtliche Konflikte wie etwa das Schlagopferrisiko bei Windkraftanlagen durch die Auswahl konfliktärmer Standorte reduziert werden (Länderarbeitsgemeinschaft der staatlichen Vogelschutzwarten in Deutschland LAG VSW, 2015). Ein detailliertes Wissen um die artspezifischen Bewegungsmuster – und damit

um die Raumanprüche – ist daher essentiell für zielführende Schutzstrategien.

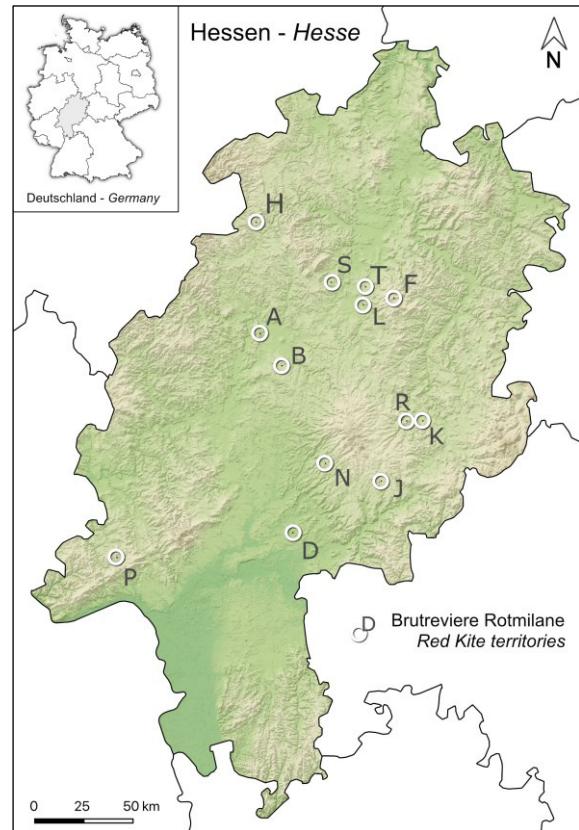
Für die vorliegende Studie haben wir mittels Satelliten-Sendern (GPS-GSM) erfasste Bewegungsdaten von 13 adulten Rotmilanen in Hessen analysiert, um ein besseres Verständnis der Raumnutzung (geflogene Distanzen, Entfernung zum Brutplatz) im Verlauf der Brutzeit und in Abhängigkeit des Geschlechts zu erhalten. Folgende Fragestellungen wurden untersucht:

- Wie gestaltet sich die Raumnutzung im Sinne von geflogenen Distanzen und mittlerer Entfernung zum Brutplatz im Verlauf der Brutzeit?
- Welche Unterschiede gibt es zwischen den Geschlechtern im Verlauf der Brutzeit?
- Verändert sich die Horstbindung im Verlauf der fünf Brutzeitphasen (Revierbesetzung, Brutzeit, Jungtieraufzucht, Bettelflugphase, Nachbrutzeit)?

## Material und Methoden

### Untersuchungsgebiet

Die Arbeiten zur vorliegenden Studie erstreckten sich über das Bundesland Hessen. Hier ist der Rotmilan nahezu flächendeckend verbreitet (Stübing et al., 2010). Ausnahmen stellen die menschlichen Ballungszentren im Rhein-Main-Gebiet dar (Frankfurt, Darmstadt, Wiesbaden, Stübing et al., 2010). Regionale Bruttichten erreichen in Nordhessen acht bis elf Brutpaare pro 100 km<sup>2</sup> (Gelpke & Stübing 2010). Im Zeitraum 2010 – 2014 brüteten ca. 1000 – 1300 Rotmilanpaaren im Bundesland (Stübing et al., 2010, Grüneberg & Karthäuser 2019).



**Abb. 1:** Lage der 13 untersuchten Rotmilan *Milvus milvus* - Reviere in Hessen, Deutschland. - Distribution of 13 Red Kite *Milvus milvus* territories investigated in Hesse, Germany. Relief-Karte: Open Geospatial Consortium (OGC) & Land Processes Distributed Active Archive Center (LP DAAC).

### Besonderung

An 13 verschiedenen Rotmilanhörsten wurde während der Jungenaufzucht 2017 je einer der beiden Brutvögel mittels der Dho-Gaza Methode (Bloom et al. 2007) gefangen. Hierzu wurde ein präparierter Uhu, *Bubo bubo*, in maximal 100 m Distanz zum Horst hinter einem acht Meter langen und vier Meter hohen Japannetz aufgestellt. Die auf den Uhu hassenden Altvögel verfingen sich im Netz, welches aus der Distanz visuell überwacht wurde. Der im Netz gefangene

Rotmilan konnte somit unmittelbar befreit und besendert werden.

Jeder auf diese Weise gefangene Vogel wurde beringt und vermessen. Das Geschlecht sprachen wir anhand von Größe, Gewicht sowie der Präsenz eines Brutflecks an. Ein solarbetriebener GPS-GSM-Sender der Firma Ornitela® wurde mittels eines Rucksack-Geschirrs aus Teflon-Band auf dem Rücken der Tiere angebracht. Inklusive des Geschirrs wiegt der Sender etwa 23 g. Somit wurden die nach Kenward (2001) maximal empfohlenen drei Prozent des Körpergewichts nicht überschritten.

Die Datenerfassung durch die GPS-Sender erfolgte von Sonnenauf- bis Sonnenuntergang. Zur verbesserten Laufleistung des Senders wurden die Intervalle zur Bestimmung der GPS-Positionen in Abhängigkeit des Akkus-Ladezustandes programmiert. Bei einer Akkukapazität von 100 % - 75 % wurde automatisiert alle fünf Minuten die aktuelle GPS-Position bestimmt und gespeichert. Bei einem Ladezustand von 75 % bis 50 % wurde das Speicherintervall auf alle 30 Minuten herabgesetzt. Ab einer Akkuleistung unterhalb von 50% wurden die Positionen nur stündlich (60 Minuten) erfasst. Fiel die Akkuleistung unter 25 % wurde nur alle acht Stunden die Position bestimmt. Bei Wieder-Aufladung der Akkus durch erhöhte Sonneneinstrahlung auf die Solareinheit stieg die Logging-Frequenz entsprechend wieder an. Die erfassten Positionen wurden täglich über das GSM-Mobilfunknetz auf einen Server übertragen und dort für die weiteren Analysen vorgehalten.

### Auswertung der Bewegungsdaten

Als Datengrundlage dieser Studie wurden die Bewegungsdaten 13 adulter Rotmilane aus dem Sommerhalbjahr 2018 verwendet. Zu Beginn der Datenaufbereitung wurden alle

Dopplungen (gleiche Zeitstempel und gleiche Position), Null-Koordinaten (kein GPS-Signal empfangen) sowie Positionen, an denen Geschwindigkeiten über 25 km/h gemessen wurden (fehlerhafte GPS-Erfassung; Ausreißer) ausgeschlossen. Anschließend wurde ein Mindestzeitabstand zwischen zwei Koordinaten von 3.000 Sekunden festgelegt. Dieser Schritt war notwendig, da die Erfassungsfrequenz - wie oben beschrieben - je nach Akkustand variierte. Gerade während der Brutzeit verbringen die weiblichen Tiere die meiste Zeit auf dem Gelege sitzend im Schatten der Baumkronen. Daher liefern die Sender der Weibchen zu dieser Zeit deutlich weniger Koordinaten als die der Männchen. Da dies Auswirkungen auf die nachfolgenden Berechnungen der geflogenen Distanzen hat, wurde ein Mindestzeitabstand von 3.000 Sekunden zwischen zwei Positionen festgelegt. Das Festlegen des Zeitabstandes führte zu großem Datenverlust, bewirkte jedoch, dass eine annähernde Normalverteilung in der Anzahl der verwendeten Geopositionen über den gesamten Zeitraum für beide Geschlechter erreicht wurde. In die Ergebnisse dieser Studie flossen daher insgesamt 33.055 Datenpunkte von fünf weiblichen und acht männlichen Rotmilanen aus dem Zeitfenster März bis September 2018 ein.

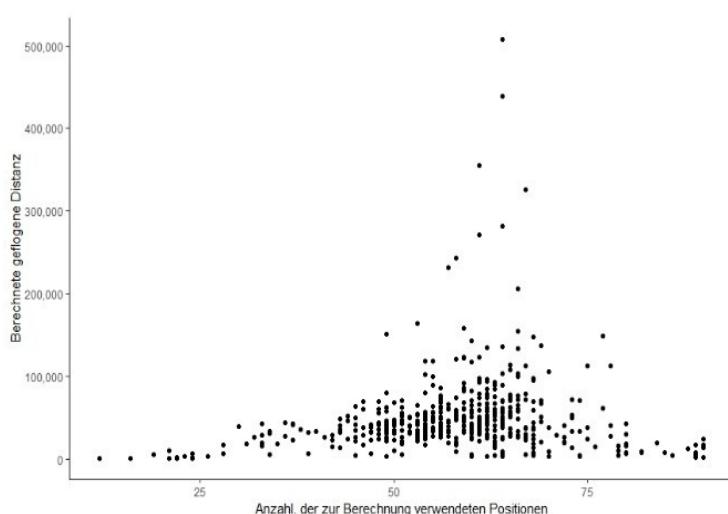
Beginnend mit dem 11. März 2018 (alle besenderten Individuen befanden sich in ihrem Brutrevier) wurden die Daten in Pentaden (fünf Tage-Schritte) zusammengefasst. Die letzte betrachtete Pentade endete mit dem 21. September 2018. Danach trat das erste der telemetrierten Tiere den Herbstzug an. Für jede dieser Pentaden wurde die geflogene Gesamtdistanz als Summe der Distanzen zwischen den erfassten Positionen errechnet. Zudem wurde die mittlere Entfernung aller Positionen zum Brutplatz pro Pentade errechnet. Für diese Berechnungen kamen die

Pakete „move“ (Kranstauber & Smolla, 2015) und „rgeos“ (Bivand et al., 2013) in der Software R (R Core Team, 2013) zur Anwendung. Dies resultierte in 546 Datenpunkten je berechneter Variable verteilt auf 39 Pentaden. Bei den weiteren Analysen wurden Datenpunkte ausgeschlossen, deren Berechnungen auf weniger als zehn Geopositionen des Individuums innerhalb der betrachteten Pentade beruhten ( $N = 4.542$  Datenpunkte).

Während der Datenaufbereitung, wurde zwar ein Mindestzeitabstand zwischen zwei Positionen (siehe oben), jedoch kein Maximalabstand festgelegt. Infolgedessen wurden zur Berechnung der geflogenen Distanzen unterschiedliche Anzahlen an Positionen genutzt. Da die zeitliche Auflösung Einfluss auf die Berechnung der geflogenen Distanzen hat überprüften wir diesen Zusammenhang visuell (Abb. 2) und mit einem Pearson-Korrelationstest aus dem „stats“-Paket der Software R (R Core Team, 2013). Da dieser normalverteilte Daten voraussetzt, wurden die geflogenen Distanzen logarithmisch transformiert. Die Testergebnisse zeigten, dass der Zusammenhang zwischen der berechneten geflogenen Distanz und der Anzahl der zur Berechnung verwendeten Positionen zwar signifikant ist ( $p < 0,001$ ), jedoch ist der Korrelationskoeffizient  $r$  mit 0,2 nur klein (0 = kein Zusammenhang, 1 = perfekter

Zusammenhang). Der Zusammenhang ist daher als sehr schwach zu beurteilen und in unseren Augen unproblematisch für die Analysen.

Der zeitliche Verlauf der geflogenen Distanzen sowie der mittleren Entfernung zum Brutplatz wurde anschließend mit der Hilfe Generalisierte Additiver Mischmodelle (GAMM) analysiert. Dazu fand das Paket „mgcv“ (Wood, 2011) Anwendung. GAMM nehmen einen nicht-linearen Zusammenhang der Variablen an. Die Modelle versuchen sich stattdessen dem gegebenen Zusammenhang bestmöglich anzunähern (Abb. 3 und Abb. 4) indem eine Glättungsfunktion (smooth-term) in die erklärenden Variablen integriert wird. In den verwendeten Modellen wurden die geflogene Distanz bzw. die mittlere Entfernung zum Brutplatz als abhängige Variable verwendet. Dazu wurden die Daten zuvor logarithmisch transformiert, um eine Normalverteilung zu erreichen. Da wir unterschiedliche Verhaltensweisen zwischen den Geschlechtern sowie eine Änderung des Verhaltens im zeitlichen Verlauf erwarteten, wurde den Modellen neben dem Geschlecht als erklärende Variable zusätzlich eine Glättungsfunktion des zeitlichen Verlaufs sowie eine Glättungsfunktion des zeitlichen Verlaufs gruppiert nach den Geschlechtern hinzugefügt. Wirken sich beide Glättungsfunktionen



**Abb.2:** Der Zusammenhang zwischen der berechneten geflogenen Distanz [m] mit der Anzahl, der zur Berechnung verwendeten Positionen ist als schwach zu beurteilen (Pearson-Korrelationstest:  $p < 0,001$ ,  $r=0,2$ ). The relation between the calculated flight distance [m] and the number of positions used for the calculation is considered weak (Pearsons correlation:  $p < 0,001$ ,  $r=0,2$ )

signifikant auf die abhängige Variable aus, kann geschlussfolgert werden, dass die Geschlechter im zeitlichen Verlauf unterschiedlichen Trends folgen (van Rijn, 2015). Um den intrinsischen Eigenschaften der Individuen Rechnung zu tragen, wurden diese als zufällige Faktoren (random factors) in den Modellen berücksichtigt.

Der Verlauf der Pentaden-bezogenen Distanzwerte wurde mittels Box-Whisker-Plots (Median) und Fehlerbalken (1.Quartil, 3. Quartil) sowie der Vertrauensintervalle der GAMM dargestellt (Abb. 3 und Abb. 4). Zur zeitlichen Einordnung der Ergebnisse wurden die vier zentralen Ereignisräume Eiablage, Schlupf, Ausflug, sowie das Verlassen der elterlichen Reviere in den Abbildungen 2 und 3 kenntlich gemacht. Dazu verwendeten wir Daten von 13 Jungtieren von sechs der untersuchten Rotmilane, die im Juni 2018 an verschiedenen Naturräumen Hessens beringt und besendert wurden. Die Horste der übrigen sieben untersuchten Rotmilane waren nicht erkletterbar. Somit konnten deren Jungtiere nicht vermessen werden. Anhand der am Besendungsdatum gemessenen Flügellänge und der Formel nach Mammen & Stubbe (1995) bestimmten wir das Alter der Jungtiere an den oben genannten sechs Horsten. Damit bestimmten wir in Folge rückwirkend den Schlupftermin sowie, ausgehend von einer durchschnittlichen Brutdauer von 34 Tagen (31 – 38 Tage, Bauer et al., 2005), den Brutbeginn des jeweiligen Altvogels. Anhand der Bewegungsdaten konnte der Brutbeginn insbesondere bei den weiblichen Tieren visuell durch die Akkumulation der Positionen auf den

Brutplatz überprüft und verifiziert werden. Zur Ermittlung des Zeitpunktes, an dem die Jungtiere die elterlichen Reviere verlassen, wurden die Bewegungsdaten von fünf besenderten und ausgeflogenen Jungtieren (s.o.) analysiert und präsentiert (Abb. 3 u. Abb. 4). Die übrigen Jungtiere waren bereits zuvor im oder am Horst noch vor dem Ausfliegen prädiert worden.

Da zwei weibliche Rotmilane ihr Verhalten auffällig stark änderten, nachdem ihre Jungen kurz vor dem Ausfliegen alle prädiert worden waren, wurden die Analyse mit einem reduzierten Datensatz wiederholt. Dazu wurden die zwei weiblichen Individuen ab der Pentade des Prädationsereignisses (Pentade 20 bzw. 21) aus dem Datensatz entfernt und die Modelle erneut gerechnet. Da die Ergebnisse konsistent blieben (s. Ergebnisteil), werden in Tabellen und Abbildungen die Gesamtdaten präsentiert.

Mit Beginn der Revierbesetzung, den vier zentralen Ereignissen (Eiablage, Schlupf, Ausflug, Verlassen des elterlichen Reviers) lassen sich somit die fünf Brutzeitphasen (Tab. 1) darstellen. Da zur Abgrenzung der Brutzeitphasen nur Daten von sechs der 13 berücksichtigten Rotmilane verwendet werden konnten und die Dauer der einzelnen Phasen aufgrund verschiedener Faktoren variieren können (Bauer et al. 2005), sind die hier gezeigten Grenzen nicht als absolut zu verstehen. Die fünf Phasen überlappen und dienen dazu, beobachtete Verhaltensweisen, im Sinne von geflohenen Distanzen und Entfernung vom Brutplatz, einzuordnen.

**Tab. 1:** Übersicht der Brutzeitphasen des Rotmilans *Milvus milvus* mit Zeitspannen und Pentaden-Nummern. *Chronological list of the five breeding phases of Red Kites Milvus milvus with time spans and pentads.*

Brutzeitphasen <i>breeding phases</i>	Zeitspannen <i>time frames</i>	Pentaden <i>pentads</i>
Revierbesetzung <i>Establishment of territory</i>	11. März – 17. April	P1 – P9
Brutzeit <i>Breeding</i>	07. April – 21. Mai	P7 – P14
Jungtieraufzucht <i>Chick rearing</i>	11. Mai – 08. Juli	P13 – P24
Bettelflugphase <i>Fledgling phase</i>	29. Juni – 02. August	P23 – P29
Nachbrutzeit <i>Post breeding phase</i>	24. Juli – 21. September	P28 – P39

## Ergebnisse

Sowohl das Geschlecht als auch die Zeit hatten einen signifikanten Einfluss auf die geflogene Distanz (GAMM:  $p<0,001$ ,  $R^2=0,56$ , reduzierter Datensatz: GAMM:  $p<0,001$ ,  $R^2=0,57$ ) bzw. auf die mittlere Entfernung zum Horst pro Pentade (GAMM:  $p<0,001$ ,  $R^2=0,56$ , reduzierter Datensatz: GAMM:  $p<0,001$ ,  $R^2=0,68$ ). Dabei zeigten die Kurven der beiden Geschlechter unterschiedliche Verläufe (Tab. 2, Abb. 3 und 3).

### Weibchen

Die von den weiblichen Rotmilanen geflogenen Distanzen wiesen im zeitlichen Verlauf starke Schwankungen auf (Abb. 3). Ausgehend von einem mittleren Niveau Anfang März fielen die geflogenen Distanzen auf ein deutliches Minimum zwischen Mitte April und Mitte Mai. Darauf folgte ein Maximum Anfang bis Mitte Juli. Ab Anfang/Mitte August pendelten sich die geflogenen Distanzen wieder in ähnlichen Wertebereichen wie Anfang März ein. Ohne die beiden weiblichen Tiere ab der Pentade des Prädationsereignisses

(Pentade 20 bzw. 21) fiel das Maximum Anfang bis Mitte Juli etwas geringer aus.

Der Verlauf der mittleren Entfernung zum Brutplatz änderte sich über die Zeit ähnlich (Abb. 4). Zunächst nahm die Entfernung zum Brutplatz ab und erreichte zwischen Mitte April und Mitte Mai ein deutliches Minimum. Anschließend stieg diese wieder an und erreichte im Juli ihr Maximum. Bis Mitte August nahm die Entfernung zum Brutplatz wieder ab. Ab dann entfernten sich die weiblichen Rotmilane ähnlich weit vom Brutplatz wie die Männchen. Auch hier fiel der Maximalwert im Juli ohne die beiden Weibchen ab der Pentade des Prädationsereignisses im Mittel etwas geringer aus.

### Männchen

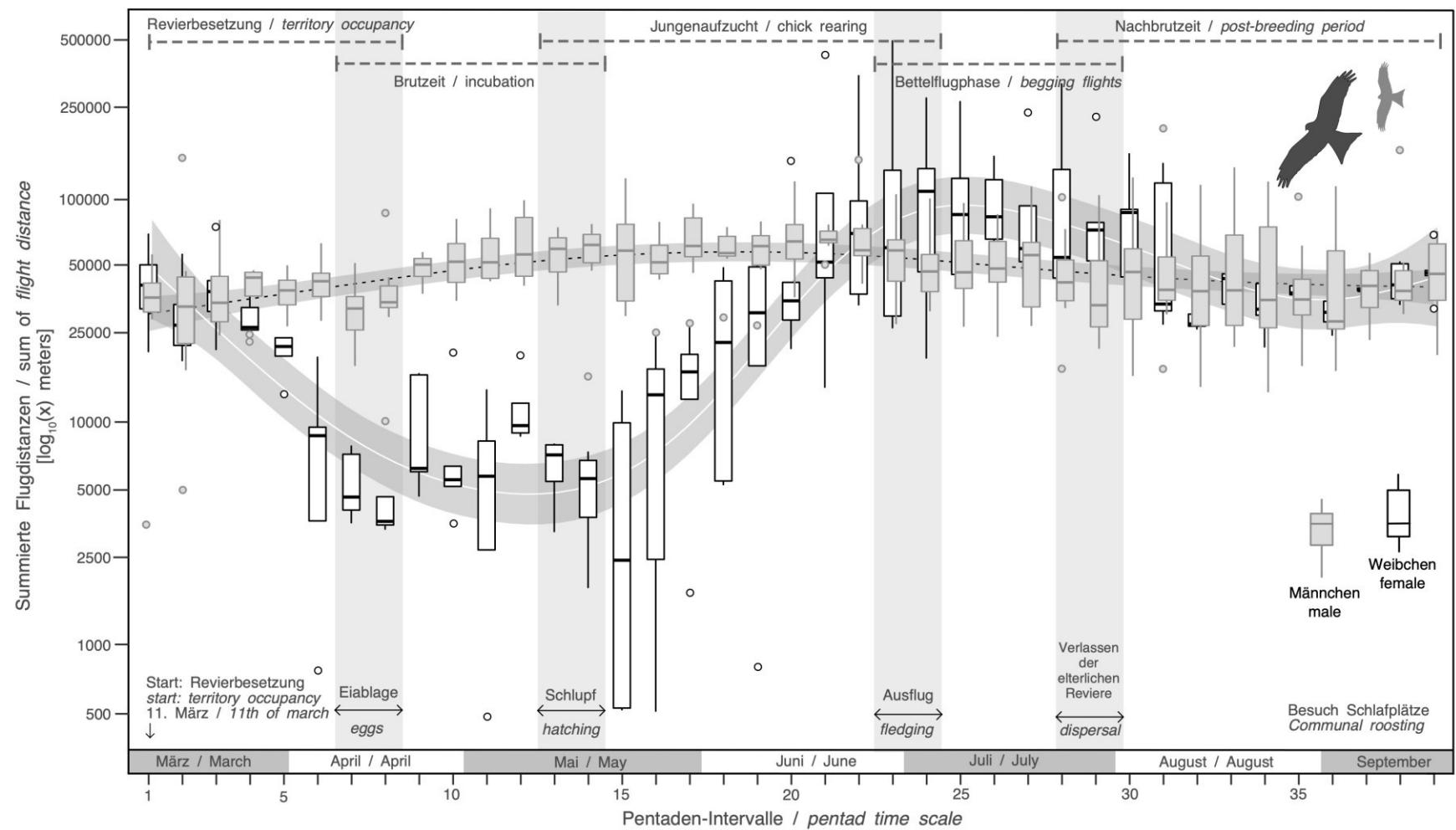
Bei den männlichen Rotmilanen schwankten die geflogenen Distanzen im zeitlichen Verlauf deutlich weniger stark, jedoch gegenläufig zu den Weibchen. Von einem mittleren Niveau zu Beginn des Studienzeitraums Anfang März stiegen die geflogenen Distanzen bis zu einem

Maximum von Mitte Mai bis Mitte Juni. Danach sanken die geflogenen Distanzen wieder und erreichten ab Anfang August wieder das Ausgangsniveau (Abb. 3).

Die mittlere Entfernung der männlichen Rotmilane zum Brutplatz änderte sich im zeitlichen Verlauf wenig, nahm jedoch im zeitlichen Verlauf stetig zu (Abb. 4).

**Tab. 2:** Summierte Flugdistanzen [km] und mittlere Entfernungen zum Brutplatz [km] von 13 Rotmilanen *Milvus milvus*. *Sum of flight distances [km] and mean distances from nest site [km] of 13 Red Kites Milvus milvus*

Brutzeitphase <i>Breeding period</i>	Re-vierbesetzung <i>territory occupancy</i>		Brutzeit <i>Incubation</i>		Jungtieraufzucht <i>Chick rearing</i>		Bettelflugphase <i>Fledgling phase</i>		Nachbrutzeit <i>Post breeding phase</i>		Alle Phasen <i>Over all</i>	
			♀	♂	♀	♂	♀	♂	♀	♂	♀	♂
Geflogene Distanz <i>Flight distance [km]</i>												
Min	0,8	3,5	0,5	10,0	0,5	15,9	19,2	17,2	21,5	13,6	0,5	3,5
Q25	6,1	31,1	4,4	38,8	7,4	48,7	46,3	36,1	33,5	28,2	13,4	34,1
Md	19,6	39,3	6,2	51,2	23,2	58,6	72,0	48,0	41,1	38,0	32,0	46,5
Q75	31,9	46,5	8,0	61,8	49,1	70,5	134,1	62,2	51,1	57,5	49,0	62,2
Max	74,0	151,2	20,2	97,5	508,3	149,3	508,3	112,5	325,8	205,7	508,3	205,7
Distanz zum Horst <i>Distance to the nest [km]</i>												
Min	0,02	0,13	0,02	0,20	0,01	0,20	0,31	0,38	0,78	0,38	0,01	0,13
Q25	0,06	0,42	0,04	0,52	0,07	0,74	1,25	0,76	1,05	0,70	0,12	0,59
Md	0,25	0,59	0,06	0,71	0,22	0,91	1,83	1,07	1,25	1,21	0,66	0,88
Q75	0,44	0,71	0,11	0,93	0,56	1,11	3,43	1,28	1,62	1,54	1,34	1,24
Max	1,88	12,42	0,17	1,39	292,97	6,38	80,48	4,03	161,94	19,95	292,97	19,95



**Abb. 3:** Verteilung der summierten Flugdistanzen [m] über die Brutzeit von 13 hessischen Rotmilanen *Milvus milvus*. Gruppierung innerhalb von Pentaden (Px = Pentade mit der Nummer x) unter Angabe des Medians, des ersten Quartils [entspricht 25% der Werte] und des dritten Quartils [entspricht 75% der Werte] sowie einzelner Ausreißer (Punkte). – *Distribution of summed flight distances [m] within 5-day intervals (pentads) over the breeding season of 13 Red Kites *Milvus milvus* in Hesse, Germany. First [25% of all values], third [75% of all values] quantile are given besides median as box-whisker-plots alongside with outliers (points).*

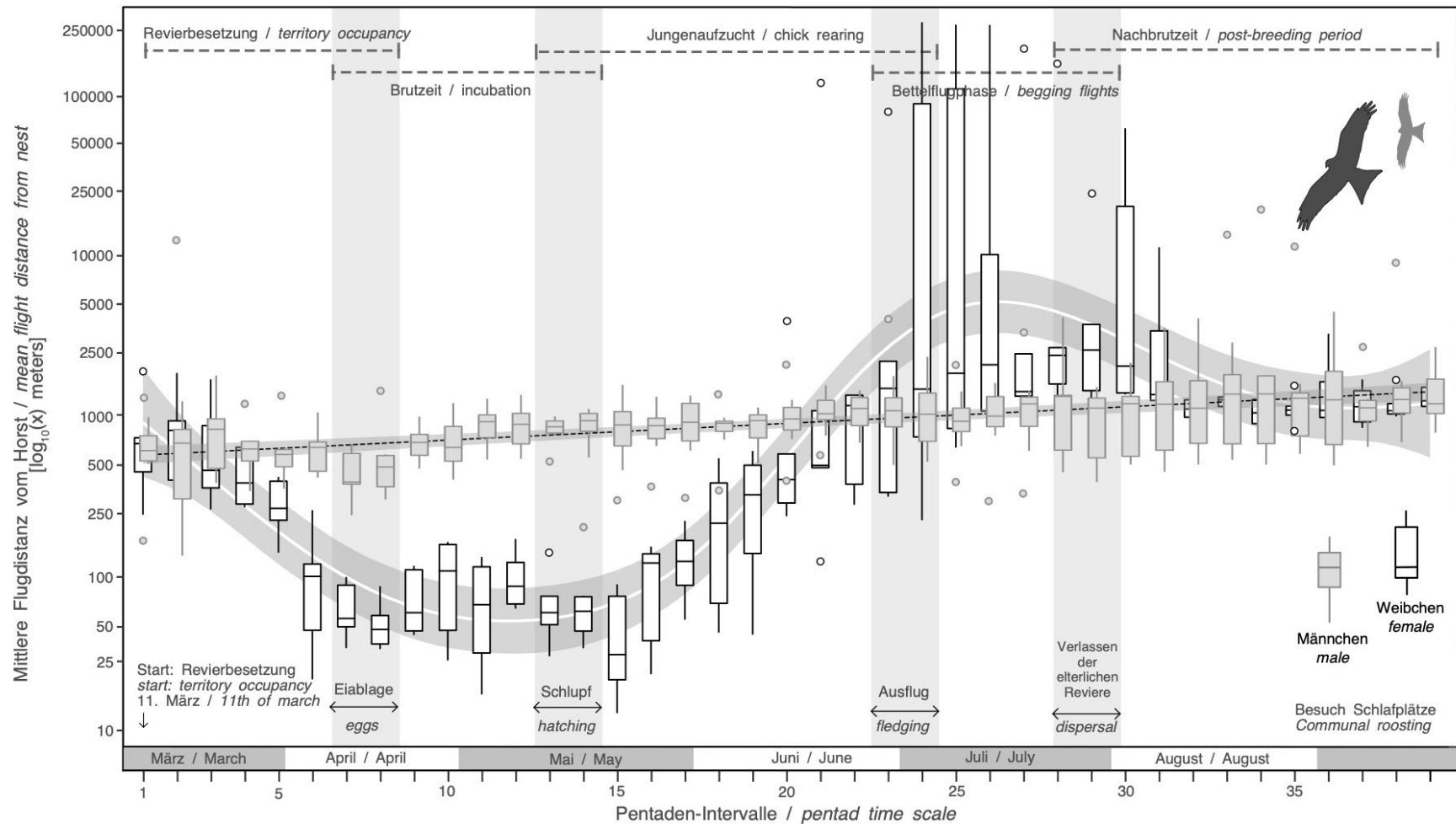


Abb. 4: Verteilung der mittleren Distanzen [m] zum Nistplatz über die Brutzeit von 13 hessischen Rotmilanen *Milvus milvus*. Gruppierung innerhalb von Pentaden unter Angabe des Medians, des ersten (25%) und des dritten Quartils (75%) sowie einzelner Ausreißer. – Distribution of mean distances [m] to nest sites within 5-day intervals (pentads) over the breeding season of 13 Red Kites *Milvus milvus* in Hesse, Germany. First [25% of all values], third [75% of all values] quantile are given besides median as box-whisker-plots alongside with outliers (points).

### Revierbesetzung

Während dieser Phase nahm die geflogene Distanz bei den weiblichen Tieren ab, die der Männchen hingegen zu (Abb. 3). Auch die mittlere Entfernung zum Horst nahm bei den weiblichen Tieren ab, wohingegen bei den männlichen Tieren die Entfernung zum Brutplatz moderat stieg (Abb. 4).

### Brutzeit

Während dieser Brutzeitphase war die geflogene Distanz bei den weiblichen Tieren im Gesamtverlauf betrachtet am geringsten; bei den männlichen Tieren nahm die geflogene Distanz weiter zu (Abb. 3). Die mittlere Entfernung zum Horst der weiblichen Tiere betrug nur wenige Dutzend Meter; bei den männlichen Tieren stieg die Entfernung zum Brutplatz weiter an (Abb. 4).

### Jungenaufzucht

Während der Jungenaufzucht stieg die geflogene Distanz der weiblichen Tiere kontinuierlich und erreichte am Ende der Phase ihr Maximum (Abb. 3). Ohne die beiden weiblichen Tiere, die nach Prädationseignis ihr Revier verließen, fiel dieses Maximum etwas geringer aus. Die männlichen Tiere legten während dieser Phase die weitesten Distanzen zurück, jedoch nahmen diese gegen Ende dieser Brutzeitphase auch wieder ab (Abb. 3). Auch die mittlere Entfernung der weiblichen Rotmilane zum Brutplatz stieg mit Fortschreiten der Jungenaufzucht. Diese entfernten sich gegen Ende der Phase weiter weg als die Männchen (Abb. 4). Auch ohne die beiden weiblichen Tiere, die nach Prädationseignis ihr Revier verließen, entfernten sich die Weibchen weiter vom Horst als die Männchen.

### Bettelflugphase

Während der Bettelflugphase zeigten die geflogenen Distanzen der weiblichen Rotmilane einen stärkeren abnehmenden Trend, als die der Männchen (Abb. 3). Auch ohne die beiden weiblichen Tiere, die sich aus ihrem Revier entfernt hatten, war dieser abnehmende Trend bei den Weibchen stärker ausgeprägt als bei den Männchen. Zum Ende dieser Brutzeitphase, am Übergang zur sich anschließenden Nachbrutzeit, glichen sich die geflogenen Distanzen zwischen den Geschlechtern wieder an (Abb. 3). Die geflogenen Distanzen nivellierten sich auch zwischen den Geschlechtern im reduzierten Datensatz auf ähnliches Niveau.

Die mittlere Entfernung zum Brutplatz war bei den weiblichen Tieren während dieser Phase am höchsten und überstieg deutlich die der Männchen (Abb. 4). Im reduzierten Datensatz war der Unterschied in der mittleren Entfernung zum Brutplatz zwischen den Geschlechtern schwächer ausgeprägt. Die Entfernung zum Brutplatz der Männchen stieg weiter geringfügig an (Abb. 4).

### Nachbrutzeit

Während der Nachbrutzeit waren keine deutlichen Unterschiede mehr in den zurückgelegten Distanzen zwischen den Geschlechtern erkennbar (Abb. 3). Dieses Muster traf auch für den reduzierten Datensatz zu. Auch die mittlere Entfernung zum Brutplatz unterschied sich nur zu Beginn der Nachbrutzeit zwischen den Geschlechtern, wobei die Weibchen sich nach wie vor weiter entfernten als die Männchen (Abb. 4). Im Verlauf der Nachbrutzeit pendelten sich die Entfernungen jedoch auf dem relativ konstanten Niveau der männlichen Tiere ein. Auch ohne die beiden weiblichen Tiere, die sich aus ihrem

Revier entfernt hatten, lag die mittlere Entfernung zum Brutplatz der Weibchen nur zu Beginn der Nachbrutzeit etwas höher als die der Männchen.

## Diskussion

Die Bewegungsdaten von 13 adulten Rotmilanen aus dem Sommerhalbjahr 2018 wurden hinsichtlich der zurückgelegten Distanzen und der mittleren Entfernung zum Brutplatz analysiert. Es konnte gezeigt werden, dass die Raumnutzung im Verlauf der fünf Brutzeitphasen insbesondere bei den weiblichen Tiere stark variierte und daher auch Unterschiede zwischen den Geschlechtern deutlich wurden.

Bemerkenswerterweise zeigten unsere Daten, dass während des gesamten Sommerhalbjahres, d.h. von März bis September eine enge Horstbindung bei beiden Geschlechtern besteht, und zwar auch, nachdem die Jungvögel bereits ausgeflogen sind. Diese Ergebnisse sind von Bedeutung für naturschutzfachliche Begutachtungen, z.B. in der Eingriffsplanung. Um ein erhöhtes Tötungsrisiko durch eine geplante Windkraftanlage auszuschließen, ist in Hessen die Raumnutzung kollisionsgefährdeter Großvögel bislang nur während der Revierbesetzung und Brutzeit zu erfassen (Hessisches Ministerium für Umwelt, Energie, Landwirtschaft und Verbraucherschutz Abteilung, 2012). Aufgrund der beständigen Horstbindung auch in der Nachbrutzeit sollte der Untersuchungszeitraum bis in den September hinein ausgeweitet werden. Zudem empfiehlt die Länderarbeitsgemeinschaft der Vogelschutzwarten einen Mindestabstand von 1,5 km zu bekannten Rotmilan-Brutplätzen, da hier etwa 60% der Flugbewegungen stattfinden (Länderarbeits-

gemeinschaft der staatlichen Vogelschutzwarten in Deutschland LAG VSW, 2015). Unsere Daten bestätigen diesen Hauptaktivitätsraum, da sich über den gesamten Untersuchungszeitraum 75% der von uns untersuchten Rotmilane im Mittel kaum außerhalb dieses Bereichs bewegten. Leichte Unterschiede in den absolut betrachteten Zahlen sind methodisch bedingt: In der Arbeit von Pfeiffer & Meyburg (2015), auf der die Abstandsempfehlung basiert, ging es vorrangig um die Jungenaufzuchtphase und die damit verbundene erhöhte Flugaktivität zur Nahrungsbeschaffung. Daher wurden zum einen nur die Positionen der Männchen zur Berechnung der Entfernung vom Horst berücksichtigt. Zum anderen blieben alle Positionen im 100 m Radius um den Horst unberücksichtigt, da der Fokus auf der Entfernung zwischen Brutplatz und regelmäßig genutzten Jagdgründen lag (Pfeiffer & Meyburg 2015). Da in der vorliegenden Studie der Bezug zum Horst für beide Geschlechter im Vordergrund stand, wurde die Entfernung zum Horst über fünf Tage ohne eine Bereinigung von Positionsdaten in Horstnähe gemittelt. Entsprechend sind auch die Positionen, die am Morgen und Abend in Horstnähe erfasst wurden, in die Berechnung des Hauptaktivitätsraums miteingegangen und resultierten daher in etwas geringen mittleren Entfernungen zum Horst. Dieser Hauptaktivitätsraum (1,5 km um den Horst) konnte in unserer Studie sogar bis in den September hinein abgebildet werden.

Die Bewegungsmuster von männlichen und weiblichen Rotmilanen unterschieden sich im Verlauf der Brutzeitphasen. Während der Revierbesetzungsphase im März entfernten sich beide Geschlechter ähnlich weit vom Brutplatz, wobei die männlichen Tiere weitere Strecken flogen als die weiblichen. In der anschließenden

Brutphase wurden die geschlechtsspezifischen Unterschiede im Bewegungsverhalten sehr deutlich. Die Weibchen entfernten sich - bedingt durch das Brutgeschäft und das anschließende Hudern der Dunenjungen - kaum vom Horst. Da die männlichen Vögel zu dieser Zeit die Weibchen mit Futter versorgen müssen (Aebischer 2009), waren ihre geflogenen Distanzen entsprechend höher. Auch die ersten Tage nach dem Schlupf der Jungtiere ist das Männchen für die Nahrungsversorgung verantwortlich. Erst wenn die Nestlinge zwei bis drei Wochen alt sind hilft das Weibchen (Aebischer 2009). Dann hat ein Jungtier einen Futterbedarf von etwa 150 g pro Tag (Bischofberger et al., 2019; Gottschalk et al., o. J.). Ausgehend von dieser Futtermenge und einer Gelegegröße von 1 – 3 Jungvögeln, müssen die Elterntiere 150 g – 450 g Nahrung zum Horst transportieren. Auch in unseren Daten zeigte sich, dass mit zunehmendem Alter der Jungtiere, und dem damit einhergehenden hohen Futterbedarf, sowohl die geflogene Distanz als auch die mittleren Entfernung zum Horst der weiblichen Tiere langsam wieder stieg (Abb. 3 und 4).

Im Übergang zwischen der Phase der Jungenaufzucht und der sich anschließenden Bettelflugphase erreichten die geflogenen Distanzen der weiblichen Tiere ihr Maximum. Auch die mittlere Entfernung zum Horst der Weibchen war in dieser Phase am höchsten und nahm erst im weiteren Verlauf wieder ab. Insbesondere die hohe mittlere Entfernung zum Horst ist durch das Verhalten zweier weiblicher Tiere nach dem Verlust ihrer Brut durch Prädation beeinflusst. So pendelte ein weiblicher Rotmilan seit dem Tag nach Brutverlust zwischen dem Brutplatz und Ostfrankreich. Ein weiteres Weibchen bewegte sich in den vier Wochen nach Verlust der Brut bis zu 200 km in östliche Richtung. Werden diese

Individuen ab der Pentade, in der die Prädation stattfand, aus dem Datensatz entfernt, bleibt der Kurvenverlauf der geflogenen Distanzen gleich. Die Differenz der geflogenen Distanzen zwischen den Geschlechtern verringert sich allerdings etwas. Bei der mittleren Entfernung zum Horst übersteigen die Distanzwerte der Weibchen die der Männchen nur wenig. Prädation ist ein natürliches Ereignis, auf das die beiden weiblichen Rotmilane mit Flugstrecken weit aus dem Brutrevier hinaus reagiert haben. Bei anderen Individuen, deren Brut vollständig prädiert wurde, wurden keine solchen extremen Bewegungen festgestellt. Entsprechend haben wir nur für die Extremata der beiden weiblichen Tiere ab dem Prädationsereignis korrigiert. Allerdings zeigt sich auch im reduzierten Datensatz eine durchgehend starke Horstbindung über die gesamte Brutsaison bis in den September hinein.

Selbstverständlich muss die hier gezeigte Abgrenzung der Brutzeitphasen der hessischen Rotmilane mit Vorsicht betrachtet werden. Wie bereits beschrieben basiert diese auf Jungtierdaten von sechs der 13 untersuchten adulten Tiere. Zudem kann die Dauer der einzelnen Phasen aufgrund verschiedener Faktoren variieren. So ist bekannt, dass die Brutdauer der Rotmilane von der Gelegegröße abhängt und demgemäß zwischen 31 und 38 Tagen variieren kann (Bauer et al. 2005). Die Dauer der Phase der Jungtieraufzucht wird zudem stark von der Nahrungsverfügbarkeit in der Umgebung des Horstes beeinflusst (Bauer et al. 2005). Auch intrinsische Faktoren, wie z.B. die Erfahrung der Alttiere, spielen sicherlich eine wichtige Rolle. Die hier visualisierten Übergänge dienen daher nur zur Orientierung, um die Bewegungsmuster der Rotmilane im Verlaufe des Brutgeschehens besser zu verstehen.

Insgesamt konnten wir zeigen, dass sich die unterschiedlichen Aufgaben männlicher und weiblicher Rotmilane während des Brutgeschehens deutlich in ihren Bewegungsmustern widerspiegeln. Diese geschlechtsspezifischen Muster bestätigen ähnliche Beobachtungen an anderen europäischen Greifvogelarten wie etwa bei Rötel-falken *Falco naumanni* (Hernández-Pliego et al. 2017) oder beim Spanischen Kaiseradler *Aquila adalberti* (Fernandez et al. 2009). Aufgrund der für beide Geschlechter gezeigten starken Horstbindung während des gesamten Sommerhalbjahres appellieren wir mit Nachdruck für eine Anpassung der Untersuchungszeiträume von Raumnutzungsgutachten.

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## **Chapter III – High collision risk of Red Kites across the entire range of occurring wind speeds**

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### **Abstract**

Land use and climate change are the main causes of changing environmental conditions and species decline worldwide. To mitigate effects of climate change, the utilization of renewable energies, e.g., via the construction of wind turbines (WT), has increased over the past decades, causing a collision risk especially for wide-ranging species such as raptors. As a better understanding of flight activity and flight altitude is crucial to develop efficient mitigation measures, we used GPS-transmitters to track 26 adult Red Kites (*Milvus milvus*) in Hesse, Germany, one of the species' distribution centres, over three consecutive years. We related the flight activity and flight altitude of the birds to the occurring wind speeds recorded at 10 m above ground and determined the proportion of flights within the critical rotor-swept area (RSA) of operating and currently planned WTs in the study area. Red Kites showed a high flight activity over the entire range of occurring wind speeds, suggesting an overall high collision risk with wind turbines, independent of wind speed. Flight activity of Red Kites was lowest at calm wind speeds of up to 2.0 m/s but increased with increasing wind speeds. However, 50% and 75% of the flights took place at wind speeds of up to 2.7 m/s and 3.6 m/s, respectively. At calm wind speeds of up to 4.4 m/s, the flight altitudes of Red Kites were constantly just above 100 m above ground but declined with approximately  $1 \text{ m} \pm 2 \text{ m}$  per 0.1 m/s at wind speeds between 4.4 m/s and 6.0 m/s. Considering that the flight activity increased with increasing wind speeds and that flight altitudes mostly ranged just above 100 m above ground, Red Kites face a constantly high collision risk at least up to wind speeds of 4.4 m/s in the study area. In line with this, the proportion of flights within the critical RSA of operating WTs hardly changed with wind speeds, ranging between 31% and 58%. Currently planned and taller WTs might reduce the proportion of flights within the RSA to 31% - 37%, which still mirrors a non-negligible collision risk. Hence, mitigation measures will remain indispensable for a sustainable expansion of wind energy. As considerable proportions of flights took place at rather calm wind speeds, we actively call for raising the cut-in wind speeds of WT. In doing so, significant parts of the Red Kites' activity in altitudes of the critical RSA could take place without collision risk. Implementing

higher cut-in wind speeds would thus support the sustainable expansion of wind energy while at the same time actively conserving a collision-prone species of international importance.

## Introduction

Climate change is considered one of the main causes for the degradation of nature (Díaz et al., 2019; IPBES, 2019; Sala et al., 2000). To minimise CO<sub>2</sub> emissions despite steadily increasing energy demand, the development and utilization of renewable energies has been expedited strongly in the past decades and e.g. the number of wind turbines (WT) has progressively increased (Drewitt & Langston, 2006a; Durstewitz et al., 2019; Tabassum-Abbas et al., 2014). The necessary expansion of wind energy utilization goes along with a number of expected effects on the society and environment, ranging from e.g. noise emission, visual disturbance, deforestation, to land erosion (Nazir et al., 2020). Hence, WTs are regularly criticised for leading to habitat loss, barrier effects and an increased collision risk, especially for highly mobile animals like bats and birds (Drewitt & Langston, 2006a; Garvin et al., 2011; Lehnert et al., 2014; Voigt et al., 2015).

Among birds especially raptors face a high collision risk, as they do not show avoidance of WTs (Hötker, 2009). As many raptors are top predators they focus on the ground or distant prey instead of looking out for threats in front or above during foraging (Péron et al., 2017). Additionally, morphological adaptions like the suprabital ridge, developed to act as a sun shade, prevent the rapidly turning rotors from being perceived (Clark, 1999; Potier et al., 2016). Raptors which predominantly perform soaring flights have an even higher collision risk as their manoeuvrability is often limited while soaring

(Péron et al., 2017). As most raptors occur in low densities and have relative low reproductive rates, an increased collision risk of a species is particularly critical during the breeding season when the loss of an individual often causes the loss of the entire brood (Garvin et al., 2011; Grünkorn et al., 2016; Kikuchi, 2008; Langston & Pullan, 2003; Péron et al., 2017; Watson et al., 2018).

Owing to their high collision risk, many raptors are in the focus of environmental risk assessments, which EU and national legislation require to minimize the impact of WTs on nature (Strategic Environmental Assessment (SEA) Directive 2001/42/EC; Environmental Impact Assessment (EIA) Directive 2014/52/EU; UVPG; Verot, 2007). Based on these assessments, pre-construction mitigation measures are taken, which include, e.g., informed micro-siting of WTs, optimising the location of WTs in relation to raptor breeding sites or regularly used foraging grounds (Allison et al., 2019; Hanssen et al., 2020; Watson et al., 2018). Post-construction, site-specific shutdown algorithms are used to regulate the operation times of a WT, based on certain local conditions. Such local conditions might be e.g., an increased activity of collision-prone species during migration or the occurrence of abiotic conditions such as certain wind speeds that favour the presence of collision-prone species at critical flight altitudes (Allison et al., 2019; Arnett et al., 2011; de Lucas et al., 2012).

Both flight activity and flight altitude are important variables for assessing the collision risk of a species. As collisions of birds only occur during flight, the collision risk increases with increasing flight activity. Hence, it is not surprising that rather active raptors, such as White-tailed Sea Eagles (*Haliaeetus albicilla*), Montagu's Harriers (*Circus pygargus*) or Red Kites (*Milvus milvus*), are among the ten most frequent collision victims at wind turbines in Europe (Dahl et al., 2013; Dürr, 2021; Heuck et al., 2019; Krone et al., 2009; K. Mammen et al., 2017; Schaub et al., 2020). First studies indicate that flight activity increases with increasing wind speeds (Heuck et al., 2019). However, collision risk is highest while flying in altitudes of the critical rotor-swept area (RSA), which is the area regularly traversed by the rotors of a WT, extending from the lower to the upper rotor-tip. Naturally, the probability of flying in the RSA differs between species: Red Kites and White-tailed Sea Eagles fly mostly at altitudes of up to 100 m or 200 m, respectively, and thus have a higher collision risk than e.g. Montagu's Harriers, which fly mostly at an altitude of < 10 m above ground (Heuck et al., 2019; Schaub et al., 2020; Tikkanen et al., 2018). Overall, flight altitude of raptors decreases with increasing wind speeds (Heuck et al., 2019; Lanzone et al., 2012; Panuccio et al., 2017). To conclude, to implement site-specific mitigation measures profound knowledge about the ecology and behaviour of the locally occurring collision-prone species is indispensable.

To contribute to the improvement of mitigation measures and thus to a sustainable expansion of wind energy, we studied the flight activity and flight altitude of Red Kites as a function of wind speed. We expected that (I) the flight activity of Red Kites increases with wind speed, while (II) the flight altitude should decrease with wind

speed. Based on these analyses, we aim on identifying wind speed ranges of highest collision risk for this soaring raptor.

## Material and Methods

### Study species

Red Kites are diurnal raptors that are endemic to Europe where their population is estimated to consist of 32,200 – 37,700 breeding pairs (BirdLife International, 2020). Their main distribution range is in Central Europe, with Germany being home to about 14,000 – 16,000 breeding pairs. Thus, Germany has a great responsibility for the protection and conservation of the species (Grüneberg & Karthäuser, 2019). Hence, Red Kites are one of the most discussed species in the context of the wind energy expansion in Germany. It is one of the most frequent raptors to collide with wind turbines in Europe and Germany (Dürr, 2021). As a synanthropic species, the Red Kite forages opportunistically for carrion, small mammals and birds as well as insects, amphibians and fish mainly in open cultivated landscapes and in smaller settlement areas. (Aebischer, 2009; Barton & Houston, 1996; BirdLife International, 2020; Heuck et al., 2019; K. Mammen et al., 2017). As it almost exclusively shows an active searching foraging behaviour, it is a rather active species that spends significant parts of the day in flight (Aebischer, 2009; Barton & Houston, 1996; Heuck et al., 2019; K. Mammen et al., 2017).

### Study area

The study was conducted in the federal state of Hesse, Germany. Except for the centres of human population, the Red Kite is distributed

here almost state-wide with regional breeding densities of up to eleven breeding pairs per 100 km<sup>2</sup> (Gelpke & Stübing 2010, Stübing et al. 2010). The state area of 21,115 km<sup>2</sup> is characterized by low mountain ranges with altitudes ranging from 75 – 950 m a.s.l. There are currently 1,133 operating WT in Hesse. An additional number of 31 turbines are about to be commissioned and a number of 267 are planned in the study area (status 14<sup>th</sup> July 2021; HLNUG 2021). The operating WT have a hub height of 111 m ± 35 m (mean ± SD hereafter) and a rotor diameter of 88 m ± 31 m (HLNUG 2021). Future WT (status: before commissioning or planned) are taller, with a hub height of 157 m ± 14 m and a rotor diameter of 144 m ± 18 m. Based on hub height and rotor diameter we calculated the critical rotor-swept area (RSA) for operating and future WT from the lower to the upper rotor tip. For the operating WT in the study area the critical RSA ranged from 67 m ± 22 m to 155 m ± 50 m above ground. The future critical RSA, based on WTs in the study area that are currently in the approval procedure or shortly before operation, is higher, ranging from 85 m ± 10 m to 229 m ± 21 m.

### Movement data

The study was based on 26 Red Kite individuals (12 females, 14 males) whose territories were scattered over the study area. These individuals were caught during the breeding seasons of 2017, 2018 and 2019 in proximity to their nests using the dho-gaza method with a stuffed Eagle Owl (*Bubo bubo*) as a lure (Bloom et al., 2007). All captured birds were measured (wing length and body mass) and banded with individual rings from the Institute of Avian Research (IAR), Vogelwarte Helgoland. We determined the sex via morphological measures and the presence of a brood patch.

Using a backpack harness made of Teflon ribbon, we fitted solar-powered GPS-GSM transmitters with a barometer (Ornitela E-25-B) on the birds' backs. The data acquisition via the transmitters depended on the battery level and varied between five-minute intervals to up to eight-hour intervals between the GPS locations during daytime only.

For the analyses, we used the movement data collected by the study individuals between 2018 and 2020. We only used data within the breeding habitats, starting with the day when all individuals had reached their territories after spring migration until the last day before the first individual started autumn migration (beginning of March to end of September, exact date depended on the year) (see Spatz et al. *in revision*) for details on how the end of the migration was determined). Data were processed by removing all zero coordinates (no GPS signal received), duplicates (same timestamp and same position), GPS locations with speeds above 35 m/s (faulty GPS acquisition; outliers) as well as positions with a recorded horizontal dilution of precision (hdop) over 10 (inaccuracy of the GPS location). Furthermore, we excluded data of all female individuals in April and May, which corresponds to the breeding season of Red Kites, when the females almost exclusively incubate the clutch (Aebischer, 2009). Hence, there is an intrinsic motivation not to fly regardless of the weather conditions. Due to mortality or transmitter failures tracking time varied between individuals ranging between a few months and three years. Overall, this resulted in a data set of 864,375 GPS locations, collected over three years by 26 individuals.

### Wind speed data

To determine the local wind speed at each GPS location, we used ERA5-Land data provided by the European Centre for Medium-Range Weather Forecasts (ECMWF; Copernicus Climate Change Service, 2019; Muñoz Sabater, J., 2019). It comprises raster data, with a resolution of  $0.1^\circ \times 0.1^\circ$  corresponding to about 11.0 km x 11.0 km and is based on re-analysed model and observation data. Amongst other variables it provides hourly u- (east-west) and v- (north-south) wind components in a standardized height of 10 m above ground. These data can be used to calculate the hourly local wind speed in 10 m above ground in m/s by using the following formula:

$$|\vec{v}| = \sqrt{u^2 + v^2}$$

Based on date and hour of the timestamps of the GPS locations, we matched the hourly local wind speed at 10 m above ground using the *raster*-package in R (Hijmans, 2016; R Core Team, 2013). All wind speeds were rounded to the nearest tenth m/s.

### Flight activity and flight altitude

GPS locations with a ground speed  $> 3$  m/s were classified as “in flight”, and GPS locations with a ground speed of  $\leq 3$  m/s as “stationary” (Nathan et al. 2012). To determine the flight activity, we divided the number of GPS locations in flight by the number of total GPS locations for each individual and wind speed at 1 m/s resolution separately.

The flight altitude was measured by the transmitters in two different ways: via GPS and via barometer sensors. The altitude determined via barometer is considered more accurate, if the barometer is re-calibrated for the local weather conditions, especially the local air pressure and temperature (Péron et al., 2020). Therefore, we

performed a post-hoc re-calibration of the barometric altitude, following the approach of Heuck et al. (2019). For a detailed description of the re-calibration please see Supplementary Material 1.

As the barometric altitude is given in meters above sea level a correction for topography was necessary to get the flight altitude above ground. Therefore, we used the EU-DEM v1.1 of the Copernicus Land Monitoring Service, which is raster data with a spatial resolution of 25 m x 25 m and a vertical accuracy of 7 m (J. C. G. González et al., 2015). We determined the topographic height above mean sea level for each GPS location using the *raster*-package in R and subtracted it from the corrected barometric altitude to get the flight altitude above ground for each GPS location (Hijmans, 2016; R Core Team, 2013).

Through processing of the altitude data, we were able to reduce the mean transmitter-specific vertical error from  $\pm 27.6$  m for GPS-altitude, and  $\pm 5.8$  m for the barometric altitude to only  $\pm 4.4$  m. In consequence, the number of points in flight, which had GPS-recorded heights below ground level decreased from 42,867 (4.9% of the total points) to 8,191 (0.9% of the total points) after correction and calibration of the barometric altitude. However, as heights below 0 m a.s.l. do not occur in the study area and Red Kites are not able to fly below ground, these points could be defined as outliers. But, as truncating the data at ground level would artificially shift the determined mean flight altitudes upwards, we left these points in the overall dataset.

For the analysis of the flight altitude of Red Kites, we only used GPS locations classified as “in flight” with corresponding altitude data ( $n = 294,611$ ).

### Statistical Analysis

To assess the impact of wind speed on (I) the flight activity patterns and (II) flight altitudes of Red Kites, we used generalized additive models (GAM; *mgcv*-package, Wood, 2011). GAMs assume a non-linear relationship between the variables and try to approximate the given relationship as closely as possible by integrating a smooth-term function in the explanatory variables. In our models, we used the smoothed wind speed as explanatory variable and added the individual bird as a random factor to account for individuality. We added the total number of GPS locations (stationary and in flight) recorded per wind speed in 0.1 m/s resolution as weighting factor in the models, to account for the different frequencies in which wind speeds occurred to avoid rarely occurring wind speeds being overvalued. As dependent variable with gaussian distribution we used (I) the flight activity and (II) the corrected and calibrated flight altitude above ground of the Red Kites

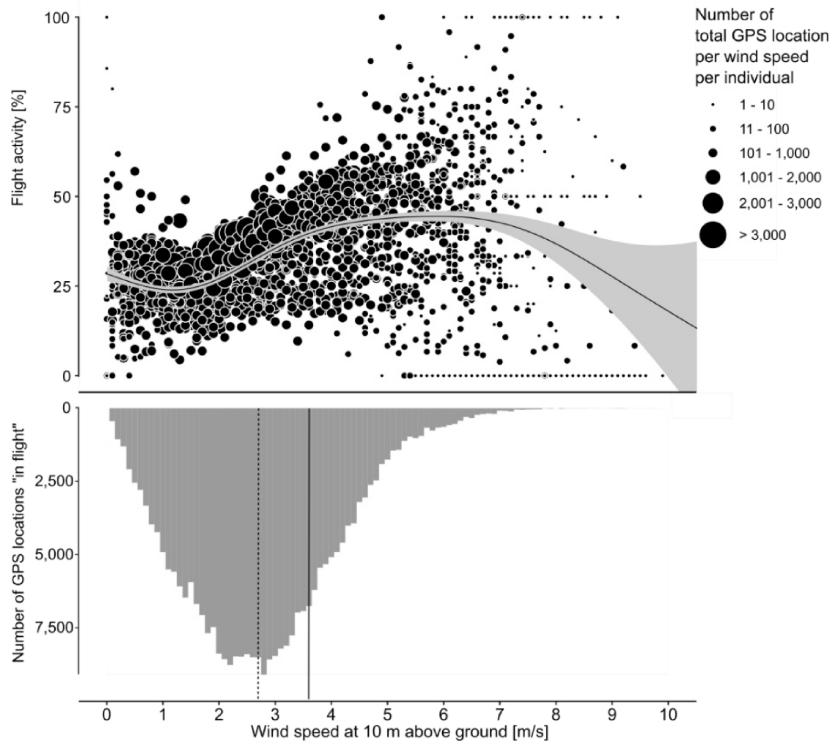
### Results

During the study period the occurring wind speeds at 10 m above ground ranged from

0.0 m/s to 10.5 m/s, with a mean  $\pm$  SD of  $2.5 \pm 1.3$  m/s. Only 0.9% of the overall data was recorded during wind speeds higher than 6 m/s (Figure 1). The range of wind speeds during which Red Kites were recorded “in flight” spanned from 0.0 m/s to 9.7 m/s with a mean  $\pm$  SD of  $2.7 \text{ m/s} \pm 1.3 \text{ m/s}$ . 50% and 75% of the GPS locations in flight were recorded at wind speeds up to 2.7 m/s and 3.6 m/s, respectively.

The flight activity of the Red Kites depended significantly on the wind speed (GAM: estimated degrees of freedom (edf) = 6.388,  $p < 0.001$ ,  $R^2_{\text{adj}} = 0.75$ , Figure 1). At wind speeds between 0.0 and 2.0 m/s the Red Kites were least active with the flight activity predicted by the model ranging around  $25.4\% \pm 0.7\%$  (mean  $\pm$  SD). Starting from wind speeds above 2.0 m/s at the flight activity of Red Kites increased with increasing wind speed. At moderate wind speeds of 4.8 m/s to 6.8 m/s the highest level of activity was reached with a mean predicted flight activity of  $44\% \pm 6.9\%$ . As very high wind speeds hardly occurred during the study period (March–September) the empirical assessment of the flight activity at wind speeds  $> 6$  m/s (covering only 0.9% of the data) was limited (Figure 1).

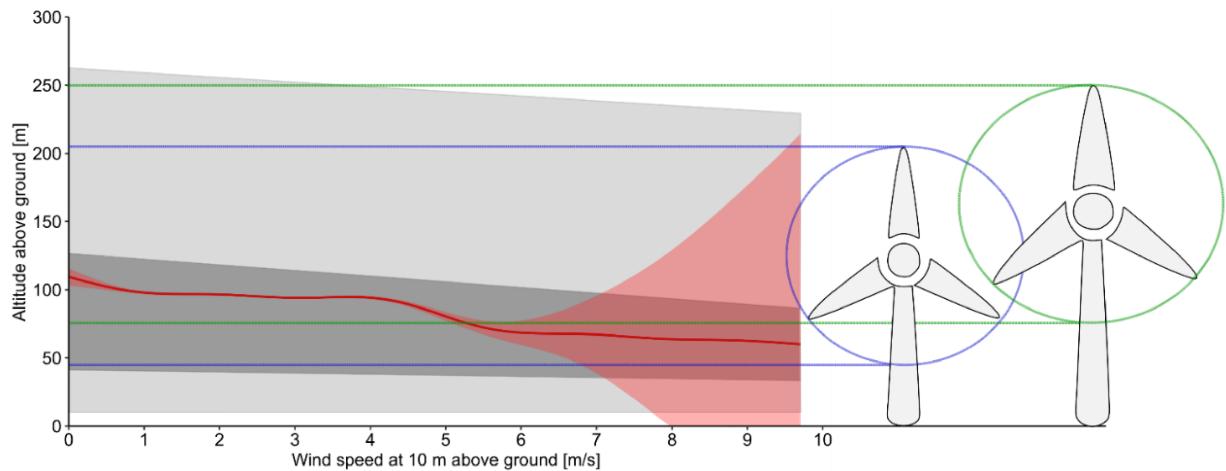
**Fig. 1:** Flight activity [%] of 26 GPS-tagged Red Kites (*Milvus milvus*) during breeding season (March-September) from 2018 to 2020 in relation to wind speed at 10 m above ground [m/s] in Hesse, Germany. (Top) The black line marks the mean flight activity predicted by the Generalized Additive Model (GAM, edf = 6.388,  $p < 0.001$ ,  $R^2_{adj} = 0.75$ ). The grey area is the confidence interval of the prediction. The size of the points gives the total number of GPS locations



(stationary and in flight) recorded per windspeed per individual. The highest flight activity of  $44\% \pm 6.9\%$  was reached in wind speeds between 4.8 and 6.8 m/s. (Bottom) Number of GPS locations recorded “in flight” per wind speed in 0.1 m/s resolution. 50% (dashed line) respectively 75% (solid line) of the recorded GPS locations “in flight” took place in wind speeds up to 2.7 m/s and 3.6 m/s.

Overall Red Kites flew at a mean altitude of  $101 \text{ m} \pm 110 \text{ m}$  above ground. The central 50% of the flights took place in heights of 38 m to 127 m above ground ( $Q_{25} - Q_{75}$ ). Across the entire range of occurring wind speeds, the flight altitude decreased non-linearly with increasing wind speed (GAM; edf = 5.93,  $p < 0.001$ ,  $R^2_{adj} = 0.029$ ; Figure 2). However, the smoothed curved could be separated in three sections: at wind speeds up

to 1.0 m/s, the flight altitude ranged around  $109 \pm 4 \text{ m}$  while decreasing by  $-1 \pm 2 \text{ m}$  per 0.1 m/s. At wind speeds between 1.0 and 4.4 m/s the flight altitude of Red Kites was stable ( $0 \text{ m} \pm 1 \text{ m}$  per 0.1 m/s) at around  $102 \text{ m} \pm 1 \text{ m}$  according to the model predictions. At wind speeds between 4.4 m/s and 6.0 m/s the mean flight altitude dropped below 100 m and declined with approximately 1 m  $\pm 2 \text{ m}$  per 0.1 m/s, ranging around  $83 \text{ m} \pm 8 \text{ m}$ .



**Fig. 2:** Distribution of the flight altitudes above ground [m] of 26 adult Red Kites (*Milvus milvus*) during breeding season (March-September) from 2018 to 2020 in relation to wind speed at 10 m above ground [m/s] in Hesse, Germany. The flight altitude depended significantly on the wind speed (red line with light red confidence interval; GAM: edf = 5.93,  $p < 0.001$ ,  $R^2_{adj} = 0.029$ ). The dark grey area corresponds to the middle 50% of the data ( $Q_{25} - Q_{75}$ ). The light grey area corresponds to the middle 95% of the data ( $Q_{2.5} - Q_{97.5}$ ). 32% – 57% of the Red Kites' flights occurred within the critical rotor-swept area (RSA) of operating wind turbines in the study area ( $67 \text{ m} \pm 22 \text{ m}$  to  $155 \text{ m} \pm 50 \text{ m}$ ; solid blue lines mark the mean + SD). As new taller wind turbines are planned ( $85 \text{ m} \pm 10 \text{ m}$  to  $229 \text{ m} \pm 21 \text{ m}$ ; solid green lines mark the mean + SD), the percentage of flights within the critical RSA would decrease to 31% - 37%.

The empirical assessment at wind speeds  $> 6 \text{ m/s}$  was limited as high wind speeds hardly occurred during the study period. (Figure 2)

Regardless of the wind speed about 32% – 57% of the Red Kites' flights were recorded in heights of the RSA of operating WTs. Despite the general trend of decreasing flight altitudes with increasing wind speeds, the percentage of flights within the RSA only slightly decreased to 31% – 56% in wind speeds between 4.4 m/s and 6.0 m/s. The critical RSA of future WTs is higher than

that of operating WTs. In these altitudes about 31% – 37% of the Red Kites' activity took place, regardless of the wind speed. Taking the general trend of decreasing flight altitudes with increasing wind speeds into account, the percentage of flights within the critical RSA of future WTs declined to 28% – 35%. Hence, with the installation of taller wind turbines the percentage of flights within the critical RSA would be reduced by 4% – 23% (Table 1).

**Tab. 1:** The flight altitude of 26 adult Red Kites during breeding season decreased with increasing wind speed non-linearly (GAM: edf = 5.93, p < 0.0001, R<sup>2</sup><sub>adj</sub> = 0.029). Wind speed sections in which flight altitude showed certain trends were identified visually from the GAM. The central 50% of the flight altitudes above ground [m] (quantiles Q<sub>25</sub> – Q<sub>75</sub>), the percentages of GPS locations recorded within the critical rotor-swept area (RSA) of operating wind turbines and of future wind turbines are given for each wind speed section and for the overall range of occurring wind speeds.

Wind speed at 10 m above ground [m/s]	0.0 – 1.0	1.1 – 4.4	4.4 – 6.0	Overall
Central 50% of flight altitudes above ground [m]	41 – 137	38 – 129	35 – 107	38 – 127
Flights within RSA of operating wind turbines [%]	32 – 58	32 – 57	31 – 56	32 – 57
Flights within RSA of future wind turbines [%]	33 – 40	31 – 38	28 – 35	31 – 37

## Discussion

Our analysis of flight activity and altitude of Red Kites during the breeding season showed that 50% and 75% of their flights took place in wind speeds up to 2.7 m/s and 3.6 m/s at 10 m above ground, respectively. The flight activity increased with wind speed until it reached a plateau of maximum activity at wind speeds of about 4.8 m/s to 6.8 m/s. The flight altitude of the Red Kites decreased non-linearly with wind speed. Regardless of wind speeds, a significant part (32% – 58 %) of their flights took place within the critical rotor swept area (RSA) of operating wind turbines (WTs) in the study area. As future WTs are planned to be taller, the RSA shifts upwards, reducing the proportion of flights within the future RSA to 31% to 37%.

Overall, Red Kites showed a high flight activity across the entire range of occurring wind speeds. In wind speeds between 0.0 m/s and 2.0 m/s, Red Kites were least active. This minimum activity of the Red Kites presumably reflects their minimum activity necessary to fulfil basic needs, as in calm wind speeds without supporting uplifts, a more active flight behaviour is necessary,

which is considered to be energy costly (Hedenström & Bone, 1993). Red Kites, however, are actively searching birds foraging in flight, and thus depend largely on less energy consuming soaring flights (Aebischer, 2009; Barton & Houston, 1996). For soaring, thermal and orographic uplifts are used that rely on suitable weather conditions (Hanssen et al., 2020; Hedenström & Bone, 1993; Péron et al., 2017). Accordingly, the flight activity of Red Kites increased with increasing wind speeds, as expected, and peaked at wind speeds of 4.8 m/s to 6.8 m/s. Our findings are in line with those of Heuck et al. (2019), who also found an increasing activity of Red Kites with increasing wind speed as well as similar ranges of occurring flight activities (here: 24% – 44%, Heuck et al. (2019; ca. 25% – 50%).

The high flight activity across the entire range of occurring wind speeds suggests an overall high collision risk with WT, independent of wind speed. This finding of our study contradicts the collision risk assessment by Schreiber (2016), where only wind speeds < 2m/s were rated with the highest risk, while further increasing wind speeds were rated with decreasing collision risk.

However, the authors of the risk assessment themselves stated that there is a knowledge gap regarding the space use of Red Kites in higher wind speeds. Our study thus highlights the potential of large datasets of transmitter-based movement data to fill such knowledge gaps and to contribute to the evaluation and development of efficient mitigation measures.

In contrast to flight activity, the overall flight altitude of Red Kites decreased non-linearly with increasing wind speeds, which is coherent with the results of Heuck et al. (2019). However, up to wind speeds of approximately 4.4 m/s the predicted mean flight altitude of Red Kites was constantly higher than 100 m above ground, which is within the critical RSA of both existing and future WTs. Flight altitudes showed a stronger decline, dropping to  $83 \text{ m} \pm 8 \text{ m}$  only with further increasing wind speeds. Taking the constant flight altitudes  $> 100 \text{ m}$  above ground and the increasing flight activity with increasing wind speeds into account, we derive a constantly high collision risk at least up to wind speeds of 4.4 m/s at 10 m above ground in the study area.

Across the entire range of occurring wind speeds, our data showed a large variance in flight altitudes of Red Kites, resulting in significant proportions of flights (up to 58%) taking place within the critical RSA of currently operating wind turbines in the study area, which corroborates the above-mentioned findings. The percentage of flights within the critical RSA in our study was comparable to the results of Mammen et al. (2017), but higher than those reported by Heuck et al. (2019) or Hötker et al. (2017). These differences are most likely due to different heights of WTs in the study areas used as basis for defining the critical RSA. Moreover, our findings show that, the current development of installing higher WTs with higher RSA may lead to a slight

decrease of collision risk for the Red Kite and other species flying at low altitudes, e.g., Montagu's Harriers (Schaub et al., 2020). However, the flight activity of 31% to 37% within the critical RSA of future WT is still high. This highlights the necessity for site-specific assessments and adaption of mitigation measures to local conditions and abundances of collision-prone species. It further shows that existing risk assessments should be adapted regularly, as WTs will continue to evolve in the future leading most likely to shifts of the RSA and an altered risk for collision-prone species.

Overall, our findings could be a basis for future mitigation measure to avoid collision risk of Red Kites at WT: About 50% of the flights took place in wind speeds of up to 2.7 m/s at 10 m above ground, and 75% in wind speeds of up to 3.6 m/s. In those rather calm wind speeds also the flight altitude was highest, ranging within the critical RSA of both, operating and future WTs. Consequently, we actively call for raising the cut-in wind speeds of WTs to enable that significant parts of the Red Kites' activity in altitudes of the critical RSA could take place without collision risk. Thus, the overall collision risk of Red Kites might get reduced significantly, especially in central areas of the Red Kite breeding population. Raising the cut-in speed of WTs has already been proven to be a useful mitigation measure for bats (e.g. Allison et al., 2019; Arnett et al., 2011). By raising the cut-in speed the nightly mortality rate of bats was reduced by 44 % to 93 %. As the power generated by WTs increases with wind speed, the annual power loss was with  $\leq 1\%$  marginal and associated financial losses were limited when cutting calm winds (Arnett et al., 2011; Lydia et al., 2014). Hence, this could be a promising approach to further promote the sustainable

expansion of renewable energy, while at the same time protecting collision-prone species.

However, one has to be aware that in our study we used wind speeds at a standardized altitude of 10 m above ground. As wind speeds increase with altitude, the here given wind speeds differ from the ones at hub height, which are relevant for the cut-in wind speeds (Bañuelos-Ruedas et al., 2010). Hence, the wind speeds should not be used without interpolation to hub height. To interpolate wind speeds for higher altitudes, it is important to consider the underlying landscape, as due to the different roughness of the various land-use types the slope in which wind speeds increase with altitude varies (e.g., slower increase of wind speeds with altitude in forests than in open landscapes; Bañuelos-Ruedas et al., 2010). Besides the landscape also the locally occurring wind speeds need to be taken into account. In our study area wind speeds higher than 6 m/s at 10m above ground hardly occurred. This might be different in other parts of the Red Kites' distribution range, hence, the wind speeds at which 50% or 75% of the activity is reached might differ. Therefore, site-specific assessments should be conducted, and the cut-in speeds adapted accordingly.

Further research is needed especially to better understand the drivers of the flight altitudes of collision-prone species. In our study the model predicting flight altitude explained the variance in the data poorly, which suggests that additional underlying drivers need to be considered. As the flight altitude and flight activity of Red Kites as well as other space use variables, such as daily flight distances or displacement from the nests changes throughout the year, additional drivers are likely to be found in the phenology of Red Kites (Heuck et al., 2019; Spatz et

al., 2019). Additionally, the landscape most likely plays a crucial role, as land use types, landscape diversity and NDVI affect the movement patterns of Red Kites (Aebischer, 2009, Spatz et al., in Review). Especially given the increase in WT construction in forests in some areas, an in-depth analysis of flight altitudes over different habitat types is indispensable for risk assessment. Presumably, Red Kites flight altitudes may be higher over forests, and the probability to fly within the critical RSA may be higher than over agricultural land. Hence, landscape-related analyses enable to improve micro-siting of wind turbines and to adapt mitigation measures even more specifically to local conditions.

In conclusion, the mere establishment of taller wind turbines will not sufficiently reduce the collision risk of Red Kites. Mitigation measures pre- and post-construction will continue to be indispensable in the future and further improvements of those are necessary to reduce the collision risk. We suggest implementing additional mitigation measures, such as raising cut-in wind speeds of WTs, which should be adapted to local conditions, hence, taking the locally occurring wind speeds as well as the surrounding landscape into account. Additionally, we suggest re-evaluating risk assessments regularly, as changing local conditions and technical improvements of WTs alter the collision risk of species. Transmitter-based movement data of reasonable sample size of collision-prone species gives valuable insights into their three-dimensional space use. With such profound knowledge site-specific mitigation measures could be improved to support a sustainable expansion of wind energy while at the same time actively conserving a collision-prone species of international importance.

## Supplementary Material

### Correction of the flight altitude

The flight altitude was measured by the transmitters (Ornitela 25B-E) in two different ways: 1) via GPS and 2) via an integrated barometer. Both methods have their constraints. The accuracy of GPS relies on the number of connected satellites (the higher the more precise) and their positions as well as on the horizontal and vertical dilution of precision (Péron et al., 2020). The barometric altitude, however, is calculated with the air pressure recorded by the transmitters' barometer that is inserted in the Barometric formula. Therefore, the international standard atmosphere is used (pressure  $p_0 = 1013.25 \text{ hPa}$ , temperature  $T = 15^\circ\text{C} = 288.15 \text{ K}$ , laps rate = 6,5 K/1.000 m). However, air pressure and temperature both depend on local weather conditions. Hence, the barometric altitude is only more accurate, when the barometer is re-calibrated in relation to the local weather conditions (Péron et al., 2020). Hence, we post-hoc re-calibrated the barometric altitude following the approach of Heuck et al (2019) to receive reliable barometric altitudes.

First, we calculated the air pressure measured by the integrated barometer  $p_h$  using the following formula:

$$p_h = p_0 \left(1 - \frac{h}{44330.77 \text{ m}}\right)^{5.255877}$$

In a second step we determined for each GPS location the three nearest weather stations of the Deutscher Wetterdienst (DWD) that provide air pressure data normalized on mean sea level. To avoid pseudo-accuracy, we tested the air pressure data of the three stations for correlation. Since the air pressure data of all three stations

was strongly correlated, we used only the air pressure of the nearest station for the subsequent correction (Table S1).

**Tab. S1:** The air pressure was highly correlated between the three weather stations nearest to the respective GPS location. Given are the correlation coefficient R and the p-value.

	Correlation coefficient R	p-value
Station 1 :	0.997	<0.0001
Station 2		
Station 2 :	0.996	<0.0001
Station 3		
Station 1 :	0.997	<0.0001
Station 3		

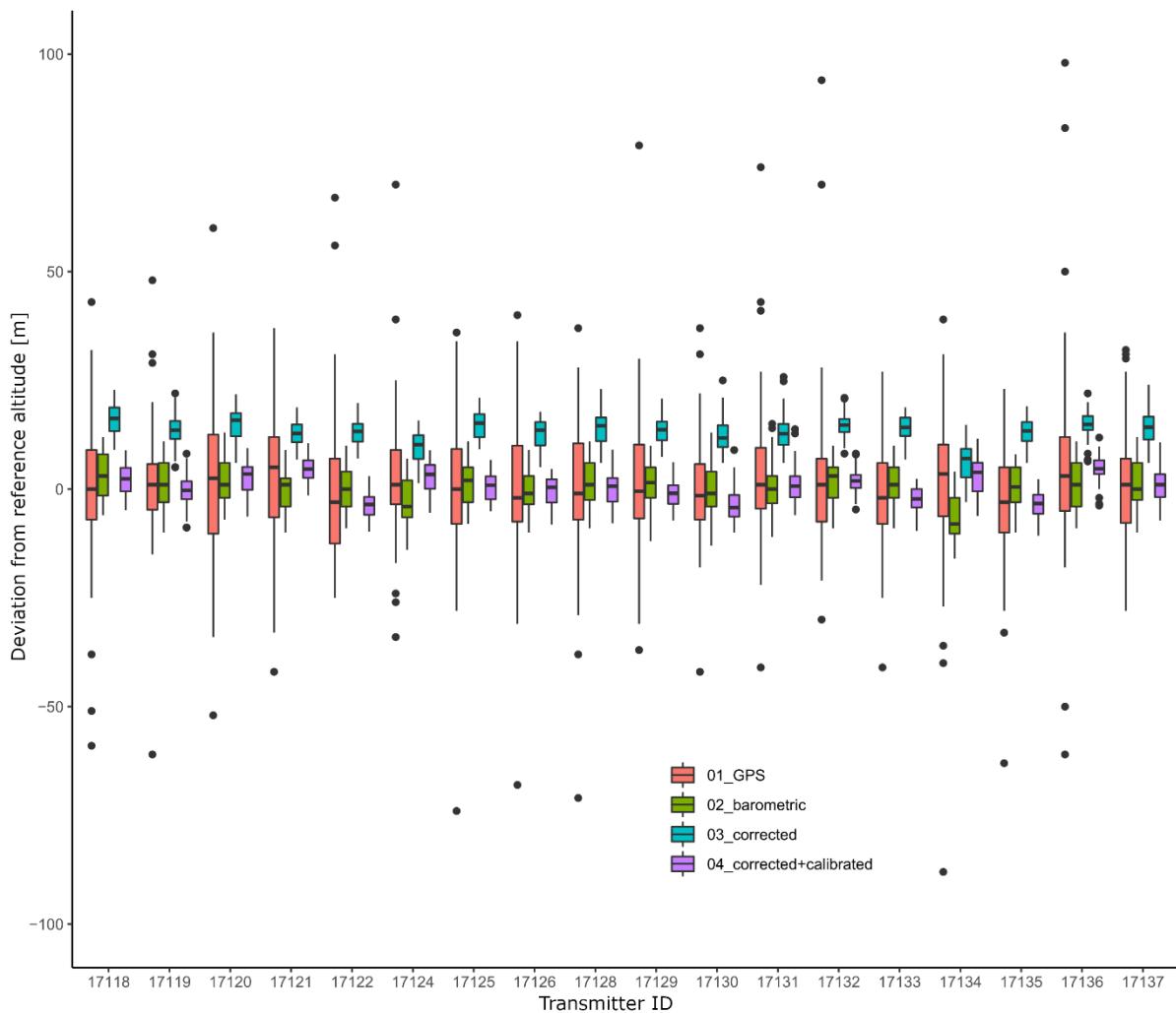
We inserted the air pressure measured by the integrated barometer  $p_h$ , the air pressure measured at the nearest weather station as  $p_0$  and the temperature measured by the transmitter  $T$  in the following formula to calculate the corrected altitude:

$$h = \frac{T}{0.0065 \frac{K}{m}} \left(1 - \left(\frac{p_h}{p_0}\right)^{0.1902632}\right)$$

In the next step a transmitter specific calibration was necessary. Therefore, we used calibration data of a transmitter test run that was performed before deploying the transmitters to the birds. As the transmitters were purchased at different times of the project, the test runs differed in timespan (36 to 48 hours) and date. During all test runs the individual transmitters laid on top of a roof under open sky, taking one GPS location approximately every 5-15 minutes. We corrected the barometric altitude of the test

run data as described above. As during the test runs the median of the GPS altitude hardly differed between transmitters and corresponded to the estimated height of the roof, this median was used as reference height for the calibration.

We determined the transmitter specific error as the difference between the corrected barometric height and the reference height. This transmitter specific error was subtracted from the corrected barometric height for calibration (Figure S1).



**Fig. S1:** Deviation of the measured altitude from the reference altitude of 18 transmitters during a transmitter test in 2017. The altitude recorded by GPS fluctuated the most (red) but had the same median altitude as the less scattered barometric altitude (green). The barometric altitude after correction for local air pressure (blue) is systematically higher than the reference altitude, which illustrates the necessity of the additional transmitter-specific calibration (purple). Two outliers (deviation of GPS altitude > 300m) are not shown for better visualization. Given are the middle 50 % of the data in the boxes, with the median as solid line and the whiskers marking values outside the box to maximum 1.5 of the inter-quartile range. Outliers are shown as dots.



## **Chapter IV – Sex, landscape diversity and primary productivity shape the seasonal space use of a migratory European raptor**

Theresa Spatz, Jakob Katzenberger, Nicolas Friess, Christian Gelpke, Eckhard Gottschalk, Martin Hormann, Steffen Koschkar, Thomas Pfeiffer, Stefan Stübing, Christoph Sudfeldt, Sascha Rösner, Dana Schabo, Nina Farwig (in review: Journal of Avian Biology)

### **Abstract**

Intrinsic and extrinsic drivers shape the space use of wide-ranging raptors. A large proportion of raptors are migrants that shift their activity ranges between summer and winter habitats, where they encounter with different environmental conditions. Analysing the effects of intrinsic and extrinsic drivers on the space use in summer and winter habitats provides crucial insights into the ecology of migratory raptors. Here, we investigated the seasonal space use by 43 Red Kites (*Milvus milvus*) tracked by GPS-transmitters across central and south-western Europe over seven years. We compared space use patterns, i.e., activity range sizes and mean daily distances of the birds between summer and winter, and analysed the influence of extrinsic (landscape diversity, primary productivity) and intrinsic factors (sex). Within summer, we investigated the influence of breeding success and sex on activity range sizes. We further analysed differences in habitat availability and habitat selection between seasons. We found that space use was smaller in summers than in winters. When compared to those of males, activity ranges of female Red Kites were larger in summers and smaller in winters, with shorter mean daily distances in both seasons. Within summer, breeding success led to decreasing activity range sizes in both sexes, whereas this effect was stronger for females than for males. Regardless of the season, landscape diversity was positively correlated with space use, whereas primary productivity was negatively correlated with it. The habitat availability differed between seasons, with agricultural landscapes being less proportionally used in summers than in winters. Overall, we showed that both intrinsic and extrinsic drivers shaped space use in both the seasons, leading to differences in space use patterns and habitat use in migratory raptors between their summer and winter habitats. Our findings underline the importance of consideration of the entire annual cycle of migratory species for conservation management.

## Introduction

Through their ability to fly, birds are highly mobile animals. Their space use is influenced by several extrinsic drivers, such as the availability and distribution of resources, and intrinsic drivers, such as sex or reproductive status (La Sorte et al., 2014; Nathan et al., 2008; Tucker et al., 2019). By understanding these drivers and their influence on space use, we can derive important information on e.g., mortality or reproduction, and thus ultimately draw conclusions about the population dynamics of these mobile animals (Morales et al., 2010; Nathan et al., 2008).

About 19% of all bird species are migrants that shift their activity ranges between summer and winter habitats to live in an environment that promotes survival (Kirby et al., 2008). By intersecting movement data of migrants with satellite-derived land cover data or vegetation indices, extrinsic drivers of space use across large spatial scales can be assessed (e.g., La Sorte et al., 2014; Mirski et al., 2021; Trierweiler et al., 2013; Tucker et al., 2019). Migrating birds follow resources, which they can explore over large spatial scales (Klaassen et al., 2010; La Sorte et al., 2014). The extent of space use further depends on landscape diversity, as more diverse landscapes provide more resources within smaller ranges (Mirski et al., 2021; Tews et al., 2004; Tucker et al., 2019). Likewise, the availability of key habitats (e.g., grasslands used for hunting) has been directly linked to space use in birds, as increasing proportions of key habitats lead to decreasing activity range sizes (Mirski et al., 2021).

In addition to these extrinsic drivers, intrinsic drivers such as territoriality and reproduction also influence space use (Brodin et al., 2003; Hernández-Pliego et al., 2017; Mirski et al.,

2021). During the breeding season, many bird species show a reproductive role specialization between sexes, with females incubating the eggs and males providing food, which often results in smaller activity ranges of females compared with that of males (Brodin et al., 2003; Hernández-Pliego et al., 2017; Mirski et al., 2021; Pfeiffer & Meyburg, 2015; Spatz et al., 2019; Wesolowski, 1994). Breeding success is also known to influence the activity range size in birds, especially that of the male parent (Pfeiffer & Meyburg, 2015). Sex-specific differences in space use may disappear at the end of the breeding season, e.g. when both sexes are engaged in chick rearing or at the end of the summer shortly before autumn migration begins (Brodin et al., 2003; Hernández-Pliego et al., 2017; Spatz et al., 2019).

Beside such variations in space use within seasons, there are also variations between seasons. For example, the Wood Thrush (*Hylocichla mustelina*) prefers smaller forest patches during the breeding season (summer), but larger forest patches during winter (Stanley et al., 2021). Male Montagu's harriers (*Circus pygargus*) fly shorter distances during winter than during summer, while females show the opposite space use pattern (Schlaich et al., 2017). Similarly, Spanish Imperial Eagle (*Aquila adalberti*) activity ranges during the non-breeding season (winter) are smaller than during the breeding season (summer) (Fernández et al., 2009). By intersecting seasonal movement data with extrinsic and intrinsic drivers, we expect to gain a better understanding of the ecology of migratory birds.

Approximately 25% of the raptors in Africa and Eurasia are migratory (Goriup & Tucker, 2007). As they have comparably large body sizes

and are often top predators, raptors have extensive space requirements (Peery, 2000). Additionally, they are used as flagship species in conservation (Sergio et al., 2006). Therefore, they are a suitable study group. We used the Red Kite (*Milvus milvus*), a short distance migratory raptor and a generalist forager, as the model species to compare the space use patterns of both sexes during summer and winter. Like many raptors, Red Kites show a strong breeding-site fidelity during summer and site fidelity during winter (Aebischer, 2009; Jenkins & Jackman, 1993; Pfeiffer & Meyburg, 2009, 2015; Shiu et al., 2006; Trierweiler et al., 2013; own observation). They are central-place foragers that show reproductive role specialization between the sexes, which is reflected in their movement during the breeding season in summer (Heuck et al., 2013; Mirski et al., 2021; Pfeiffer & Meyburg, 2015). Furthermore, although Red Kites are territorial during the breeding season, they show communal roosting in the late post-breeding period during summer and during winter, as well as communal foraging in highly attractive foraging grounds (Aebischer, 2009). Using GPS-data of 43 adult Red Kites (16 females, 27 males), collected over five summers and six winters, we calculated activity ranges and mean daily distances, and related these to landscape parameters, namely landscape diversity and primary productivity, of summer and winter habitats. We further compared the habitat availability within the activity ranges and the habitat selection between seasons.

### **(I) Effect of landscape diversity, primary productivity and season on activity range and daily distance**

Owing to the communal roosting in winter and the territoriality of Red Kites during summer, we expected (1 a) larger activity ranges and daily distances during winter than during summer, but

(1 b) the activity ranges and daily distances to decrease with increasing landscape diversity and increasing primary productivity, regardless of the season. Owing to the reproductive role specialization of Red Kites during the breeding season, we expected (1 c) no differences between sexes during winter, but smaller activity ranges and daily distances for females than for males during summer. Within summer, we expected (1 d) the activity ranges of non-breeders or unsuccessfully breeding Red Kites to be larger than those of successfully breeding individuals; however, within successfully breeding Red Kites the activity range of females should be smaller than that of males.

### **(II) Differences in habitat availability and habitat use between seasons**

As winter and summer habitats of Red Kites are located in distinct areas with different landscape features, we expected (2 a) differences in the availability of various land-use types within the activity ranges between summer and winter habitats and checked for individual preferences in the habitat availability that persist over seasons (e.g., high amounts of grassland within the activity range of an individual in winter and summer habitats). In the second step, we analysed the overall use of certain habitats of Red Kites and compared them between seasons. We expected (2 b) land-use types significant for foraging (agricultural landscapes and grasslands) to be used with similar intensity during summer and winter, while the land-use types significant for nesting (forests) to be used more in summer than in winter.

## Materials and Methods

### Study species

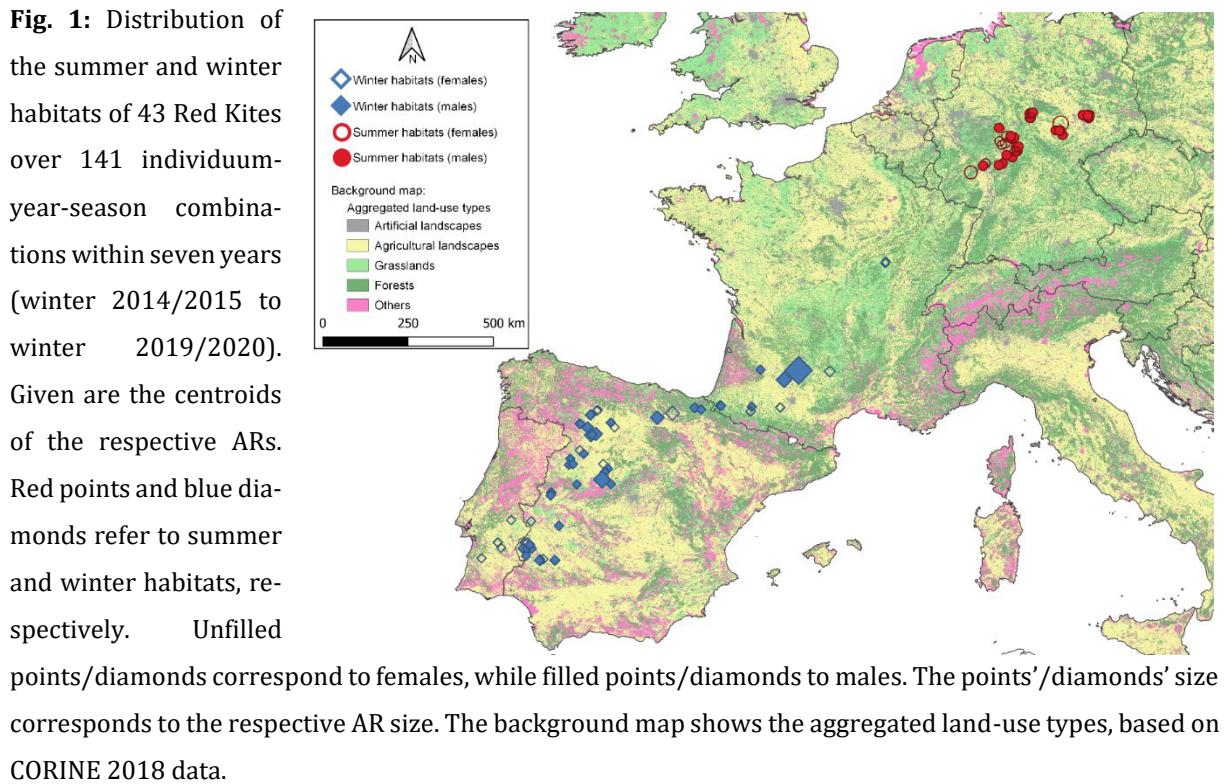
The Red Kite is a diurnal raptor, which is endemic to Europe. Its population is estimated to consist of 32,200 – 37,700 breeding pairs (BirdLife International, 2020). Of these, 14,000 – 16,000 pairs breed within Germany, which corresponds to 37% – 50% of the world population (Grüneberg & Karthäuser, 2019). The Red Kite forages mainly in agricultural landscapes and grasslands as well as in smaller settlement areas (Aebischer, 2009; BirdLife International, 2020). It feeds opportunistically on small mammals, smaller birds, fish, insects, and carrion (Aebischer, 2009; BirdLife International, 2020; Bischofberger et al., 2019). The Red Kite nests in trees near forest edges or in rows of single trees and shows a high breeding-site fidelity (Aebischer, 2009; Gelpke & Hormann, 2010). The Red Kite shows reproductive role specialization: the female incubates the clutch and broods the chicks, and only when the nestlings are about two to three weeks old it helps with the search for food, while the male provides the main part of it (Aebischer, 2009; Pfeiffer & Meyburg, 2015). Territoriality weakens shortly before the start of migration, when Red Kites often spend the night at communal roosts (Aebischer, 2009; Spatz et al., 2019). Such communal roosts are also used, but often changed irregularly in the wintering habitats, where at least some Red Kites show site fidelity over several years (Pfeiffer & Meyburg, 2009; own observations).

### Data collection

The summer habitats of all animals studied were in the following federal states in Germany: Hesse, Thuringia, Saxony and Lower Saxony. These states are reported to represent 30% of the German Red Kite population (Grüneberg & Karthäuser, 2019). The winter habitats were in different regions of Spain ( $n = 60$ ), France ( $n = 17$ ) and Portugal ( $n = 5$ ; Figure 1).

During the breeding seasons of 2014 to 2019, we fitted GPS-transmitters to 43 adult Red Kites (16 female, 27 male). All birds were caught during chick rearing in proximity to their nests using the dho-gaza method with a stuffed Eagle Owl (*Bubo bubo*) as a lure (Bloom et al., 2007). We measured the wing length and mass of the captured birds and banded them with individual rings from the respective bird ringing centre. Sex was determined by the measures and the presence of a brood patch.

The GPS-transmitters were fitted to the backs of the birds with a backpack harness made of Teflon ribbon. We used two different GPS-transmitter types: e-obs SOLAR-GPS-ACC and Ornitala E-20-B or OT-E25B. All transmitters were equipped with an integrated battery and a solar panel for power supply. The frequency of GPS-fixes by the transmitters depended on the battery level and varied from five minutes to eight-hour intervals during daytime. Each individual provided data for one to eight seasons from winter 2014 to summer 2020.



Additionally, we recorded the individual annual breeding success, defined as at least one successful juvenile fledging from the nest. The assessment of the breeding success depended on the local conditions. Wherever possible, and only if the necessary permits were available, trained tree climbers accessed the nests of the Red Kites to measure the chicks and band them with rings from the respective bird ringing centre. On not accessible nests we determined their breeding success with suitable optical aids. Breeding success data was available for 53 of the 59 summer datasets and consisted of 19 female summers (12 individuals) and 34 male summers (22 individuals), with 30 successful (12 females, 18 males) and 23 unsuccessful (7 females, 16 males) breeding attempts. The latter included 4 different individuals (1 females, 3 males) that each did not breed in one year.

### Processing of movement data

The initial step of data processing comprised the clean-up and standardisation of the movement data. All duplicates (same timestamp and same position), zero coordinates (no GPS signal received), as well as positions with speeds above 30 m/s (faulty GPS acquisition; outliers) were excluded. As the frequency of data acquisition depended on the battery level, we aligned the minimum time interval between two coordinates to  $60 \pm 15$  minutes to equalise the data density between individuals, resulting in an average of  $16 \pm 2$  fixes per individual per day during summer and  $9 \pm 2$  fixes per individual per day during winter. These number of fixes per individual per day hardly varied between the years (see Supplementary Material 1). In total we used 270,781 data points, distributed over 141 individual-season combinations (82 winter and 59 summer) collected by 43 individuals over eleven year-season combinations (winter 2014/2015 to winter 2019/2020).

### **Delimitation of winter/summer habitats**

We defined the stay in their winter or summer habitats as the timespan between the first day after the end of migration and the last day before the start of the consecutive migration, for each individuum separately. Most Red Kites left their summer habitats mid/end of September, while some individuals left not before November or December in single years. The same could be applied to spring migration as most Red Kites left their winter habitats mid/end of February, but some individuals had already started spring migration in January, while others not before March. Due to this high individuality, we used the data from August to January and December to April to determine the individual start and end dates of migration. To determine these dates, we conducted broken stick regressions, a data-driven approach that is related to change point analysis that has already been successfully used for other migratory bird species (Limiñana et al., 2008; Soriano-Redondo et al., 2020). For each individual we calculated the straight-line distance between all consecutive locations within one day to determine the daily distance covered by the individuum and summed it cumulatively over time. When plotting the cumulative daily distance over time, abrupt behavioural changes became visible as breaks in the curve. For example, the curve showed a steeper slope during migration as the individual daily distance was higher. We identified the breaks that referred to start and end of the individual migration by using the *segmented*-package in R (Muggeo, 2008; R Core Team, 2013).

The method had its limitations when the movement data showed gaps due to low battery level or no reception of GPS signal or if an individual changed its whereabouts irregularly, a behaviour that was shown by some individuals,

especially in winter habitats. In such cases we determined the beginning and end of migration using a combination of visual inspection of the data and daily displacement of an individual, calculated as straight-line distance between the first and last location of a day. If the daily displacement was more than 50 km, we declared the day as a migration day. To ensure that we do not falsely define a stop-over as a stay in the winter habitat, especially when individuals changed their whereabouts irregularly, we only used the longest timespan without migratory movements as stay in the respective habitats. On average, the stay in the summer habitats lasted for  $221 \pm 19$  days (mean  $\pm$  standard deviation (SD); range: 157 – 270 days) and that in the winter habitat lasted for  $94 \pm 25$  days (mean  $\pm$  SD; range: 26 – 136 days).

### **Calculation of the activity ranges and mean daily distances**

We determined the activity range (AR) for each individuum-year-season combination with the *akde*-function in ctmm R (Calabrese et al., 2016). As some adult Red Kites shifted between roost sites during winter, the use of Ornstein-Uhlenbeck- or Ornstein-Uhlenbeck-Foraging models, which account for autocorrelation of positions within the movement data, led to an overestimation of the used area. We therefore used an independent identically distributed model, which determined the AR closest to the respective data points, and therefore suited the data best. However, it does not account for autocorrelation and is therefore equivalent to the calculation of utility distributions with Kernel Density Estimation (KDE; Calabrese et al., 2016). All further analyses were based on the core 95% of the AR to exclude single explorative flights.

For each individuum and all days with more than three fixes, we calculated the straight-line distances between all consecutive locations within a day and summed them to determine the daily distances. These daily distances were averaged to a mean daily distance (MD) for each individuum-year-season combination.

### Environmental data

Our analyses regarding landscape diversity, habitat availability, and habitat use were based on CORINE Land Cover 2018 (CLC), funded by the European Union. This dataset divides the European surface into 100 m × 100 m grid cells and classifies them into 44 different land-use types (Büttner et al., 2017). Our study area had 38 of the 44 land-use types. As we aimed to compare the habitat availability within the ARs and the use of land-use types between seasons, we merged the observed land-use types into five aggregated land-use types of higher order to achieve comparability between the summer and winter habitats of Red Kites. We chose the following five aggregated land-use types as they reflect very distinct habitats that are relevant for Red Kites. Agricultural landscapes and grasslands are the main foraging habitats of Red Kites (Aebischer, 2009). Forests, especially the forest edges are at least partly used by Red Kites as breeding habitats (Aebischer, 2009). Artificial surfaces are mainly areas with high amounts of sealed grounds and high human population densities, which Red Kites usually avoid (Hessische Gesellschaft für Ornithologie und Naturschutz, 2010; Heuck et al., 2013). All other occurring less common land-use types were combined in the land-use type Others (see Supplementary Materials 2 for detailed description of the aggregated land-use types). In the following, we determined the proportions of

each of the five aggregated land-use types within the ARs of all individuum-year-season combinations.

Landscape diversity has already been linked successfully to the ARs of generalist raptors (Mirska et al., 2021; Navarro-López & Fargallo, 2015). Hence, we used the proportions of the aggregated land-use types within the ARs to calculate the Shannon's-diversity index for the ARs of all individuum-year-season combinations to assess landscape diversity. All values were centred and scaled.

To assess the primary productivity within the ARs of the Red Kites, we used normalized difference vegetation index (NDVI) data. NDVI is the most common proxy for primary productivity (Fernández-Tizón et al., 2020). NDVI has already been linked successfully to the abundance of arthropods or small mammals, as primary and secondary productivity are positively correlated (Fernández-Tizón et al., 2020; Smith et al., 2016; Trierweiler et al., 2013). We therefore assume NDVI to be a good proxy for food availability for a generalist like the Red Kite. NDVI data was derived from PROBA-V NDVI collection 300 m, generated by the land service of Copernicus, the Earth Observation program of the European Commission. It is 10-days composite raster data with a grid cell size of 300 m × 300 m, available for the entire study period. We extracted the NDVI values that occurred within the ARs at the time of use and calculated a mean NDVI for each individuum-year-season combination. All values were centred and scaled before fitting the models.

### **Effect of landscape diversity, primary productivity and season on activity range and daily distances**

(1 a – c) Based on the data of 141 individuum-year-season combinations provided by 43 adult Red Kites, we compared the AR sizes and MDs between winter and summer, and assessed the impact of landscape diversity and primary productivity on them, while taking sex-specific differences into account. Therefore, we used generalized linear mixed effect models (*glmmTMB* R-package, Brooks et al., 2017), with individual as a random factor and gaussian distribution in the log-transformed response variables. As fixed effects, we integrated season, sex, landscape diversity, and mean primary productivity within the ARs, as well as their interactions with season. In the MD-model, we further integrated the number of data points per day as offset, as the calculation of the daily distance is sensitive to the number of points used for the calculation. For each model we performed backwards model selection based on effect sizes/z-values.

(1 d) Based on a subset of the data (53 summers) for which information about the breeding success was available, we tested the effect of breeding success on the summer ARs of adult Red Kites, taking sex-specific differences into account. For this, we used a linear mixed effect model (*lme4* R-package; Bates et al., 2016) with the log-transformed summer AR sizes as response variable. The explanatory variables sex and breeding success were used as binary variables (1: breeding success, 0: no breeding success). The individuum was added as random factor.

### **Differences in habitat availability and habitat use between seasons**

For all individuals with data of at least one summer and one winter ( $n = 33$  individuals), we determined habitat availability and habitat use based on the five aggregated land-use types. As Red Kites show site fidelity in winter and summer habitats and the number of seasons per individual ranged from one to eight, the availability and use of certain land-use types could have been over- or underestimated. Therefore, we determined the mean habitat availability within the ARs as well as the mean habitat use for each individuum separately for summer and winter, as described hereafter: We determined the individual-specific habitat availability as proportions of the five aggregated land-use types present within the individual ARs and used them to calculate the individual mean habitat availability during winter and summer. To evaluate the individual-specific habitat use, we determined the proportions of the five aggregated land-use types present at the 270,781 GPS-locations and used them to calculate the individual mean habitat use during winter and summer.

(2 a) To determine differences in the availability of the different land-use types within the ARs between summer and winter, we used non-metric multidimensional scaling (NMDS). We calculated the Bray-Curtis distances, a dissimilarity measure to detect ecological gradients, based on the individual mean habitat availability within the respective winter and summer ARs (Faith et al., 1987). We Hellinger-transformed these distances and arranged them in a three-dimensional space (*metaMDS*-function in *vegan*-package, Oksanen et al., 2020). With a subsequently performed ANOSIM (*vegan*-package, Oksanen et al., 2020) we checked for

significant differences in the habitat availability between winter and summer.

(2 b) To assess if individual preferences in habitat availability persist over seasons (e.g., individuals with high amounts of grassland available in summer habitats prefer high amounts of grassland available also in winter habitat), we used the function *protest* of the *vegan*-package, to perform a subsequent Procrustes analysis (Oksanen et al., 2020). The Procrustes analysis rotates the habitat availability of the two seasons based on the data score matrices gained by the formerly performed NMDS, and tries to maximize similarity between them. The *protest*-function does this repeatedly and estimates the significance (Oksanen et al., 2020). A match between the two matrices in our case would mean that there are individual preferences in the availability of certain habitats that persist over seasons.

(2 c) To compare the habitat use of Red Kites between their winter and summer habitats, we compared the individual mean habitat availability with the individual mean habitat use in both winter and summer. Therefore, we calculated Manly's selectivity index ( $\omega_i$ ) for each of the five aggregated land-use types by dividing the individual mean use of a land-use type by the individual mean availability of the respective land-use type in winter and summer. If  $\omega_i = 1$ , the use corresponds to the availability of the land-use

type. If  $\omega_i > 1$ , the use is over-proportional to the availability; hence, there is a preference of an individual for this land-use type. If  $\omega_i < 1$ , the usage is under-proportional; hence, there is an avoidance of an individual for this land-use type. To test if within seasons a land-use type was used significantly more or less than expected from its availability, we compared the distribution of  $\omega_i$ -values of each land-use type against 1, using a Wilcoxon test for non-normally distributed data. With additional Wilcoxon tests we compared the  $\omega_i$ -values of each land-use type between seasons to identify differences in the use of the five aggregated land-use types between summer and winter habitats.

## Results

We compared the space use and habitat selection of migratory Red Kites between summer and winter habitats. The activity range (AR) size ranged from 2.6 km<sup>2</sup> to 13,504.0 km<sup>2</sup> during summer and from 7.9 km<sup>2</sup> to 33,337.1 km<sup>2</sup> during winter (see Supplementary Material for a distribution plot of the AR data 3). The mean daily distance (MD) flown by adult Red Kites ranged from 5.0 – 34.3 km and 5.4 – 49.9 km in summer and winter, respectively (Table 1).

**Tab. 1:** AR sizes [ $\text{km}^2$ ] and MDs [km] of 141 individuum-year-season combinations provided by 43 adult Red Kites during winter and summer. Range (min, max, quantiles), median and mean with SD are given for both sexes [ $\text{♀♀}$  = females,  $\text{♂♂}$  = males], separately.

		Activity range sizes [ $\text{km}^2$ ]						Mean daily distances [km]					
							Mean $\pm$ SD						Mean $\pm$ SD
		Min	Qu $^{0.25}$	Median	Qu $^{0.75}$	Max		Min	Qu $^{0.25}$	Median	Qu $^{0.75}$	Max	
Winter	♀ n = 28	7.9	55.9	101.1	196.1	8,880.6	115.7 $\pm$ 4.9	5.4	10.4	14.8	17.5	42.9	13.6 $\pm$ 0.002
	♂ n = 54	13.2	72.5	280.5	655.3	33,337.7	288.9 $\pm$ 6.3	7.6	13.2	19.3	27.7	49.9	18.8 $\pm$ 0.002
Summer	♀ n = 19	2.6	8.8	16.7	66.0	13,504.0	36.0 $\pm$ 10.8	5.0	7.5	8.8	11.0	31.7	9.4 $\pm$ 0.002
	♂ n = 40	3.1	8.5	13.2	23.3	649.5	15.9 $\pm$ 2.8	7.3	11.3	14.3	15.6	34.3	13.9 $\pm$ 0.001

### Effect of landscape diversity, primary productivity and season on activity ranges and daily distances

Our models were able to explain a considerable proportion of the variability in space use of Red Kites using the intrinsic and extrinsic factors (40–53%; Table 2).

(1 a) AR sizes and MDs of Red Kites were smaller during summer than during winter ( $\text{AR}_{\text{season(winter)}} 0.96 \pm 0.40$  (Est.  $\pm$  SE, hereafter),  $p = 0.015$ ;  $\text{MD}_{\text{season(winter)}} 0.74 \pm 0.06$ ,  $p < 0.001$ ).

(1 b) AR sizes and MDs increased with increasing landscape diversity ( $\text{AR}_{\text{landscape diversity}}: 0.65 \pm 0.14$ ,  $p < 0.001$ ;  $\text{MD}_{\text{landscape diversity}}: 0.12 \pm 0.03$ ,  $p < 0.001$ ). AR sizes and MDs decreased with increasing primary productivity ( $\text{AR}_{\text{primary productivity}}: -0.38 \pm 0.15$ ,  $p < 0.01$ ;  $\text{MD}_{\text{primary productivity}}: -0.13 \pm 0.03$ ,  $p < 0.001$ ; Table 2).

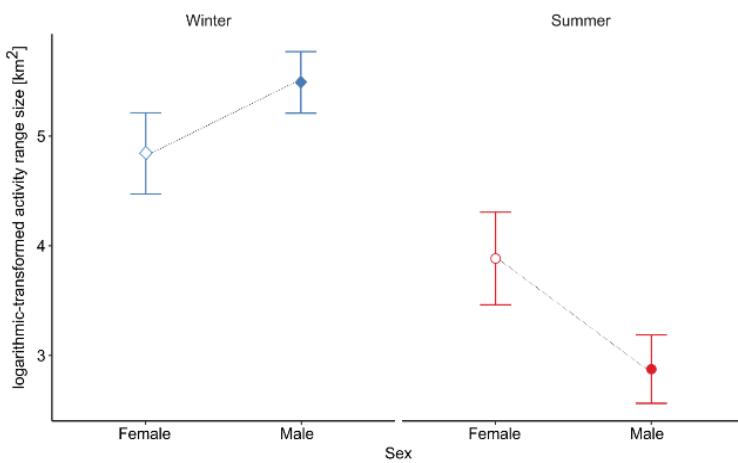
(1 c) In both the seasons, the MDs of females were shorter than those of males

( $\text{MD}_{\text{sex(♂)}}: 0.23 \pm 0.12$ ,  $p = 0.047$ ). The ARs of females in winter were smaller than those of males, but larger than those of males during summer ( $\text{AR}_{\text{sex(♂)}}: -1.01 \pm 0.51$ ,  $p = 0.049$ ;  $\text{MD}_{\text{season(winter)}} : \text{sex(♂)}: 1.66 \pm 0.45$ ,  $p < 0.001$ ; Figure 2).

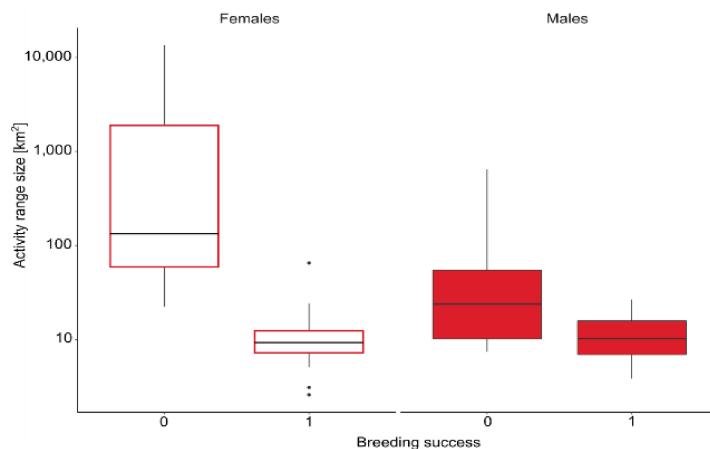
(1 d) In summer the ARs of successfully breeding Red Kites were smaller than those of non-breeders or unsuccessfully breeding individuals ( $\text{AR}_{\text{breeding success}}: -3.58 \pm 0.65$ ,  $p < 0.001$ ). Within the successfully breeding Red Kites, both sexes showed similar ARs sizes, whereas unsuccessfully breeding Red Kites females showed larger ARs than males ( $\text{AR}_{\text{sex(♂)}}: -2.47 \pm 0.64$ ,  $p < 0.001$ ;  $\text{AR}_{\text{breeding success}}: -3.58 \pm 0.65$ ,  $p < 0.001$ ;  $\text{AR}_{\text{sex(♂)}} : \text{breeding success}: 2.70 \pm 0.79$ ,  $p < 0.001$ ; Figure 3; Table 3 and 4). The model explained 67.7% of the variance in the data.

**Tab. 2:** Model output for the generalized linear mixed models (GLMM) relating the log(AR sizes [ $\text{km}^2$ ]) and the log(MDs[km]) of 141 individuum-year-season combinations provided by 43 adult Red Kites to season, sex, landscape diversity (Shannon diversity), and primary production (NDVI). Shown are the estimates of the resulting coefficients, their standard errors (SE), and test statistics.

	log(Activity range sizes [ $\text{km}^2$ ])				log(Mean daily distances [km])			
	Estimate	SE	z-value	p-value	Estimate	SE	z-value	p-value
(Intercept)	3.88	0.42	9.21	<0.001***	6.59	0.10	66.93	<0.001***
Season (winter)	0.96	0.40	2.43	0.015*	0.74	0.06	13.40	<0.001***
Sex ( $\delta$ )	-1.01	0.51	-1.97	0.049*	0.23	0.12	1.99	0.047*
Shannon diversity	0.65	0.14	4.67	<0.001***	0.12	0.03	3.89	<0.001***
NDVI	-0.38	0.15	-2.57	0.010*	-0.13	0.03	-3.89	<0.001***
Season (winter): Sex ( $\delta$ )	1.66	0.45	3.65	<0.001***				
Random Effect	Variance	SD			Variance	SD		
(Individuum)	1.21	1.10			0.10	0.32		
	R <sup>2</sup> marginal:	40.7 %			R <sup>2</sup> marginal:	53.3 %		
	R <sup>2</sup> conditional:	67.4 %			R <sup>2</sup> conditional:	81.4 %		



**Fig. 2:** Effect plot of the generalized linear mixed model used to compare the sizes of the ARs between seasons: red points (summer) and blue diamonds (winter) mark the estimates, bars show the standard error given by the model. During summer, the ARs of female Red Kites (unfilled) were larger than those of males (filled). Conversely during winter, females showed smaller ARs compared to male Red Kites.



**Fig. 3:** Variation in AR sizes of 34 adult Red Kites in summer: Red Kites with breeding success showed smaller ARs than those without breeding success. The AR size of females that were unsuccessful in breeding increased more than that of unsuccessfully breeding males (Table 3). Note the logarithmic scale of the y-axis

**Tab. 3:** AR sizes of successfully and unsuccessfully breeding Red Kites during summer, based on breeding success data of 53 summers provided by 12 female and 22 male Red Kites. Range (min, max and quantiles), median, and mean with SD are given for both sexes [ $\text{♀}$  = females,  $\text{♂}$  = males].

		Activity range sizes [km <sup>2</sup> ]					
		Min	Qu <sup>0.25</sup>	Median	Qu <sup>0.75</sup>	Max	Mean ± SD
successfully breeding	$\text{♀}$ n = 12	2.6	7.2	9.2	12.3	64.9	9.7 ± 2.4
	$\text{♂}$ n = 18	3.8	6.9	10.2	15.7	26.5	10.6 ± 1.8
unsuccessfully breeding	$\text{♀}$ n = 7	22.2	59.0	133.2	1,892.3	13,504.0	337.4 ± 12.4
	$\text{♂}$ n = 16	7.4	10.1	23.8	54.5	649.5	29.9 ± 3.4

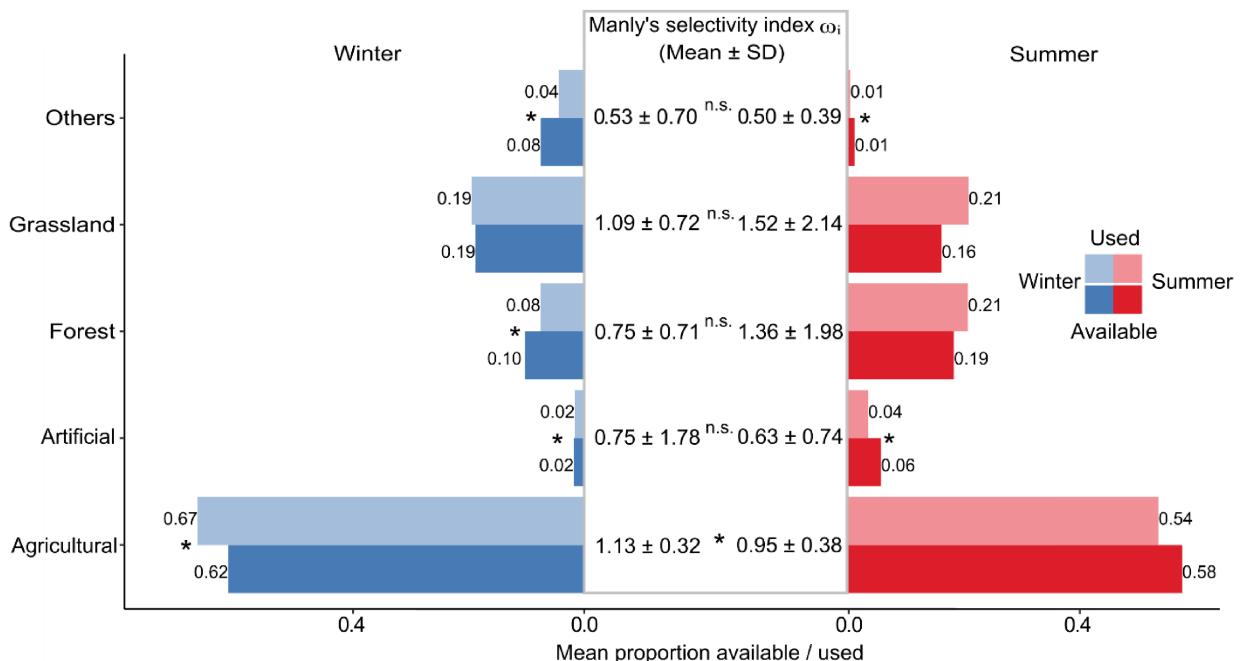
**Tab. 4:** Model output for the linear mixed effect models relating the log(AR size in km<sup>2</sup>) of 34 Red Kites in summer to their breeding success. Shown are the estimates of the resulting coefficients, their standard errors (SE), and test statistics.

	Estimate	SE	t-value	p-value
(Intercept)	5.83	0.51	11.54	<0.001***
Sex ( $\text{♂♂}$ )	-2.47	0.64	-4.02	<0.001***
Breeding success	-3.58	0.65	-5.54	<0.001***
Sex ( $\text{♂♂}$ ): Breeding success	2.70	0.79	3.41	0.001**
Random Effect (Individuum)		Variance	SD	
	0.71	0.85		
R <sup>2</sup> marginal:		43.9 %		
R <sup>2</sup> conditional:		67.7 %		

## Differences in habitat availability and habitat use between seasons

(2 a) The habitat availability of the various land-use types within the ARs differed between winter and summer (NMDS:  $k = 3$ , stress = 0.08; ANOSIM:  $R = 0.22$ ,  $p = 0.001$ , permutations=999; Supplementary Material 4). There were no individual preferences in habitat availability that persisted over seasons (Procrustes analysis:  $r = 0.13$ ,  $p = 0.77$ , permutations = 999). The dominating land-use type within the ARs in both seasons were agricultural landscapes, followed by grasslands and forests in different order (Figure 4)

(2 b) In summer habitats, Red Kites used artificial landscapes and others significantly less than that expected from availability (Wilcoxon tests:  $p_{\text{artificial}} = 0.001$ ,  $p_{\text{others}} = 0.003$ ). In winter habitats, Red Kites used artificial landscapes, forests and others significantly less, but agricultural landscapes significantly more than that expected from availability (Wilcoxon test:  $p_{\text{artificial}} < 0.001$ ,  $p_{\text{agricultural}} = 0.005$ ,  $p_{\text{forest}} < 0.001$ ,  $p_{\text{others}} < 0.001$ ; Figure 4; Supplementary Material 5).



**Fig. 4:** Mean proportion of available (dark) and used (light) land-use types within the ARs of 33 adult Red Kites in winter (left/blue) and summer (right/red). We compared the use of the various land-use types within seasons based on Manly's selectivity indices ( $\omega_i$ ) for each land-use type, given as mean  $\pm$  SD. We tested for a significantly different use of land-use types than that expected from its availability during the seasons with a Wilcoxon test against 1. Significant differences in use and availability within seasons are marked with \* at the bars' ends.  $\omega_i$  were compared between seasons using Wilcoxon tests to identify significant differences in the use of the various land-use types between summer and winter habitats. Significant differences in use and availability between seasons are marked with \* in the figure's centre. Only agricultural landscapes were used significantly more in winter than in summer (Wilcoxon test:  $p = 0.03$ ; see also Supplementary Material 5).

While Red Kites used grasslands and forests in similar intensity in both seasons, agricultural landscapes were used significantly less during summer than during winter (Wilcoxon tests:  $p_{\text{grassland}} = 0.49$ ,  $p_{\text{forest}} = 0.07$ ,  $p_{\text{agricultural}} = 0.03$ ). There were no differences between seasons in the use of the remaining land-use types.

## Discussion

Our findings show that activity ranges (AR) and the mean daily distances (MD) of Red Kites were larger in winter than in summer, were associated with both landscape diversity and primary productivity and differed between sexes. While ARs and MDs increased with increasing landscape diversity, they decreased with increasing primary productivity. Females had shorter MDs than males, regardless of the season. Female Red Kites used smaller ARs than males during winter, while the opposite was the case during summer. During summer, the size of the ARs decreased with breeding success. The habitat availability within the ARs and the use of agricultural landscapes differed between seasons.

### Effect of landscape diversity, primary productivity and season on activity ranges and daily distances

As expected, and in line with other birds of prey such as the Golden Eagle (*Aquila chrysaetos*) and the Spanish Imperial Eagle (*Aquila adalberti*), the size of ARs and MDs of migratory Red Kites were smaller during summer, compared to that during winter (Fernández et al., 2009; Marzluff et al., 1997). It is likely that these patterns are driven at least partly by their territoriality during

summer. Although territories are blurred after fledging, the distance of Red Kites to their nest hardly changes throughout summer (Spatz et al., 2019). Hence, territoriality of Red Kites persists during the entire summer, and lessens only shortly before the start of migration when the Red Kites still spend some nights in their territories but also start using communal roosts. Given the duration of time at the summer habitats, these comparatively few night outs at communal roosts do not carry any weight in the calculation of the AR sizes. Wintering Red Kites however, tend to change communal roosts irregularly, leading to larger ARs (Aebischer, 2009; Heredia et al., 1991). Moreover, as residential and wintering Red Kites co-occur in winter habitats, there is a high intra- and interspecific competition for food, which affects space use (Bildstein, 2004; Powell et al., 2021). The larger ARs of Red Kites in winter could therefore also be driven by the competition for food sources, as wintering Red Kites use different habitats than residents (Heredia et al., 1991). Similar to the residential Red Kites in which males made higher use of ecotones and cultivated fields while showing larger ARs and daily distances than females, the use of different food sources could also be a possible explanation for the larger ARs of males compared to females in winter (Heredia et al., 1991). However, in contrast to our expectations, in summer, female Red Kites used larger ARs than males. Larger ARs of females than that of males in summer were also reported for Lesser Spotted Eagles (*Clanga pomarina*, Mirski et al., 2021). The authors explained this with a lower territoriality of females and a higher number of explorative visits in other territories and nests potentially to find territories of better quality. Male Red Kites, however, are probably more territorial than

females. Considering that our study was conducted in one of the distribution centres of the Red Kite, where relatively high population densities occur, we can assume high numbers of neighbouring Red Kite territories, which most likely led to a more restricted space use of male Red Kites in summer. However, for Red Kites, our finding of larger ARs of females than that of males contrasts with a previous study by Pfeiffer and Meyburg (2015), which used a slightly different methodological approach.

Taking a closer look at the ARs in summer revealed that their size is strongly affected by the breeding success of the individual: the ARs of successfully breeding Red Kites were significantly smaller and did not differ between sexes, in contrast to individuals that had lost their brood or were non-breeders in a respective year. The ARs of females without breeding success increased more than those of males without breeding success (Figure 3). In fact, we observed four female individuals that left their territory for a few days or even weeks after they lost their brood. However, since success and failure of broods are natural and regularly occurring events in summer and were present for both sexes in our dataset, we included both of them in our comparative analyses between summer and winter space use. Successfully reproducing Red Kites showed no difference in the activity range size between the sexes in summer. It is known, that during the breeding and nestling period female Red Kites partially have a very restricted space use, as they incubate the eggs and start helping with providing food only when the nestlings are about two to three weeks old (Aebischer, 2009; Pfeiffer & Meyburg, 2015). However, such a temporally restricted space use of successfully breeding females implies that they also have periods with increased space use

demands, resulting in similar ARs for females and males over the whole summer. Telemetry studies on juvenile Red Kites in Switzerland showed that females typically show more extensive prospecting behaviour than males, which could also apply to older individuals (Scherler, 2020).

Our findings show that there are sex-specific differences in AR sizes and MDs between summer and winter habitats. It remains a challenge for future studies to disentangle to what extent intra- and interspecific competition influences the space use of female and male Red Kites in summer and winter habitats.

In line with our expectations, AR sizes and MDs decreased with increasing primary productivity (NDVI). NDVI has been used as proxy for food availability in many other raptor species, as it can be linked to the abundance of prey species such as arthropods or small mammals (Klaassen et al., 2014; La Sorte et al., 2014; Schaub et al., 2020; Smith et al., 2016; Trierweiler et al., 2013). Hence, the result supports our assumption that NDVI is also a good proxy for resource availability for a generalist like the Red Kite. Here we chose to aggregate the NDVI to a mean value for the respective individual-year-season combination to compare the conditions in winter and summer habitats on a rather coarse scale, and to evaluate if the Red Kites respond to it in similar way in both seasons. However, as NDVI is available as 10-days composite data, further studies could focus on linking the variation in space use of Red Kites to the variability in environment on a higher temporal and spatial scale.

Contrary to our expectations, the AR sizes and the MDs increased with increasing landscape diversity. This finding is counter-intuitive for a food opportunist like the Red Kite, as a diverse

landscape should provide various and sufficient resources at a small spatial scale (Mirsiki et al., 2021; Tucker et al., 2019). However, besides small mammals and birds, large parts of the diet of Red Kites consists of carrion (Bischofberger et al., 2019; Heredia et al., 1991). Carrion is a less predictable and often widely distributed food source and leads to increasing AR sizes in raptors foraging on it (Griffin & Baskett, 1985; Rolando, 2002). Another explanation for this counterintuitive pattern may be the coarse temporal and spatial resolution of our land-use data. The used land-use data gives the status of habitat availability in 2018; hence, potential variations in land-use types within the seven years of data collection were not considered. Moreover, land-use data was comprised of only five aggregated land-use types. Hence, higher amounts of rather unattractive foraging grounds, like forests, led to an increased landscape diversity. Therefore, we might arrive at a different result if the landscape diversity was analysed with focus on the main foraging habitats of Red Kites: agricultural landscapes, grasslands, and smaller settlements. However, this would require more finely resolved spatial and temporal land-use data, which unfortunately was not available over the entire study area and period. As Red Kites are soaring raptors that hunt visually, preferably over very low vegetation (Aebischer, 2009; Karthäuser et al., 2019; Mebs & Schmidt-Rothmund, 2014; Wakeley, 1978), different growth rates of crops and different harvesting times, as well as the prevalence of interspersed fallows or freshly mown meadows would most likely lead to smaller ARs and shorter distances. Furthermore, artificial food provisioning like dump sites or livestock carcass disposal sites are known to be important food sources for Red Kites especially in their winter

habitats (Serrano, 1999). Hence, further research with higher resolution land-use data and the inclusion of artificial food sources could help to identify the key landscape elements that shape the space use of Red Kites in winter and summer habitats.

#### **Differences in habitat availability and habitat use between seasons**

The habitat availability within the ARs differed significantly between seasons. In the summer habitats, the five aggregated land-use types occurred more balanced compared to winter habitats. We found no individual preferences in the habitat availability that persisted across seasons (e.g., high proportion of grasslands within the AR of an individuum in both seasons). Hence, predictions on favoured land-use types cannot be made across seasons. Common to all ARs was a high proportion of agricultural landscapes, which were also used most intensely in both the seasons. This underlines the importance of this land-use type as foraging habitat for Red Kites (Aebischer, 2009). However, agricultural landscapes were used more intensively in winter than in summer, which might be due to agricultural fields being mostly fallow or with sparse vegetation during winter and therefore prey may be more easily accessible for the visually hunting Red Kites (Aebischer, 2009). Considering this, further knowledge about the effects of different crops and structural richness on the suitability of hunting ground would be of advantage. As expected, grasslands were used in both seasons with similar intensity, as they are valuable foraging grounds for Red Kites (Aebischer, 2009). Forests were the second most common land-use type in summer and the third most common land-use type in winter. The intensity of forest use did

not differ significantly between seasons, but there was a tendency of more intense use in summer habitats than in winter habitats. In winter habitats, resident Red Kites are territorial throughout the year, leading to a more intense use of forests (and shrub lands) by resident Red Kites than by wintering individuals (Heredia et al., 1991). Forest edges (and lines of single trees) are especially important breeding habitats of Red Kites (Aebischer, 2009). Breeding site is a key element that decisively influences habitat use of central-place foragers like Red Kites (Carrete &

Donázar, 2005; Heuck et al., 2013). However, there is a high variance in the preferred nesting sites of Red Kites from single trees to forest edges. Despite their role as breeding habitat, closed forests are not very attractive for scavenging or hunting Red Kites, as the vegetation is too dense to forage visually (Aebischer, 2009). In summer, this limited attractiveness paired with the use as breeding habitat by some individuals, led to a wide span of selectivity of forests, and therefore no difference in use between the seasons.

## Conclusion

Our study revealed that space use of migratory Red Kites differed between seasons and was associated with both landscape diversity and primary productivity. In summer, especially breeding success has a decisive role on space use. Extrinsic drivers, such as key habitats, and intrinsic drivers, such as sex, influenced space use in both seasons, although often in different ways than anticipated. As both seasons contribute to a vital population, these findings underline the importance of consideration of the entire annual cycle of migratory species in future studies and conservation practices. Further studies should focus on the interplay of extrinsic and intrinsic drivers and how they shape space-use patterns of migratory raptors.

## Supplementary Material 1

**Tab. S1:** The number of fixes per individual and day, given as mean  $\pm$  SD, hardly differed between years.

	2014	2015	2016	2017	2018	2019
summer	16 $\pm$ 2	17 $\pm$ 1	15 $\pm$ 2	15 $\pm$ 2	17 $\pm$ 2	17 $\pm$ 0
winter	6 $\pm$ 1	10 $\pm$ 2	10 $\pm$ 2	10 $\pm$ 2	9 $\pm$ 2	9 $\pm$ 2

## Supplementary Material 2:

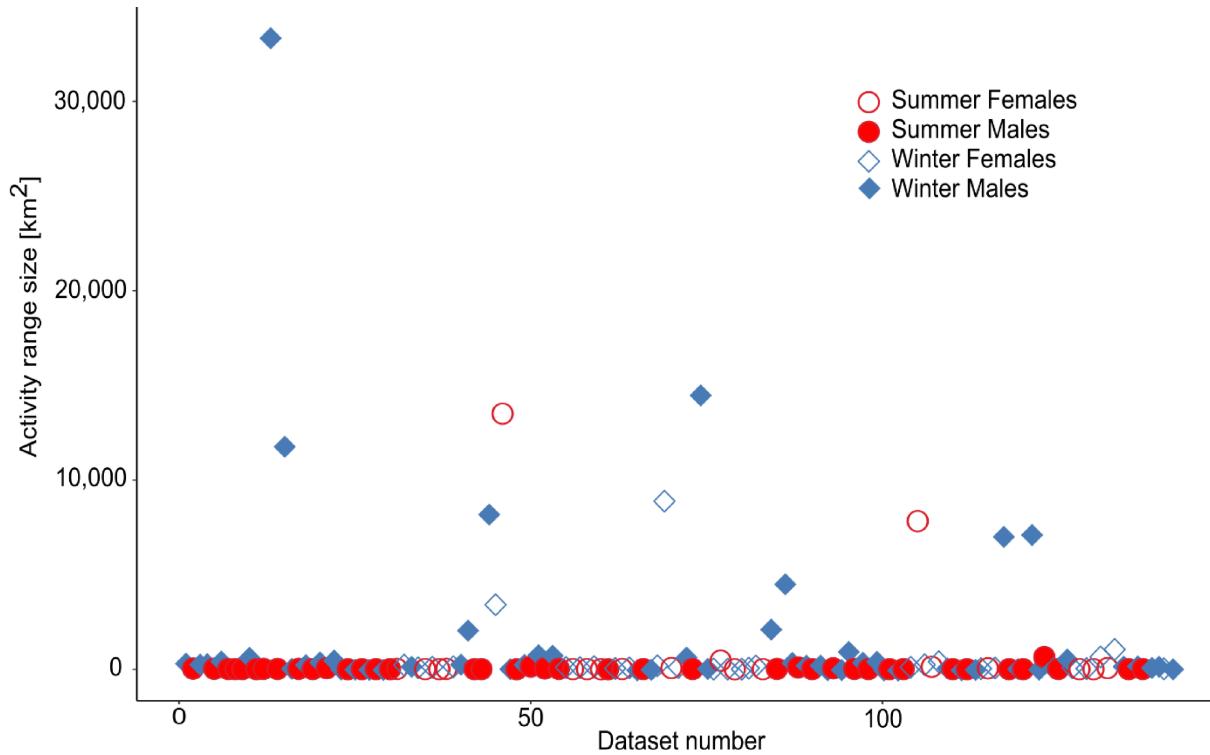
**Tab. S2:** The aggregated land-use types: The landcover was analysed based on Corine 2018 data. In total 38 different land-use types occurred within the activity ranges of the studied Red Kites. The occurring land-use types were merged into five aggregated land-use types, largely following the Corine 2018 nomenclature. This aggregation into very distinct habitats of high relevance for Red Kites was necessary to make the land-use availability comparable between summer and winter habitats of Red Kites.

Aggregated		CLC-	Corine Label 1	Corine Label 2	Corine Label 3
land-use	type				
Artificial	111	Artificial surfaces	Urban fabric	Continuous urban fabric	
	112	Artificial surfaces	Urban fabric	Discontinuous urban fabric	
	121	Artificial surfaces	Industrial, commercial and transport units	Industrial or commercial units	
	122	Artificial surfaces	Industrial, commercial and transport units	Road and rail networks and associated land	
	123	Artificial surfaces	Industrial, commercial and transport units	Port areas	
	124	Artificial surfaces	Industrial, commercial and transport units	Airports	
	131	Artificial surfaces	Mine, dump and construction sites	Mineral extraction sites	
	132	Artificial surfaces	Mine, dump and construction sites	Dump sites	
	133	Artificial surfaces	Mine, dump and construction sites	Construction sites	
	141	Artificial surfaces	Artificial, non-agricultural vegetated areas	Green urban areas	
Agricultural	142	Artificial surfaces	Artificial, non-agricultural vegetated areas	Sport and leisure facilities	
	211	Agricultural areas	Arable land	Non-irrigated arable land	
	212	Agricultural areas	Arable land	Permanently irrigated land	
	213	Agricultural areas	Arable land	Rice fields	
	221	Agricultural areas	Permanent crops	Vineyards	
Grassland	222	Agricultural areas	Permanent crops	Fruit trees and berry plantations	
	223	Agricultural areas	Permanent crops	Olive groves	
Grassland	231	Agricultural areas	Pastures	Pastures	

	241	Agricultural areas	Heterogeneous agricultural areas	Annual crops associated with permanent crops
	242	Agricultural areas	Heterogeneous agricultural areas	Complex cultivation patterns
Agricultural	243	Agricultural areas	Heterogeneous agricultural areas	Land principally occupied by agriculture, with significant areas of natural vegetation
	244	Agricultural areas	Heterogeneous agricultural areas	Agro-forestry areas
	311	Forest and semi natural areas	Forests	Broad-leaved forest
Forest	312	Forest and semi natural areas	Forests	Coniferous forest
	313	Forest and semi natural areas	Forests	Mixed forest
Grassland	321	Forest and semi natural areas	Scrub and/or herbaceous vegetation associations	Natural grasslands
	322	Forest and semi natural areas	Scrub and/or herbaceous vegetation associations	Moors and heathland
	323	Forest and semi natural areas	Scrub and/or herbaceous vegetation associations	Sclerophyllous vegetation
	324	Forest and semi natural areas	Scrub and/or herbaceous vegetation associations	Transitional woodland-shrub
Others	331	Forest and semi natural areas	Open spaces with little or no vegetation	Beaches, dunes, sands
	332	Forest and semi natural areas	Open spaces with little or no vegetation	Bare rocks
	333	Forest and semi natural areas	Open spaces with little or no vegetation	Sparsely vegetated areas
	334	Forest and semi natural areas	Open spaces with little or no vegetation	Burnt areas
	335	Forest and semi natural areas	Open spaces with little or no vegetation	Glaciers and perpetual snow
	411	Wetlands	Inland wetlands	Inland marshes
	412	Wetlands	Inland wetlands	Peat bogs

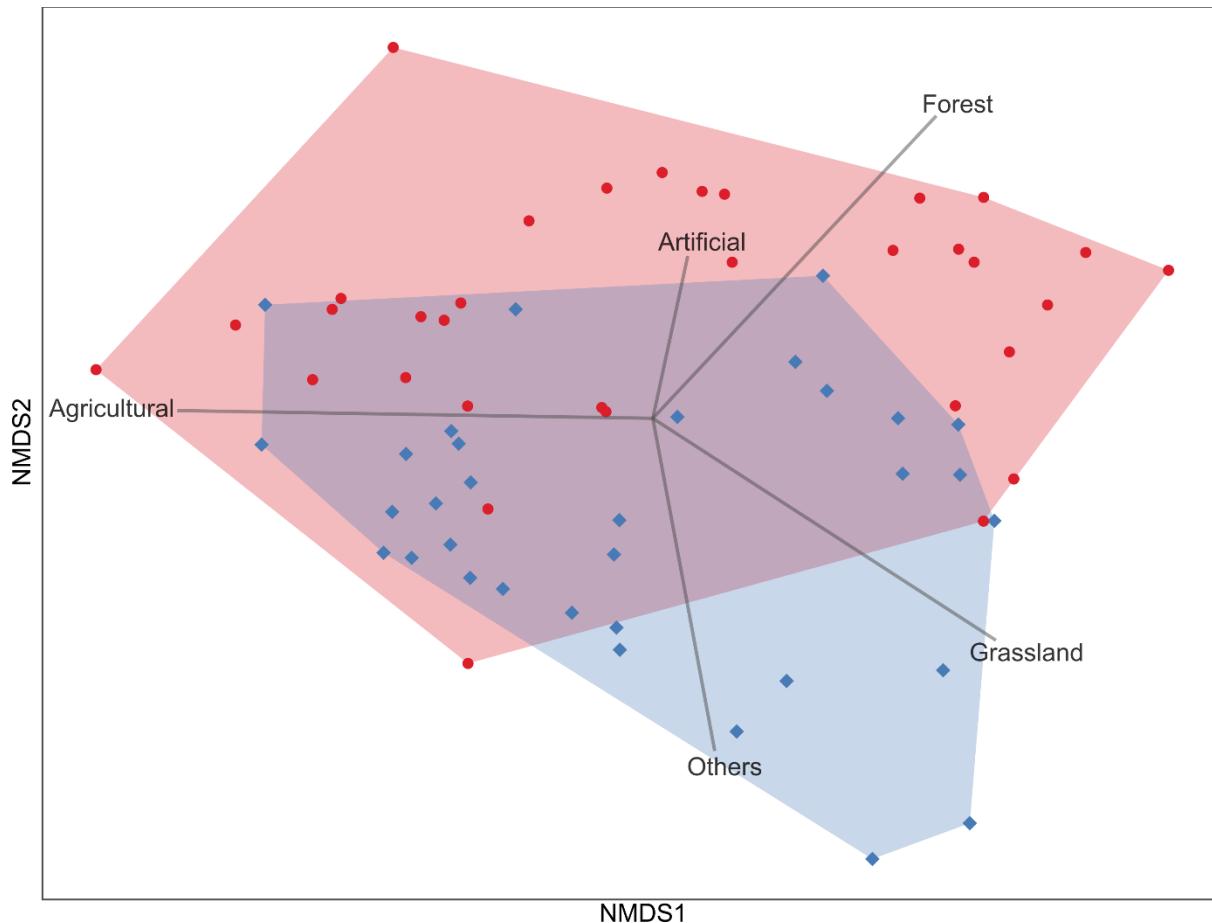
421	Wetlands	Maritime wetlands	Salt marshes
422	Wetlands	Maritime wetlands	Salines
423	Wetlands	Maritime wetlands	Intertidal flats
511	Water bodies	Inland waters	Water courses
512	Water bodies	Inland waters	Water bodies
521	Water bodies	Marine waters	Coastal lagoons
522	Water bodies	Marine waters	Estuaries
523	Water bodies	Marine waters	Sea and ocean

### Supplementary Material 3



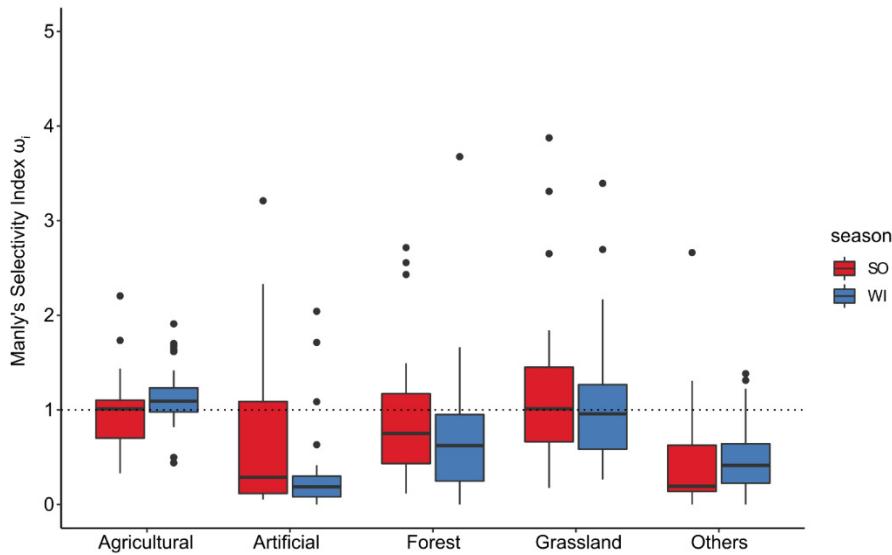
**Fig. S3:** Distribution of the raw AR sizes. As they are non-normally distributed, we log-transformed them for analysing in linear models. Red points mark ARs in summer and blue diamonds the ARs in winter. ARs of female Red Kites are unfilled, while those of males are filled.

#### Supplementary Material 4



**Fig. S4:** Plot of the non-metric multidimensional scaling (NMDS), which reached a solution with three dimensions ( $k = 3$ ) and stress = 0.08. Season significantly divided the data in two groups (ANOSIM:  $R = 0.22$ ,  $p = 0.001$ , permutations = 999). A subsequent procrustes-analysis showed no correlation of the landscape compositions within the activity ranges between seasons ( $r = 0.13$ ,  $p = 0.75$ , permutations = 999).

## Supplementary Material 5



**Fig. S5:** Manly's Selectivity Indices  $\omega_i$  for the five aggregated land-use types in summer and winter: The box corresponds to the middle 50% of the data, with the median as solid line. The whiskers mark values outside the box to maximum 1.5 of the inter-quartile range. Outliers are shown as points. For better presentability, three outliers are not shown in the graph ( $\omega_i > 5$ ).  $\omega_i > 1$  indicates an overproportional use,  $\omega_i < 1$  an underproportional use of the respective land-use type. Only agricultural landscapes were used significantly less during summer than during winter (Wilcoxon-Test:  $p = 0.03$ ). All other land-use types were used with similar intensity in both seasons

**Tab. S5:** Manly's Selectivity Indices  $\omega_i$  given as mean  $\pm$  standard deviation and range for all land-use types in summer and winter.  $\omega_i > 1$  indicates an over-proportional,  $\omega_i < 1$  an under-proportional use of a land-use type. We tested for significant differences in the use of the land-use types within seasons with Wilcoxon-Tests against 1. We also tested for significant differences in the use of the land-use types between seasons using Wilcoxon-Tests on the non-normally distributed  $\omega_i$ -values.

	Summer			Between seasons		Winter	
	Range	Mean $\pm$ SD	p-value	p-value	Range	Mean $\pm$ SD	p-value
Artificial	0.05 – 3.21	0.63 $\pm$ 0.74	0.001	0.12	0.00 – 8.62	0.75 $\pm$ 1.78	<0.001
Agricultural	0.33 – 2.20	0.95 $\pm$ 0.38	1.00	0.03	0.44 – 1.91	1.13 $\pm$ 0.32	0.005
Grassland	0.18 – 12.3	1.52 $\pm$ 2.14	0.11	0.49	0.26 – 3.39	1.09 $\pm$ 0.72	0.42
Forest	0.12 – 10.6	1.36 $\pm$ 1.98	0.17	0.07	0.00 – 3.68	0.75 $\pm$ 0.71	<0.001
Others	0.00 – 2.66	0.53 $\pm$ 0.70	0.003	0.42	0.00 – 1.38	0.50 $\pm$ 0.39	<0.001

## General Conclusions

Changing environmental conditions due to land use and climate change are the major threats to global biodiversity, causing species declines worldwide (IPBES, 2019; Sala et al., 2000). To counteract effects of climate change, the expansion of wind energy utilization was intensified over the past decades leading to additional threats, like barrier effects and an increased collision risk, especially for highly mobile animals such as birds. To mitigate the effects of changing environmental conditions and to enable the necessary energy transition, efficient conservation measures for highly mobile raptors are necessary.

In my thesis, I investigated the space and habitat use of Red Kites, a flagship species for bird conservation in Germany that is highly discussed in context of the expansion of wind energy utilization in Germany. By examining intrinsic and extrinsic drivers of the space and habitat use of the Red Kites on different temporal and spatial scales, I aimed to contribute to the evaluation and development of efficient conservation measures for this and other highly mobile animals threatened by todays changing environmental conditions.

In Chapter I, I studied the space and habitat use of reproductive Red Kites in different periods within the breeding season. I aimed on assessing the influence of intrinsic drivers

(reproductive instinct and sex) on the space and habitat use and whether their influence change in course of the breeding season. I focused on three different periods within the breeding season: territory occupancy, incubation, and chick rearing. I calculated period-specific activity ranges of twelve individuals and determined their sizes. I assessed the proportion of eight different land use types within the activity ranges – arable land, forest, grassland, other agricultural land, groves, villages, water bodies, other land use types – and calculated their mean proportions per period. In the next step, these mean proportions of the eight land use types per period were compared to the availability of the respective land use types within the study area to assess habitat use. There was a large variance in the size of the period-specific activity ranges. Only the activity range sizes of females during the incubation period were significantly smaller than those of all other periods or those of males. This finding is in line with the reproductive role specialization shown by Red Kites and other raptors, where females incubate the eggs and thus show a very restricted space use during incubation period, while males provide the food (Aebischer, 2009; Hernández-Pliego et al., 2017; Mirski et al., 2021; Pfeiffer & Meyburg, 2015). Leaving incubation period aside, both sexes have similar range demands. The analysis of the habitat use revealed that Red Kites used forests proportionally less than would be

expected from their availability, regardless of the period. This illustrates that forests are rather unattractive for Red Kites, as the vegetation is too dense to forage visually like the Red Kite. And in their choice of nest site location Red Kites are highly variable, from single trees to the edge of the forest but rarely in its middle (Aebischer, 2009; Gelpke & Hormann, 2010; Heuck et al., 2013). Arable land, however, was used more than would be expected from its availability, regardless of the period, which highlights the Red Kites' attachment to agricultural landscapes (Aebischer, 2009; Gelpke & Hormann, 2010; Heuck et al., 2013).

In Chapter II, I focused on the space use of adult Red Kites and its intrinsic drivers during the entire breeding season, by calculating flight distances and distances to the nest pentads-wise. Based on measurement and movement data of GPS-tracked juvenile Red Kites as well as literature values, I determined timeframes in which key-events such as start of incubation, hatching of the juveniles from the eggs or fledging of the juveniles from the parental nest took place. Using these timeframes, the pentads were assigned to five successive periods within the breeding season: territory occupation, incubation, chick rearing, fledgling period, and post-breeding period. In the following, I analysed the flight distance and the mean distance to the nest over time and in relation to sex using Generalized Additive Models (GAMs). The flight distance and mean distance to the nest of females changed non-linearly over time, with minima during incubation period and maxima around the fledging of the juveniles, when they also have the highest nutrient demand. An additional model showed that the maxima were influenced by the breeding success: after excluding two females that showed extraordinary wide-ranging flights after they had lost their

entire brood, the GAM-curves especially of the mean distance to the nest flattened but the overall pattern remained the same. The flight distance of male Red Kites was slightly hump shaped, with its maximum in the early chick rearing period, indicating the males' role as provider (Aebischer, 2009; Pfeiffer & Meyburg, 2015). The males' mean distance to the nest increased only slightly over time, highlighting that territoriality persists across the entire breeding season. The results revealed strong differences between males and females in both variables. The flight distance and the mean distance to the nest of females during incubation period were shorter than those of males, due to the reproductive role specialisation of Red Kites (Aebischer, 2009; Pfeiffer & Meyburg, 2015). However, both flight distance and mean distance to the nest of females exceeded those of males around the fledging of the juveniles, indicating territoriality of Red Kites being more pronounced in males than in females.

In Chapter III, I analysed the influence of local abiotic conditions on the space use of Red Kites by assessing the flight activity and flight altitude of Red Kites in relation to wind speeds during the breeding season. First, I related the flight activity to the occurring wind speeds at 10 m above ground and determined the wind speeds up to which significant parts of the flights (50% and 75%) were performed. Further, I examined the relationship of flight altitude with occurring wind speeds and assessed the proportion of flights within the rotor-swept area of operating wind turbines and of such that are currently planned in the study area. Both variables, flight activity and flight altitude, showed a high variance and were significantly, non-linearly influenced by wind speeds. While during calm wind speeds up to 2 m/s the flight activity of Red Kites hardly changed, it increased with increasing wind

speeds till it reached a plateau of maximum activity around 4.8 – 6.8 m/s. Increasing flight activity of Red Kites with increasing wind speeds were also found in previous studies (Heuck et al., 2019). As collisions with wind turbines only occur during flying and consequently the collision risk increases with increasing flight activity, however, my findings contradict existing risk assessments that rated wind speeds of up to 2 m/s with the highest risk score and further increasing wind speeds with decreasing risk scores (Schreiber, 2016). 50% and 75% of the flights took place at rather calm wind speeds of up to 2.7 m/s and 3.6 m/s, respectively. Additionally, the flight altitudes hardly changed in calm wind speeds ranging just above 100 m above ground and dropped below 100 m above ground only when wind speeds exceeded 4.4 m/s. Despite these decreasing flight altitudes with increasing moderate wind speeds, significant parts of the flights (32% - 57%) took place within the critical rotor-swept area of operating wind turbines. Future wind turbines are planned taller, hence, the proportion of flights within the rotor-swept area might decline. However, the proportion of flights within the rotor-swept area of future wind turbines stayed with 31% – 37% not negligible.

In Chapter IV, I compared the space and habitat use of Red Kites between summer and winter habitats. I used movement data collected by 43 adult Red Kites over seven years to calculate activity range sizes and mean daily distances and address the question whether space use differs between seasons. Further, I analysed the influence of intrinsic drivers (sex, reproductive status) and extrinsic drivers (primary productivity as proxy for resource availability, landscape diversity) on the space use in these distinct habitats. Furthermore, I compared the seasonal habitat availability within the activity ranges and

tested whether the use of certain land use types differed between seasons. I found activity range sizes to be significantly larger in winter than in summer, which might be due to the territoriality of Red Kites in summer and the irregular change of communal roosts in winter but could also be affected by higher intra- and interspecific food competition in winter (Bildstein, 2004; Powell et al., 2021). Within winter females had smaller activity ranges than males. This could hint on the use of different food sources, as resident Red Kites in the winter habitats showed the same difference between sexes while using also different land use types (Heredia et al., 1991). Within summer, breeding success of an individual played a crucial role: The activity range sizes of adult Red Kites did not differ for successfully breeding individuals but were larger for females than for males for unsuccessfully breeding individuals, which again highlights the more pronounced territoriality of male Red Kites. Regardless of the season, I found activity range sizes to increase significantly with increasing primary productivity (NDVI), which confirms primary productivity as suitable proxy for resource availability also for generalist species such as the Red Kite. However, increasing landscape diversity (calculated as Shannon-Diversity) led to decreasing activity range sizes and mean daily distances, regardless of the season, which was most likely due to the coarse resolution of the used land use data that was aggregated to only five different land use types. In line with summer and winter habitats being located in distinct areas of Europe, the availability of the five aggregated land use types within the activity ranges differed significantly between seasons. However, agricultural landscapes were used significantly more in winter than in summer, and there was a trend of forest being used less in winter than in summer, which once again reflects the

Red Kites affinity with open agricultural landscapes.

In all my studies differences between sexes and a high intraspecific variance in the space use variables were evident, suggesting a pronounced individuality of Red Kites. Individuality is particularly challenging for the development and evaluation of conservation measures as sufficiently large sample sizes are indispensable to identify space use patterns and their drivers. As my studies were based on many individuals, my findings provide important insights into the ecology of Red Kites to support the conservation of this flagship species for bird conservation in Germany.

The results of my study presented in Chapter I show that agricultural landscapes are of crucial importance for Red Kites. Therefore, Red Kites are particularly affected by the intensification of agriculture, where the increasing use of fertilisers and rodenticides, the loss of structures and the cultivation of fast-growing, dense crops lead to a decreasing food supply or cause direct and indirect poisoning (Knott et al., 2009). The fact that these changed environmental conditions in agricultural landscapes threaten many bird species is reflected in the continuous population declines of many agricultural bird species (Deutsche Akademie der Technikwissenschaften et al., 2020; Lemoine et al., 2007). Extensification of agriculture is therefore crucial to preserve important habitats and secure safe food sources. To raise awareness of this, the role of the Red Kite as a flagship species is of particular importance. As the Red Kite is easy to recognise due to its size and noticeable forked tail, it is easier to arouse public interest. Red kites are therefore well suited to draw attention to the threats posed by changing environmental conditions in agricultural landscapes and the importance of

conservation measures such as extensification approaches (Aebischer, 2009; Katzenberger, 2021; Mebs & Schmidt-Rothmund, 2014). The public interest generated increases acceptance and support for conservation measures that benefit not only the Red Kite, but also other species threatened by changing environmental conditions in agricultural landscapes.

My study presented in Chapter II revealed that territoriality was more pronounced in males than in females and persisted during the entire breeding season. This underlines the need to consider both sexes and the entire breeding season (March – September) in conservation measures like pre- and post-construction mitigation measures of wind turbines. Reducing potential threats during the entire breeding season is particularly important, as the loss of a parental individual usually causes the loss of the entire brood (Santema & Kempenaers, 2018). Considering that breeding success increases as parental birds become more experienced the loss of an experienced individual during the breeding season may also reduce the breeding success in subsequent breeding seasons (Forslund & Pärt, 1995). As Red Kites, like other raptors, have low reproductive rates, the loss of an experienced individual during breeding season may therefore have negative effects on population level (Garvin et al., 2011; Grünkorn et al., 2016; Kikuchi, 2008). As the Red Kite breeding season coincides with that of other Central European bird species, the consideration of the Red Kite's entire breeding season in conservation and mitigation measures might also reduce threats for other highly mobile and collision-prone bird species.

My findings of increasing flight activity with increasing wind speeds, presented in Chapter III, contradict existing risk assessments that rate the collision risk of Red Kites highest in

rather calm wind speeds up to 2 m/s (Schreiber, 2016). However, the authors of the risk assessment themselves pointed out that there is a knowledge gap for the Red Kites' behaviour in higher wind speeds, which I was able to close at least for the study region. Hence, the risk assessment of wind speeds for Red Kites should be adapted accordingly for the study region. Furthermore, the results of my study showed that increasing the size of wind turbines does not significantly reduce the collision risk of Red Kites but may even increase the risk for other collision-prone species such as the White-tailed Sea Eagles (*Haliaeetus albicilla*) that fly preferably in higher altitudes (Tikkanen et al., 2018). Thus, efficient mitigation measures are still needed in future for which my results provided some promising starting points. As significant parts of the Red Kites' flights took place in rather calm wind speeds while they also fly in altitudes within the critical rotor-swept area of both, currently operating and planned wind turbines, raising cut-in speeds of wind turbines should be considered as additional mitigation measure. This approach has already been implemented successfully for bats and reduced the nightly mortality rates by 44% to 93% while keeping the loss of produced energy with  $\leq 1\%$  low (Arnett et al., 2011; Lydia et al., 2014). However, it is important to adapt cut-in speeds like any other mitigation measure to local conditions, taking e.g., the local occurrence of collision-prone species, the surrounding landscape and locally occurring wind speeds into account. As wind turbines will continue to be developed further and considering climate change might lead to altered local wind regimes, mitigation measures and risk assessments should be updated regularly to meet the local conditions and the needs of the locally occurring highly mobile species.

In Chapter IV I found significant differences in the space and habitat use of Red Kites between their summer and winter habitats. As the conditions in the winter habitats and during migration influence survival, fitness and presumably also the breeding success of an individual, these findings highlight the importance to consider the entire annual cycle of migratory species for conservation management (Marra et al., 1998). This is particularly challenging, as important drivers for space and habitat use in one season do not necessarily have the same impact in the other season, leading to differences in the space and habitat use between seasons. For example, reproductive instinct and territoriality play an important role in summer but no or only a subordinate role during winter, resulting in a more restricted space use in summer than in winter (Brodin et al., 2003; Hernández-Pliego et al., 2017; Mirski et al., 2021). By identifying drivers that persists over seasons levers that support the population in both seasons can be revealed. In my study I identified primary productivity and landscape diversity to shape the space use of Red Kites, regardless of the season, both of which are related to the availability of resources. Resource availability, notably food availability, shapes the space use of raptors, as it is a limiting factor for populations (La Sorte et al., 2014; Newton, 1998). Consequently, by preserving foraging habitats that provide sufficient and secure prey it is possible to support their populations across the entire year, but also other species threatened by the changing environmental conditions in agricultural landscapes.

To conclude, my studies on the space and habitat use of Red Kites across different temporal and spatial scales have revealed important intrinsic and extrinsic drivers for movement. This

enabled me to draw important conclusions for the evaluation and development of conservation measures to meet our special responsibility for the protection and conservation of this species. However, the findings of my studies have raised additional questions, the investigation of which could further optimise the conservation management of the Red Kite and other highly mobile animals threatened by today's changing environmental conditions.

Firstly, I confirmed arable land to be a key habitat for Red Kites during breeding season, while agricultural landscapes were used more intensively in winter than in summer most likely due to an easier accessibility of prey when fields are fallow or have sparse vegetation. As prey accessibility is crucial for the visually hunting Red Kites, further knowledge about the effects of different crops on the space and habitat use of Red Kites within the breeding season would be of advantage to improve food availability.

Secondly, in almost all my studies I found significant differences in space use between male and female Red Kites. While during the breeding season most of these differences could be explained by their reproductive role specialization, this explanation did not apply to the differences in space use detected between sexes in winter. It thus remains a challenge for future studies to disentangle which additional drivers influence the space use of female and male Red Kites in winter habitats. The next step would then be to link the conditions in the winter habitats and during migration to the consecutive breeding season to assess carry-over effects from one season to the other.

Thirdly, I was able to show that flight activity and flight altitude of Red Kites depend on wind speeds. To verify whether the overall pattern observed is robust for the species, it would be beneficial to study the flight activity and flight altitude of Red Kites as a function of wind speed also in other areas of their distribution range. In such analysis, the underlying landscape should be considered as it most likely affects the flight altitude of Red Kites, too. Moreover, by analysing flight activity and flight altitude also of other highly mobile and collision-prone bird species in relation to wind speed, it could be evaluated whether raising cut-in speeds might be a useful additional mitigation measure for them, too. With the so gained knowledge, post-construction mitigation measures could get significantly improved. Additionally, the influence of land use types and characteristic structures in the landscape on the flight direction of Red Kites could provide fundamental knowledge for the micro-siting of wind turbines.

There is already a high awareness of changing environmental conditions and declining number of species we face in times of land-use and climate change, and much is already being done to resolve it. Nevertheless, it will remain indispensable to regularly reevaluate existing conservation measures and to develop new integrative ones. Here, the conservation of flagship species like the Red Kite can help to mitigate risks and maintain suitable habitats not only for this species, but also for other highly mobile animals threatened by today's changing environmental conditions.

## References

- Aebischer, A. (2009). Der Rotmilan: Ein faszinierender Greifvogel. Haupt.
- Allison, T. D., Diffendorfer, J. E., Baerwald, E. F., Beston, J. A., Drake, D., Hale, A. M., Hein, C. D., Huso, M. M., Loss, S. R., Lovich, J. E., Strickland, M. D., Williams, K. A., & Winder, V. L. (2019). Impacts to wildlife of wind energy siting and operation in the United States. 21, 24.
- Arnett, E. B., Huso, M. M., Schirmacher, M. R., & Hayes, J. P. (2011). Altering turbine speed reduces bat mortality at wind-energy facilities. *Frontiers in Ecology and the Environment*, 9(4), 209–214. <https://doi.org/10.1890/100103>
- Bañuelos-Ruedas, F., Angeles-Camacho, C., & Rios-Marcuello, S. (2010). Analysis and validation of the methodology used in the extrapolation of wind speed data at different heights. *Renewable and Sustainable Energy Reviews*, 14(8), 2383–2391. <https://doi.org/10.1016/j.rser.2010.05.001>
- Barton, N. W., & Houston, D. C. (1996). Factors influencing the size of some internal organs in raptors. *Journal of Raptor Research*, 30(4), 219–223.
- Bates, D., Maechler, M., Bolker, B., Walker, S., (2015). Fitting Linear Mixed-Effects Models Using lme4. *Journal of Statistical Software*, 67(1), 1–48. <https://doi.org/10.18637/jss.v067.i01>.
- Bauer, H. G., Bezzel, E., & Fiedler, W. (Hrsg.). (2005). Das Kompendium der Vögel Mitteleuropas: Alles über Biologie, Gefährdung und Schutz (Bd. 1). AULA-Verlag.
- Bergen, F. (2001). Untersuchungen zum Einfluss der Errichtung und des Betriebs von Windenergieanlagen auf Vögel im Binnenland [Dissertation, Ruhr Universität Bochum]. <http://core.ac.uk/download/pdf/14609613.pdf>
- Berny, P., & Gaillet, J.-R. (2008). Acute poisoning of red kites (*Milvus milvus*) in France: Data from the SAGIR network. *Journal of wildlife diseases*, 44(2), 417–426.
- Bildstein, K. L. (2004). Raptor migration in the Neotropics: Patterns, processes and consequences. *Ornitología Neotropical*, 15, 83–99.
- BirdLife International. (2018). *Milvus milvus*. The IUCN Red List of Threatened Species 2018: E.T22695072A131877336.

- <https://dx.doi.org/10.2305/IUCN.UK.2018-2.RLTS.T22695072A131877336.en>
- BirdLife International. (2020). *Milvus milvus*. The IUCN Red List of Threatened Species 2020: E.T22695072A181651010. <https://dx.doi.org/10.2305/IUCN.UK.2020-3.RLTS.T22695072A181651010.en>
- Bischofberger, I., Kamrad, M., Sindl, L., Bayo, R., Katzenberger, J., Laux, B., Müller, B., Horchler, B., Helms, F., Beining, F., Michels, P., Stricker, V., Krämer, M., & Gottschalk, E. (2019). Werden junge Rotmilane (*Milvus milvus*) satt? – Nahrungs mengen und Nahrungszusammensetzung in drei Regionen Deutschlands. Vogelwelt, 139, 87–99.
- Bivand, R. S., Pebesma, E., & Gómez-Rubio, V. (2013). Applied Spatial Data Analysis with R. Springer New York. <http://link.springer.com/10.1007/978-1-4614-7618-4>
- Bloom, P. H., Clark, W. S., & Kidd, J. W. (2007). Capture techniques. In D. M. Bird & K. L. Bildstein (Hrsg.), Raptor research and management techniques (2. Aufl, S. 193–219). Hancock House Publ.
- Blouin-Demers, G., & Weatherhead, P. J. (2002). Implications of movement patterns for gene flow in black rat snakes (*Elaphe obsoleta*). Canadian Journal of Zoology, 80(7), 1162–1172. <https://doi.org/10.1139/z02-096>
- Brodin, A., Ingemar Jönsson, K., & Holmgren, N. (2003). Optimal energy allocation and behaviour in female raptorial birds during the nestling period. Écoscience, 10(2), 140–150. <https://doi.org/10.1080/11956860.2003.11682760>
- Brooks, M., E., Kristensen, K., Benthem, K. J., van Magnusson, A., Berg, C. W., Nielsen, A., Skaug, H. J., Mächler, M., & Bolker, B., M. (2017). GlmmTMB balances speed and flexibility among packages for zero-inflated generalized linear mixed modeling. The R Journal, 9(2), 378. <https://doi.org/10.32614/RJ-2017-066>
- Büttner, G., Kosztra, B., Soukup, T., Sousa, A., & Langanke, T. (2017). CLC2018 technical guidelines (European Environment Agency, Hrsg.).
- Calabrese, J. M., Fleming, C. H., & Gurarie, E. (2016). ctmm: An R package for analyzing animal relocation data as a continuous-time stochastic process. Methods in Ecology and Evolution, 7(9), 1124–1132. <https://doi.org/10.1111/2041-210X.12559>
- Campioni, L., Delgado, M. del M., Lourenço, R., Bastianelli, G., Fernández, N., & Penteriani, V. (2013). Individual and spatio-temporal variations in the home range behaviour of a long-lived, territorial species. Oecologia, 172(2), 371–385. <https://doi.org/10.1007/s00442-012-2493-7>
- Carrete, M., & Donázar, J. A. (2005). Application of central-place foraging theory shows the importance of Mediterranean

- dehesas for the conservation of the cinereous vulture, *Aegypius monachus*. Biological Conservation, 126(4), 582–590. <https://doi.org/10.1016/j.biocon.2005.06.031>
- Clark, W. S. (1999). A Field Guide to the Raptors of Europe, the Middle East, and North Africa. Oxford University Press.
- Convention on the conservation of migratory species of wild animals, EEC, 210 OJ L (1979). <http://data.europa.eu/eli/conv/1982/461/oj/eng>
- Copernicus Climate Change Service. (2019). ERA5-Land hourly data from 2001 to present [Data set]. ECMWF. [https://doi.org/10.24381/CDS.E2161B\\_AC](https://doi.org/10.24381/CDS.E2161B_AC)
- Cortés-Avizanda, A., Carrete, M., & Donázar, J. (2010). Managing supplementary feeding for avian scavengers: Guidelines for optimal design using ecological criteria. Biological Conservation, 143, 1707–1715. <https://doi.org/10.1016/j.biocon.2010.04.016>
- Dahl, E. L., May, R., Hoel, P., Bevanger, K., Pedersen, H., Røskift, E., & Stokke, B. (2013). Wind Energy and Wildlife Conservation White-Tailed Eagles (*Haliaeetus albicilla*) at the Smøla Wind-Power Plant, Central Norway, Lack Behavioral Flight Responses to Wind Turbines. Wildlife Society Bulletin, 37, 66–74. <https://doi.org/10.1002/wsb.258>
- de Lucas, M., Ferrer, M., Bechard, M. J., & Muñoz, A. R. (2012). Griffon vulture mortality at wind farms in southern Spain: Distribution of fatalities and active mitigation measures. Biological Conservation, 147(1), 184–189. <https://doi.org/10.1016/j.biocon.2011.12.029>
- Deutsche Akademie der Technikwissenschaften, Deutsche Akademie der Naturforscher Leopoldina, & Union der Deutschen Akademien der Wissenschaften (Hrsg.). (2020). Biodiversität und Management von Agrarlandschaften: Umfassendes Handeln ist jetzt wichtig: Stellungnahme. Deutsche Akademie der Naturforscher Leopoldina e.V. - Nationale Akademie der Wissenschaften.
- Díaz, S., Settele, J., Brondízio, E. S., Ngo, H. T., Agard, J., Arneth, A., Balvanera, P., Brauman, K. A., Butchart, S. H. M., Chan, K. M. A., Garibaldi, L. A., Ichii, K., Liu, J., Subramanian, S. M., Midgley, G. F., Miloslavich, P., Molnár, Z., Obura, D., Pfaff, A., ... Zayas, C. N. (2019). Pervasive human-driven decline of life on Earth points to the need for transformative change. Science, 366(6471), eaax3100. <https://doi.org/10.1126/science.aax3100>
- Directive 2001/42/EC of the European Parliament and of the Council of 27 June 2001 on the assessment of the effects of certain plans and programmes on the environment, Pub. L. No. 32001L0042, 197 197 (2001). <http://data.europa.eu/eli/dir/2001/42/oj/eng>

## References

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- Directive 2009/147/EC of the European Parliament and of the Council of 30 November 2009 on the conservation of wild birds, CONSIL, EP, 020 OJ L (2009). <http://data.europa.eu/eli/dir/2009/147/oj/eng>
- Directive 2014/52/EU of the European Parliament and of the Council of 16 April 2014 amending Directive 2011/92/EU on the assessment of the effects of certain public and private projects on the environment Text with EEA relevance, Pub. L. No. 32014L0052, 124 124 (2014). <http://data.europa.eu/eli/dir/2014/52/oj/eng>
- Donald, P. F., Green, R. E., & Heath, M. F. (2001). Agricultural intensification and the collapse of Europe's farmland bird populations. *Proceedings of the Royal Society B: Biological Sciences*, 268(1462), 25–29. <https://doi.org/10.1098/rspb.2000.1325>
- Drewitt, A. L., & Langston, R. H. (2006a). Assessing the impacts of wind farms on birds. *Ibis*, 148(s1), 29–42.
- Drewitt, A. L., & Langston, R. H. W. (2006b). Assessing the impacts of wind farms on birds. *Ibis*, 148(s1), 29–42. <https://doi.org/10.1111/j.1474-919X.2006.00516.x>
- Dürr, T. (2021, Mai 7). Vogelverluste an Windenergieanlagen in Deutschland—Daten aus der zentralen Fundkartei der Staatlichen Vogelschutzwarte im Landesamt für Umwelt, Gesundheit und Verbraucherschutz Brandenburg. [http://www.lugv.brandenburg.de/cms/media.php/lbm1.a.3310.de/wka\\_voegel\\_de.xls](http://www.lugv.brandenburg.de/cms/media.php/lbm1.a.3310.de/wka_voegel_de.xls)
- Durstewitz, M., Berkhouit, V., Faulstich, S., Görg, P., Große, L., Hahn, B., Lutz, M.-A., Mayer, J., Pfaffel, S., Rehwald, F., & Spriestersbach, S. (2019). Windenergie Report Deutschland 2018. Fraunhofer IRB-Verlag. [http://windmonitor.iee.fraunhofer.de/opencms/export/sites/windmonitor/img/Windmonitor-2018/WERD\\_2018.pdf](http://windmonitor.iee.fraunhofer.de/opencms/export/sites/windmonitor/img/Windmonitor-2018/WERD_2018.pdf)
- Faith, D. P., Minchin, P. R., & Belbin, L. (1987). Compositional dissimilarity as a robust measure of ecological distance. *Vegetatio*, 69, 57–68. <https://doi.org/10.1007/BF00038687>
- Farfán, M. A., Vargas, J. M., Duarte, J., & Real, R. (2009). What is the impact of wind farms on birds? A case study in southern Spain. *Biodiversity and Conservation*, 18(14), 3743–3758. <https://doi.org/10.1007/s10531-009-9677-4>
- Fernández, M., Oria, J., Sánchez, R., González, L. M., & Margalida, A. (2009). Space use of adult Spanish Imperial Eagles *Aquila adalberti*. *Acta Ornithologica*, 44(1), 17–26. <https://doi.org/10.3161/000164509X464849>
- Fernández-Tizón, M., Emmenegger, T., Perner, J., & Hahn, S. (2020). Arthropod biomass

- increase in spring correlates with NDVI in grassland habitat. *The Science of Nature*, 107(5), 42. <https://doi.org/10.1007/s00114-020-01698-7>
- Forslund, P., & Pärt, T. (1995). Age and reproduction in birds—Hypotheses and tests. *Trends in Ecology & Evolution*, 10(9), 374–378. [https://doi.org/10.1016/S0169-5347\(00\)89141-7](https://doi.org/10.1016/S0169-5347(00)89141-7)
- Garvin, J. C., Jennelle, C. S., Drake, D., & Grodsky, S. M. (2011). Response of raptors to a windfarm. *Journal of Applied Ecology*, 48(1), 199–209. <https://doi.org/10.1111/j.1365-2664.2010.01912.x>
- Gelpke, C., & Hormann, M. (2010). Artenhilfskonzept Rotmilan (*Milvus milvus*) in Hessen. Gutachten im Auftrag der Staatlichen Vogelschutzwarte für Hessen, Rheinland-Pfalz und das Saarland.
- González, J. C. G., Redondo, J. A., & Garzón, A. (2015). EU-DEM Upgrade—Documentation EEA User Manual.
- González, L. M., Margalida, A., Sánchez, R., & Oria, J. (2006). Supplementary feeding as an effective tool for improving breeding success in the Spanish imperial eagle (*Aquila adalberti*). *Biological Conservation*, 129(4), 477–486. <https://doi.org/10.1016/j.biocon.2005.11.014>
- Goriup, P., & Tucker, G. (2007). Assessment of the merits of a CMS instrument covering migratory raptors in Africa and Eurasia. DEFRA. [https://www.cms.int/sites/default/files/document/Inf\\_07\\_Assessments\\_CMS.instruments\\_0.pdf](https://www.cms.int/sites/default/files/document/Inf_07_Assessments_CMS.instruments_0.pdf)
- Gottschalk, E., Wasmund, N., Sauer, B., & Bayoh, R. (o. J.). Nahrungsmangel beim Rotmilan *Milvus milvus*? Was können zusätzliche Mahdflächen zur Nahrungsverfügbarkeit beitragen?
- Griffin, C. R., & Baskett, T. S. (1985). Food availability and winter range sizes of immature and adult Bald Eagles. *The Journal of Wildlife Management*, 49(3), 592. <https://doi.org/10.2307/3801677>
- Grüneberg, C., & Karthäuser, J. (2019). Verbreitung und Bestand des Rotmilans *Milvus milvus* in Deutschland – Ergebnisse der bundesweiten Kartierung 2010–2014. *Vogelwelt*, 139, 101–116.
- Grünkorn, T., Blew, J., Coppack, T., Krüger, O., Nehls, G., Potiek, A., Reichenbach, M., von Rönn, J., Timmermann, H., & Weitekamp, S. (2016). Ermittlung der Kollisionsraten von (Greif-)Vögeln und Schaffung planungsbezogener Grundlagen für die Prognose und Bewertung des Kollisionsrisikos durch Windenergieanlagen (PROGRESS). Schlussbericht zum durch das Bundesministerium für Wirtschaft und Energie (BMWi) im Rahmen des 6. Energieforschungsprogramms der Bundesregierung geförderten Verbundvorhaben PROGRESS, FKZ 0325300A-D.

## References

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- <http://bioconsult-sh.de/site/assets/files/1561/1561-1.pdf>
- Hagemeijer, W. J. M., & Blair, M. J. (1997). The EBBC-Atlas of European breeding Birds—Their Distribution and Abundance. (Poyser, Hrsg.). Bloomsbury Specialist.
- Hanssen, F., May, R., & Nygård, T. (2020). High-Resolution Modeling of Uplift Landscapes can Inform Micrositing of Wind Turbines for Soaring Raptors. *Environmental Management*, 66(3), 319–332. <https://doi.org/10.1007/s00267-020-01318-0>
- Harrison, X. A., Blount, J. D., Inger, R., Norris, D. R., & Bearhop, S. (2011). Carry-over effects as drivers of fitness differences in animals. *Journal of Animal Ecology*, 80(1), 4–18. <https://doi.org/10.1111/j.1365-2656.2010.01740.x>
- Hedenström, A., & Bone, Q. (1993). Migration by soaring or flapping flight in birds: The relative importance of energy cost and speed. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences*, 342(1302), 353–361. <https://doi.org/10.1098/rstb.1993.0164>
- Hegemann, A., & Knüwer, H. (2005). Illegale Greifvogelverfolgung—Ausmaße und Gegenmaßnahmen am Beispiel Nordrhein-Westfalens. *Berichte zum Vogelschutz*, 42, 87–95.
- Heredia, B., Alonso, J. C., & Hiraldo, F. (1991). Space and habitat use by Red Kites *Milvus milvus* during winter in the Guadalquivir marshes: A comparison between resident and wintering populations. *Ibis*, 133(4), 374–381. <https://doi.org/10.1111/j.1474-919X.1991.tb04585.x>
- Hernández-Pliego, J., Rodríguez, C., & Bustamante, J. (2017). A few long versus many short foraging trips: Different foraging strategies of lesser kestrel sexes during breeding. *Movement Ecology*, 5(1), 8. <https://doi.org/10.1186/s40462-017-0100-6>
- Hessische Gesellschaft für Ornithologie und Naturschutz (Hrsg.). (2010). Vögel in Hessen: Die Brutvögel Hessens in Raum und Zeit; Brutvogelatlas (1. Aufl.). HGON.
- Hessische Verwaltung für Bodenmanagement und Geoinformation. (2016). Produktkatalog Heft 5—Allgemeine Informationen. [https://hvbg.hessen.de/irj/servlet/prt/portal/prtroot/slimp.CMReader/HMWVL\\_15/HVBG\\_InterneT/med/203/2035b53d-8be3-6417-9cda-a2b417c0cf46,22222222-2222-2222-2222-2222222222222222](https://hvbg.hessen.de/irj/servlet/prt/portal/prtroot/slimp.CMReader/HMWVL_15/HVBG_InterneT/med/203/2035b53d-8be3-6417-9cda-a2b417c0cf46,22222222-2222-2222-2222-2222222222222222)
- Hessisches Ministerium für Umwelt, Energie, Landwirtschaft und Verbraucherschutz Abteilung. (2012). Leitfaden Berücksichtigung der Naturschutzbelaenge bei der Planung und Genehmigung von Windkraftanlagen (WKA) in Hessen. <http://www.energieland.hessen.de/mm/wka-leitfaden.pdf>

## References

---

- Heuck, C., Brandl, R., Albrecht, J., & Gottschalk, T. K. (2013). The potential distribution of the Red Kite in Germany. *Journal of Ornithology*, 154(4), 911–921. <https://doi.org/10.1007/s10336-013-0955-2>
- Heuck, C., Sommerhage, M., Stelbrink, P., Höfs, C., Geisler, K., Gelpke, C., & Koschkar, S. (2019). Untersuchung des Flugverhaltens von Rotmilanen in Abhängigkeit von Wetter und Landnutzung unter besonderer Berücksichtigung vorhandener Windenergieanlagen im Vogelschutzgebiet Vogelsberg – Abschlussbericht. Im Auftrag des Hessischen Ministerium für Wirtschaft, Energie, Verkehr und Wohnen, 125.
- Hijmans, R. J. (2016). Introduction to the 'raster' package (version 2.5-8). <ftp://ftp.rdis.com/mirror/R/web/packages/raster/vignettes/Raster.pdf>
- Hötker, H. (2009). Birds of Prey and Wind Farms: Analysis of Problems and Possible Solutions. [https://bergenhusen.nabu.de/imperia/md/images/bergenhusen/bmuwindkraftundgreifwebsite/bird\\_of\\_pray\\_an\\_wind-farms\\_documentation\\_2009.pdf](https://bergenhusen.nabu.de/imperia/md/images/bergenhusen/bmuwindkraftundgreifwebsite/bird_of_pray_an_wind-farms_documentation_2009.pdf)
- Hötker, H., Mammen, K., Mammen, U., & Rasran, L. (2017). Red Kites and Wind Farms—Telemetry Data from the Core Breeding Range. In J. Köppel (Hrsg.), *Wind Energy and Wildlife Interactions: Presentations from the CWW2015 Conference* (S. 3–15). Springer International Publishing.
- [https://doi.org/10.1007/978-3-319-51272-3\\_1](https://doi.org/10.1007/978-3-319-51272-3_1)
- IPBES. (2019). Summary for policymakers of the global assessment report on biodiversity and ecosystem services. Zenodo. <https://doi.org/10.5281/ZENODO.3553579>
- Jenkins, J. M., & Jackman, R. E. (1993). Mate and nest site fidelity in a resident population of Bald Eagles. *The Condor*, 95(4), 1053–1056. <https://doi.org/10.2307/1369447>
- Karthäuser, J., Katzenberger, J., & Sudfeldt, C. (2019). Evaluation von Maßnahmen zur Verbesserung des Nahrungsangebotes für den Rotmilan *Milvus milvus* in intensiv genutzten Agrarlandschaften. *Vogelwelt*, 139, 71–86.
- Katzenberger, J. K. (2021). Habitat use and population viability of the Red Kite (*Milvus milvus*) in Germany [Georg-August-University Göttingen]. <https://doi.org/10.53846/goediss-8583>
- Kenward, R. (2001). *A manual for wildlife radio tagging*. Academic Press.
- Kikuchi, R. (2008). Adverse impacts of wind power generation on collision behaviour of birds and anti-predator behaviour of squirrels. *Journal for Nature Conservation*, 16(1), 44–55. <https://doi.org/10.1016/j.jnc.2007.11.001>

- Kirby, J. S., Stattersfield, A. J., Butchart, S. H. M., Evans, M. I., Grimmett, R. F. A., Jones, V. R., O'Sullivan, J., Tucker, G. M., & Newton, I. (2008). Key conservation issues for migratory land- and waterbird species on the world's major flyways. *Bird Conservation International*, 18(S1), S49–S73. <https://doi.org/10.1017/S0959270908000439>
- Klaassen, R. H. G., Hake, M., Strandberg, R., Koks, B. J., Trierweiler, C., Exo, K.-M., Bairlein, F., & Alerstam, T. (2014). When and where does mortality occur in migratory birds? Direct evidence from long-term satellite tracking of raptors. *Journal of Animal Ecology*, 83(1), 176–184. <https://doi.org/10.1111/1365-2656.12135>
- Knott, J., Newberry, P., & Barov, B. (2009). Species Action Plan for the red kite *Milvus milvus* in the European Union (S. 55). BirdLife International, European Union. [http://ec.europa.eu/environment/nature/conservation/wildbirds/action\\_plans/docs/milvus\\_milvus.pdf](http://ec.europa.eu/environment/nature/conservation/wildbirds/action_plans/docs/milvus_milvus.pdf)
- Kranstauber, B., & Smolla, M. (2015). Package „move“. <https://cran.r-project.org/web/packages/move/move.pdf>
- Krone, O., Berger, A., & Schulte, R. (2009). Recording movement and activity pattern of a White-tailed Sea Eagle (*Haliaeetus albicilla*) by a GPS datalogger. *Journal of Ornithology*, 150(1), 273–280. <https://doi.org/10.1007/s10336-008-0347-1>
- La Sorte, F. A., Fink, D., Hochachka, W. M., DeLong, J. P., & Kelling, S. (2014). Spring phenology of ecological productivity contributes to the use of looped migration strategies by birds. *Proceedings of the Royal Society B: Biological Sciences*, 281(1793), 20140984. <https://doi.org/10.1098/rspb.2014.0984>
- Länderarbeitsgemeinschaft der staatlichen Vogelschutzwarten in Deutschland LAG VSW. (2015). Abstandsempfehlungen für Windenergieanlagen zu bedeutsamen Vogellebensräumen sowie Brutplätzen ausgewählter Vogelarten (Stand April 2015). [http://www.lugv.brandenburg.de/media\\_fast/4055/abstands-empfehlungen\\_lag\\_vsw\\_2014.pdf](http://www.lugv.brandenburg.de/media_fast/4055/abstands-empfehlungen_lag_vsw_2014.pdf)
- Langgemach, T., & Dürr, T. (2018). Informationen über Einflüsse der Windenergienutzung auf Vögel. Landesamt für Umwelt Brandenburg - Staatliche Vogelschutzwarte. [http://www.lfu.brandenburg.de/cms/media.php/lbm1.a.3310.de/vsw\\_dok-wind\\_voegel.pdf](http://www.lfu.brandenburg.de/cms/media.php/lbm1.a.3310.de/vsw_dok-wind_voegel.pdf)
- Langston, R., & Pullan, J. (2003). Windfarms and Birds: An analysis of the effects of windfarms on birds, and guidance on environmental assessment criteria and site selection issues. 58.
- Lanzone, M. J., Miller, T. A., Turk, P., Brandes, D., Halverson, C., Maisonneuve, C., Tremblay, J., Cooper, J., O'Malley, K., Brooks, R. P., & Katzner, T. (2012). Flight responses by a migratory soaring raptor to

- changing meteorological conditions. *Biology Letters*, 8(5), 710–713. <https://doi.org/10.1098/rsbl.2012.0359>
- Lehnert, L. S., Kramer-Schadt, S., Schönborn, S., Lindecke, O., Niermann, I., & Voigt, C. C. (2014). Wind Farm Facilities in Germany Kill Noctule Bats from Near and Far. *PLoS ONE*, 9(8), e103106. <https://doi.org/10.1371/journal.pone.0103106>
- Lemoine, N., Bauer, H.-G., Peintinger, M., & Böhning-Gaese, K. (2007). Effects of climate and land-use change on species abundance in a Central European bird community. *Conservation Biology: The Journal of the Society for Conservation Biology*, 21(2), 495–503. <https://doi.org/10.1111/j.1523-1739.2006.00633.x>
- Lerch, U., Nachtigall, W., & Langgemach, T. (2014). Land zum Leben—Praktische Maßnahmen zum Schutz des Rotmilans. Deutscher Verband für Landschaftspflege e.V. (DVL). [http://rotmilan.org/en\\_wordpress/wp-content/uploads/2014/11/Praktische-Ma%C3%9Fnahmen-Rotmilan-Land-zum-Leben.pdf](http://rotmilan.org/en_wordpress/wp-content/uploads/2014/11/Praktische-Ma%C3%9Fnahmen-Rotmilan-Land-zum-Leben.pdf)
- Leung, D. Y. C., & Yang, Y. (2012). Wind energy development and its environmental impact: A review. *Renewable and Sustainable Energy Reviews*, 16(1), 1031–1039. <https://doi.org/10.1016/j.rser.2011.09.024>
- Limiñana, R., Soutullo, A., López-López, P., & Urios, V. (2008). Pre-migratory movements of adult Montagu's Harriers *Circus pygargus*. *Ardea*, 96(1), 81–90. <https://doi.org/10.5253/078.096.0109>
- López-López, P., García-Ripollés, C., & Urios, V. (2014). Food predictability determines space use of endangered vultures: Implications for management of supplementary feeding. *Ecological Applications*, 24(5), 938–949. <https://doi.org/10.1890/13-2000.1>
- Lydia, M., Kumar, S. S., Selvakumar, A. I., & Prem Kumar, G. E. (2014). A comprehensive review on wind turbine power curve modeling techniques. *Renewable and Sustainable Energy Reviews*, 30, 452–460. <https://doi.org/10.1016/j.rser.2013.10.030>
- Lyster, S. (1989). Convention on the Conservation of Migratory Species of Wild Animals (The Bonn Convention). [http://heinonlinebackup.com/hol-cgi-bin/get\\_pdf.cgi?handle=hein.journals/narj29&section=67](http://heinonlinebackup.com/hol-cgi-bin/get_pdf.cgi?handle=hein.journals/narj29&section=67)
- Mammen, K., Mammen, U., & Resetaritz, A. (2013). In: Hötker, H., Krone, O. & Nehls, G.: Greifvögel und Windkraftanlagen: Problemanalyse und Lösungsvorschläge. Schlussbericht für das Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit. Michael-Otto-Institut im NABU, Leibniz-Institut für Zoo- und Wildtierforschung, BioConsult SH.

## References

---

- Mammen, K., Mammen, U., & Resetaritz, A. (2017). Red Kite. In H. Hötker, O. Krone, & G. Nehls (Hrsg.), *Birds of Prey and Wind Farms: Analysis of Problems and Possible Solutions* (S. 13–95). Springer International Publishing. [https://doi.org/10.1007/978-3-319-53402-2\\_3](https://doi.org/10.1007/978-3-319-53402-2_3)
- Mammen, U., Mammen, K., Kratzsch, L., Resetaritz, A., & Siano, R. (2009). Interactions of Red Kites and wind farms: Results of radio telemetry and field observations. In Hötker et al. (2009): *Birds of Prey and Wind Farms: Analysis of Problems and Possible Solutions*, 14–21.
- Mammen, U., Nicolai, B., Böhner, J., Mammen, K., Wehrmann, J., Fischer, S., & Dornbusch, G. (2014). Artenhilfsprogramm Rotmilan des Landes Sachsen-Anhalt. Landesamt für Umweltschutz Sachsen-Anhalt.
- Mammen, U., & Stubbe, M. (1995). Alterseinschätzung und Brutbeginn des Rotmilans (*Milvus milvus*). *Vogel und Umwelt*, 8, 91–98.
- Marra, P. P., Hobson, K. A., & Holmes, R. T. (1998). Linking Winter and Summer Events in a Migratory Bird by Using Stable-Carbon Isotopes. *Science*, 282(5395), 1884–1886. <https://doi.org/10.1126/science.282.5395.1884>
- Martínez-Abráin, A., Tavecchia, G., Regan, H. M., Jiménez, J., Surroca, M., & Oro, D. (2012). Effects of wind farms and food scarcity on a large scavenging bird species following an epidemic of bovine spongiform encephalopathy. *Journal of Applied Ecology*, 49(1), 109–117. <https://doi.org/10.1111/j.1365-2664.2011.02080.x>
- Marzluff, J. M., Knick, S. T., Vekasy, M. S., & Schueck, L. S. (1997). Spatial use and habitat selection of Golden Eagles in Southwestern Idaho. *The Auk*, 114(4), 673–687. <https://doi.org/10.2307/4089287>
- McClure, C. J. W., Westrip, J. R. S., Johnson, J. A., Schulwitz, S. E., Virani, M. Z., Davies, R., Symes, A., Wheatley, H., Thorstrom, R., Amar, A., Buij, R., Jones, V. R., Williams, N. P., Buechley, E. R., & Butchart, S. H. M. (2018). State of the world's raptors: Distributions, threats, and conservation recommendations. *Biological Conservation*, 227, 390–402. <https://doi.org/10.1016/j.biocon.2018.08.012>
- Mebs, T., & Schmidt-Rothmund, D. (2014). *Die Greifvögel Europas, Nordafrikas und Vorderasiens: Biologie, Kennzeichen, Bestände* (2. Auflage). Kosmos.
- Mirski, P., Cenian, Z., Dagys, M., Darócz, S., Dementavičius, D., Maciorowski, G., Menderski, S., Nowak, D., Pongrácz, Á., Prommer, M., Sellis, U., Siekiera, J., Szinai, P., Tumieli, T., Wójciak, J., Zeitz, R., & Väli, Ü. (2021). Sex-, landscape- and climate-dependent patterns of home-range size – a macroscale study on an avian generalist predator. *Ibis*, 163(2), 641–657. <https://doi.org/10.1111/ibi.12894>

## References

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- Morales, J. M., Moorcroft, P. R., Matthiopoulos, J., Frair, J. L., Kie, J. G., Powell, R. A., Merrill, E. H., & Haydon, D. T. (2010). Building the bridge between animal movement and population dynamics. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 365(1550), 2289–2301. <https://doi.org/10.1098/rstb.2010.0082>
- Mueller, T., & Fagan, W. F. (2008). Search and navigation in dynamic environments— from individual behaviors to population distributions. *Oikos*, 117(5), 654–664.
- Muggeo, V. M. (2008). segmented: An R package to fit regression models with broken-line relationships. *R News*, 8(1), 20–25.
- Muñoz Sabater, J. (2019). ERA5-Land hourly data from 1981 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS).
- Nachtigall, W. (2008). Der Rotmilan (*Milvus milvus*, L. 1758) in Sachsen und Südbrandenburg – Untersuchungen zu Verbreitung und Ökologie. Martin-Luther-Universität Halle-Wittenberg.
- Nathan, R., Getz, W. M., Revilla, E., Holyoak, M., Kadmon, R., Saltz, D., & Smouse, P. E. (2008). A movement ecology paradigm for unifying organismal movement research. *Proceedings of the National Academy of Sciences of the United States of America*, 105(49), 19052–19059. <https://doi.org/10.1073/pnas.0800375105>
- Navarro-López, J., & Fargallo, J. A. (2015). Trophic niche in a raptor species: The relationship between diet diversity, habitat diversity and territory quality. *PLOS ONE*, 10(6), e0128855. <https://doi.org/10.1371/journal.pone.0128855>
- Nazir, M. S., Ali, N., Bilal, M., & Iqbal, H. M. N. (2020). Potential environmental impacts of wind energy development: A global perspective. *Current Opinion in Environmental Science & Health*, 13, 85–90. <https://doi.org/10.1016/j.coesh.2020.01.002>
- Negro, J. J., & Grande, J. M. (2001). Territorial signalling: A new hypothesis to explain frequent copulation in raptorial birds. *Animal Behaviour*, 62(4), 803–809. <https://doi.org/10.1006/anbe.2001.1811>
- Newton, I. (1998). Population Limitation in Birds. Academic Press.
- Odum, E. P., & Kuenzler, E. J. (1955). Measurement of Territory and Home Range Size in Birds. *The Auk*, 72(2), 128–137. <https://doi.org/10.2307/4081419>
- Oksanen, J., Blanchet, F. G., Kindt, R., Legendre, P., Minchin, P. R., O'Hara, R. B., Simpson, G. L., Solymos, P., Stevens, M. H. H., & Wagner, H. (2020). Vegan: Community ecology package. R package version 2.5-7. <http://CRAN.R-project.org/package=vegan>

- Ortlieb, R. (1989). Der Rotmilan: *Milvus milvus* (3., überarb. Aufl). Ziemsen.
- Panuccio, M., Duchi, A., Lucia, G., & Agostini, N. (2017). Species-Specific Behaviour of Raptors Migrating Across the Turkish Straits in Relation to Weather and Geography. *Ardeola*, 64(2), 305–324. <https://doi.org/10.13157/arla.64.2.2017.ra2>
- Peery, M. Z. (2000). Factors affecting interspecies variation in home-range size of raptors. *The Auk*, 117(2), 511–517. <https://doi.org/10.1093/auk/117.2.511>
- Péron, G., Calabrese, J. M., Duriez, O., Fleming, C. H., García-Jiménez, R., Johnston, A., Lambertucci, S. A., Safi, K., & Shepard, E. L. C. (2020). The challenges of estimating the distribution of flight heights from telemetry or altimetry data. *Animal Biotelemetry*, 8(1), 5. <https://doi.org/10.1186/s40317-020-00194-z>
- Péron, G., Fleming, C. H., Duriez, O., Fluhr, J., Itty, C., Lambertucci, S., Safi, K., Shepard, E. L. C., & Calabrese, J. M. (2017). The energy landscape predicts flight height and wind turbine collision hazard in three species of large soaring raptor. *Journal of Applied Ecology*, 54(6), 1895–1906. <https://doi.org/10.1111/1365-2664.12909>
- Pfeiffer, T., & Meyburg, B.-U. (2009). Satelliten-telemetrische Untersuchungen zum Zug- und Überwinterungsverhalten thüringischer Rotmilane *Milvus milvus*. *Vogelwarte*, 47, 171–187.
- Pfeiffer, T., & Meyburg, B.-U. (2015). GPS tracking of Red Kites (*Milvus milvus*) reveals fledgling number is negatively correlated with home range size. *Journal of Ornithology*, 156(4), 963–975. <https://doi.org/10.1007/s10336-015-1230-5>
- Potier, S., Bonadonna, F., Kelber, A., Martin, G. R., Isard, P.-F., Dulaurent, T., & Duriez, O. (2016). Visual abilities in two raptors with different ecology. *Journal of Experimental Biology*, 219(17), 2639–2649. <https://doi.org/10.1242/jeb.142083>
- Powell, L. L., Ames, E. M., Wright, J. R., Matthiopoulos, J., & Marra, P. P. (2021). Interspecific competition between resident and wintering birds: Experimental evidence and consequences of coexistence. *Ecology*, 102(2), e03208. <https://doi.org/10.1002/ecy.3208>
- R Core Team. (2013). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. <http://www.R-project.org/>.
- Reid, T., Krüger, S., Whitfield, D. P., & Amar, A. (2015). Using spatial analyses of bearded vulture movements in southern Africa to inform wind turbine placement. *Journal of Applied Ecology*, 52(4), 881–892. <https://doi.org/10.1111/1365-2664.12468>

## References

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- Ridley, M., & Hill, D. (2018). Effects of Innovation in Agriculture on the Environment (SSRN Scholarly Paper ID 3853558). Social Science Research Network. <https://doi.org/10.2139/ssrn.3853558>
- Rolando, A. (2002). On the ecology of home range in birds. *Revue d'écologie*, 57(1), 53–73.
- Roth, J. E., Kelly, J. P., Sydeman, W. J., & Colwell, M. A. (2004). Sex Differences in Space Use of Breeding Common Ravens in Western Marin County, California. *The Condor*, 106(3), 529–539. <https://doi.org/10.1093/condor/106.3.529>
- Safi, K., Kranstauber, B., Weinzierl, R., Griffin, L., Rees, E. C., Cabot, D., Cruz, S., Proano, C., Takekawa, J. Y., Newman, S. H., Waldenström, J., Bengtsson, D., Kays, R., Wikelski, M., & Bohrer, G. (2013). Flying with the wind: Scale dependency of speed and direction measurements in modelling wind support in avian flight. *Movement Ecology*, 1(4). <https://doi.org/10.1186/2051-3933-1-4>
- Sala, O. E., Chapin, F. S., Armesto, J. J., Berlow, E., Bloomfield, J., Dirzo, R., Huber-Sanwald, E., Huenneke, L. F., Jackson, R. B., Kinzig, A., & others. (2000). Global biodiversity scenarios for the year 2100. *Science*, 287(5459), 1770–1774.
- Santema, P., & Kempenaers, B. (2018). Complete brood failure in an altricial bird is almost always associated with the sudden and permanent disappearance of a parent. *Journal of Animal Ecology*, 87(5), 1239–1250. <https://doi.org/10.1111/1365-2656.12848>
- Sauerbrei, R., Ekschmitt, K., Wolters, V., & Gottschalk, T. K. (2014). Increased energy maize production reduces farmland bird diversity. *GCB Bioenergy*, 6(3), 265–274. <https://doi.org/10.1111/gcbb.12146>
- Schaldach, R., Ernst, A., Volland, J., Hüfner, R., & Schügel, J. (2016). Abschlussbericht: Auswirkungen des Globalen Wandels auf Ökosystemdienstleistungen in Hessen [Abschlussbericht]. Fachzentrum Klimawandel Hessen im Hessischen Landesamt für Naturschutz, Umwelt und Geologie. [https://www.hlnug.de/fileadmin/dokumente/klima/INKLIM\\_A/natur-und-landschaft/oekosystemdienstleistungen.pdf](https://www.hlnug.de/fileadmin/dokumente/klima/INKLIM_A/natur-und-landschaft/oekosystemdienstleistungen.pdf)
- Schaub, T., Klaassen, R. H. G., Bouten, W., Schlaich, A. E., & Koks, B. J. (2020). Collision risk of Montagu's Harriers *Circus pygargus* with wind turbines derived from high-resolution GPS tracking. *Ibis*, 162(2), 520–534. <https://doi.org/10.1111/ibi.12788>
- Scherler, P. (2020). Drivers of Departure and Prospecting in Dispersing Juvenile Red Kites (*Milvus milvus*) [Dissertation, University of Zurich]. <https://www.zora.uzh.ch/id/eprint/201135/>

- Schlaich, A. E., Bouten, W., Bretagnolle, V., Heldbjerg, H., Klaassen, R. H. G., Sørensen, I. H., Villers, A., & Both, C. (2017). A circannual perspective on daily and total flight distances in a long-distance migratory raptor, the Montagu's harrier, *Circus pygargus*. *Biology Letters*, 13(6), 20170073. <https://doi.org/10.1098/rsbl.2017.0073>
- Schreiber, D. M. (2016). Abschaltzeiten für Windkraftanlagen zur Vermeidung und Verminderung von Vogelkollisionen. [https://www.fachagentur-windenergie.de/fileadmin/files/Veranstaltungen/Runder\\_Tisch\\_Vermeidungsmassnahmen/1\\_Run-der\\_Tisch\\_24.02.2016/Studie\\_Abschaltzeiten\\_Dr.\\_Schreiber\\_LKR\\_Osnabrueck\\_2016.pdf](https://www.fachagentur-windenergie.de/fileadmin/files/Veranstaltungen/Runder_Tisch_Vermeidungsmassnahmen/1_Run-der_Tisch_24.02.2016/Studie_Abschaltzeiten_Dr._Schreiber_LKR_Osnabrueck_2016.pdf)
- Seoane, J., Viñuela, J., Diaz-Delgado, R., & Bustamante, J. (2003). The effects of land use and climate on red kite distribution in the Iberian peninsula. *Biological Conservation*, 111(3), 401–414.
- Sergio, F., Caro, T., Brown, D., Clucas, B., Hunter, J., Ketchum, J., Mchugh, K., & Hiraldo, F. (2008). Top Predators as Conservation Tools: Ecological Rationale, Assumptions, and Efficacy. *Annual Review of Ecology Evolution and Systematics*, 39, 1–19. <https://doi.org/10.1146/annurev.ecolsys.39.110707.173545>
- Sergio, F., Newton, I., Marchesi, L., & Pedrini, P. (2006). Ecologically justified charisma: Preservation of top predators delivers biodiversity conservation. *Journal of Applied Ecology*, 43(6), 1049–1055. <https://doi.org/10.1111/j.1365-2664.2006.01218.x>
- Sergio, F., Tavecchia, G., Blas, J., Tanferna, A., & Hiraldo, F. (2021). Demographic modeling to fine-tune conservation targets: Importance of pre-adults for the decline of an endangered raptor. *Ecological Applications*, 31(3), e2266. <https://doi.org/10.1002/eap.2266>
- Serrano, D. (1999). Dumps for dead livestock and the conservation of wintering Red Kites (*Milvus milvus*). *Journal of Raptor Research*, 33, 338–340.
- Shiu, H.-J., Tokita, K., Morishita, E., Hiraoka, E., Wu, Y., Nakamura, H., & Higuchi, H. (2006). Route and site fidelity of two migratory raptors: Grey-faced Buzzards *Buteastur indicus* and Honey-buzzards *Pernis apivorus*. *Ornithological Science*, 5(2), 151–156. [https://doi.org/10.2326/1347-0558\(2006\)5\[151:RASFOT\]2.0.CO;2](https://doi.org/10.2326/1347-0558(2006)5[151:RASFOT]2.0.CO;2)
- Smart, J., Amar, A., Sim, I. M. W., Etheridge, B., Cameron, D., Christie, G., & Wilson, J. D. (2010). Illegal killing slows population recovery of a re-introduced raptor of high conservation concern – The red kite *Milvus milvus*. *Biological Conservation*, 143(5), 1278–1286. <https://doi.org/10.1016/j.biocon.2010.03.002>
- Smith, S., Steenhoff, K., McClure, C., & Heath, J. (2016). Data associated with „earlier

- nesting by predatory bird is associated with human responses to climate change". Biological Sciences Data. <https://doi.org/10.18122/B2PC78>
- Soriano-Redondo, A., Acácio, M., Franco, A. M. A., Martins, B. H., Moreira, F., Rogerson, K., & Catry, I. (2020). Testing alternative methods for estimation of bird migration phenology from GPS tracking data. *Ibis*, 162(2), 581–588. <https://doi.org/10.1111/ibi.12809>
- Soriano-Redondo, A., Bearhop, S., Lock, L., Votier, S. C., & Hilton, G. M. (2017). Internet-based monitoring of public perception of conservation. *Biological Conservation*, 206, 304–309. <https://doi.org/10.1016/j.biocon.2016.11.031>
- Spatz, T., Schabo, D. G., Farwig, N., & Rösner, S. (2019). Raumnutzung des Rotmilans *Milvus milvus* im Verlauf der Brutzeit: Eine Analyse mittels GPS-basierter Bewegungsdaten. *Vogelwelt*, 139, 161–169.
- Stanley, C. Q., Dudash, M. R., Ryder, T. B., Shriver, W. G., Serno, K., Adalsteinsson, S., & Marra, P. P. (2021). Seasonal variation in habitat selection for a Neotropical migratory songbird using high-resolution GPS tracking. *Ecosphere*, 12(3), e03421. <https://doi.org/10.1002/ecs2.3421>
- Stübing, S., Korn, M., Kreuziger, J., Werner, M., & Conz, O. (2010). Vögel in Hessen: Die Brutvögel Hessens in Raum und Zeit; Brutvogelatlas (Hessische Gesellschaft für Ornithologie und Naturschutz, Hrsg.; 1. Aufl.). HGON.
- Tabassum-Abbas, Premalatha, M., Abbas, T., & Abbas, S. A. (2014). Wind energy: Increasing deployment, rising environmental concerns. *Renewable and Sustainable Energy Reviews*, 31, 270–288. <https://doi.org/10.1016/j.rser.2013.11.019>
- Tews, J., Brose, U., Grimm, V., Tielbörger, K., Wichmann, M. C., Schwager, M., & Jeltsch, F. (2004). Animal species diversity driven by habitat heterogeneity/diversity: The importance of keystone structures. *Journal of Biogeography*, 31(1), 79–92. <https://doi.org/10.1046/j.0305-0270.2003.00994.x>
- Tikkanen, H., Balotari-Chiebao, F., Laaksonen, T., Pakanen, V.-M., & Rytkönen, S. (2018). Habitat use of flying subadult White-tailed Eagles (*Haliaeetus albicilla*): Implications for land use and wind power plant planning. 95, 14.
- Trierweiler, C., Mullié, W. C., Drent, R. H., Exo, K.-M., Komdeur, J., Bairlein, F., Harouna, A., de Bakker, M., & Koks, B. J. (2013). A Palaearctic migratory raptor species tracks shifting prey availability within its wintering range in the Sahel. *Journal of Animal Ecology*, 82(1), 107–120. <https://doi.org/10.1111/j.1365-2656.2012.02036.x>
- Tucker, M. A., Alexandrou, O., Bierregaard, R. O., Bildstein, K. L., Böhning-Gaese, K., Bracis, C., Brzorad, J. N., Buechley, E. R., Cabot, D.,

- Calabrese, J. M., Carrapato, C., Chiaradia, A., Davenport, L. C., Davidson, S. C., Desholm, M., DeSorbo, C. R., Domenech, R., Enggist, P., Fagan, W. F., ... Mueller, T. (2019). Large birds travel farther in homogeneous environments. *Global Ecology and Biogeography*, 28(5), 576–587. <https://doi.org/10.1111/geb.12875>
- van Rijn, J. (2015). Overview GAMM analysis of time series data. [www.sfs.uni-tuebingen.de/~jvanrij/Tutorial/GAMM.html](http://www.sfs.uni-tuebingen.de/~jvanrij/Tutorial/GAMM.html), last accessed 19.05.2019
- Verot, P. (2007). Interpretation and Implementation of the SEA Directive. Chalmers University of Technology.
- Villafuerte, R., Viñuela, J., & Blanco, J. C. (1998). Extensive predator persecution caused by population crash in a game species: The case of red kites and rabbits in Spain. *Biological Conservation*, 84(1), 181–188. [https://doi.org/10.1016/S0006-3207\(97\)00094-3](https://doi.org/10.1016/S0006-3207(97)00094-3)
- Voigt, C. C., Lehnert, L. S., Petersons, G., Adorf, F., & Bach, L. (2015). Wildlife and renewable energy: German politics cross migratory bats. *European Journal of Wildlife Research*, 61(2), 213–219. <https://doi.org/10.1007/s10344-015-0903-y>
- Wakeley, J. S. (1978). Factors affecting the use of hunting sites by Ferruginous Hawks. *The Condor*, 80(3), 316–326. <https://doi.org/10.2307/1368042>
- Walz, J. (2008). Aktionsraumnutzung und Territorialverhalten von Rot-und Schwarzmilanpaaren (*Milvus milvus*, *M. migrans*) bei Neuansiedlungen in Horstnähe. *Ornithol. Jh. Bad.-Württ*, 24, 21–38.
- Watson, R. T., Kolar, P. S., Ferrer, M., Nygård, T., Johnston, N., Hunt, W. G., Smit-Robinson, H. A., Farmer, C. J., Huso, M., & Katzner, T. E. (2018). Raptor Interactions With Wind Energy: Case Studies From Around the World. *Journal of Raptor Research*, 52(1), 1–18. <https://doi.org/10.3356/JRR-16-100.1>
- Wesolowski, T. (1994). On the origin of parental care and the early evolution of male and female parental roles in birds. *The American Naturalist*, 143(1), 39–58.
- Wickham, H. (2016). *ggplot2: Elegant Graphics for Data Analysis* (2nd ed. 2016). Springer International Publishing: Imprint: Springer. <https://doi.org/10.1007/978-3-319-24277-4>
- Wood, S. N. (2011). Fast stable restricted maximum likelihood and marginal likelihood estimation of semiparametric generalized linear models: Estimation of Semiparametric Generalized Linear Models. *Journal of the Royal Statistical Society: Series B (Statistical Methodology)*, 73(1), 3–36. <https://doi.org/10.1111/j.1467-9868.2010.00749.x>

## References

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Die Seite 109 (Curriculum Vitae) enthält persönliche Daten und ist daher nicht Bestandteil der Online-Veröffentlichung.



## **Erklärung**

Hiermit versichere ich, dass ich meine Dissertation mit dem Titel „What drives you? Space and habitat use of Red Kites (*Milvus milvus*) across different temporal and spatial scales“ selbstständig und ohne unerlaubte Hilfe verfasst habe. Ich habe mich keiner als der in ihr angegebenen Quellen oder Hilfsmittel bedient und alle vollständig oder singgemäß übernommenen Zitate als solche gekennzeichnet. Diese Dissertation wurde in der vorliegenden oder einer ihr ähnlichen Form noch bei keiner anderen in- oder ausländischen Hochschule eingereicht und hat noch keinen sonstigen Prüfungszwecken gedient.

Unterschrift (Theresa Doris Spatz)

Marburg an der Lahn, März 2022