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Enhancing monitoring and transboundary collaboration for conserving migratory species under global change: The priority case of the red kite

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ABSTRACT

Calls for urgent action to conserve biodiversity under global change are increasing, and conservation of migratory species in this context poses special challenges. In the last two decades the Convention on the

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Anthropogenic mortality
Climate change
Conservation strategy
Migratory bird
Full annual cycle

Conservation of Migratory Species of Wild Animals (CMS) has provided a framework for several subsidiary instruments including action plans for migratory bird species, but the effectiveness and transferability of these plans remain unclear. Such laws and policies have been credited with positive outcomes for the conservation of migratory species, but the lack of international coordination and on-ground implementation pose major challenges. While research on migratory populations has received growing attention, considerably less emphasis has been given to integrating ecological information throughout the annual cycle for examining strategies to conserve migratory species at multiple scales in the face of global change. We fill this gap through a case study examining the ecological status and conservation of a migratory raptor and facultative scavenger, the red kite (*Milvus milvus*), whose current breeding range is limited to Europe and is associated with agricultural landscapes and restricted to the temperate zone. Based on our review, conservation actions have been successful at recovering red kite populations within certain regions. Populations however remain depleted along the southernmost edge of the geographic range where many migratory red kites from northern strongholds overwinter. This led us to a forward-looking and integrated strategy that emphasizes international coordination involving researchers and conservation practitioners to enhance the science-policy-action interface. We identify and explore key issues for conserving the red kite under global change, including enhancing conservation actions within and outside protected areas, recovering depleted populations, accounting for climate change, and transboundary coordination in adaptive conservation and management actions. The integrated conservation strategy is sufficiently general such that it can be adapted to inform conservation of other highly mobile species subject to global change.

1. Introduction

We are in an era of rapid biodiversity loss (Brondizio et al., 2019; Dirzo et al., 2014) driven by global change (Diaz et al., 2019), which comprises the continuous alteration of Earth's chemical, biological, and physical processes as a function of human agency (Vitousek, 1994). As the current population of 7.6 billion humans is expected to reach 9.7 billion in 2050 (UN DESA, 2019), the causes of global change – including shifts in climate and land cover along with direct wildlife persecution – are expected to intensify if human societies do not change their way of living (IPCC, 2014; Leclere et al., 2020). Although the processes underlying global change become progressively clearer, their consequences remain complex. Feedbacks between ecological and social systems are difficult to predict, and this challenges effective mitigation of biodiversity loss and major drivers of this loss (Williams et al., 2020). Since the Convention on Biological Diversity (CBD) in 1992, official calls by global entities for urgent action to conserve biodiversity are increasing (Almond et al., 2020; Brondizio et al., 2019; IPCC, 2014) along with works that highlight the need of interdisciplinarity and more integrated approaches (Leclere et al., 2020; Williams et al., 2020).

In line with these calls for action, legal instruments for nature conservation have experienced a sharp growth worldwide (UNEP, 2019). These instruments exist at diverse levels, including global, continental, national, and regional scales (Leopold et al., 2018; Trouwborst, 2009). Although environmental laws and policies have been credited with positive outcomes for species conservation (Sanderson et al., 2016; Taylor et al., 2005), lack of enforcement and compliance with the implemented regulations poses a major challenge for achieving their objectives (UNEP, 2019; Watzold and Schwerdtner, 2005). Factors hindering the effectiveness of conservation policies include under-resourcing, data paucity, deprioritizing against economic gain, and especially the lack of transboundary coordination from sub-national to international levels (Thornton et al., 2018).

International coordination is particularly relevant for conserving biodiversity in the face of global change (e.g., Pinsky et al., 2018). Between 18% and 80% of species per region are expected to shift their distributions due to climate change, many times resulting in species occupying novel geopolitical units (Scheffers and Pecl, 2019; Titley et al., 2021). In this regard, coordinating policies among countries to conserve migratory species that redistribute their ranges under global change poses a great challenge (Gallo-Cajiao et al., 2019; Miller et al., 2018; Szabo et al., 2016). An even more difficult challenge is developing successful and transferrable approaches for the conservation of migratory species (Anderson and Padding, 2015; Runge et al., 2017; Trouw-borst, 2010). In the last two decades the Convention on the Conservation of Migratory Species of Wild Animals (CMS), the main international convention specialized in the conservation of migratory species, has provided a legal foundation for coordinated international conservation efforts. This culminated in a framework for several subsidiary instruments including the Memorandum of Understanding on the Conservation of Migratory Birds of Prey in Africa and Eurasia (Raptors MoU) along with the Agreement on the Conservation of African-Eurasian Migratory Waterbirds (AEWA) and related species action plans. The effectiveness and transferability of these plans however remain mostly unchecked (e.g., Trouwborst, 2012).

Seasonal movements of migratory species often take them to distant habitats in multiple countries, leading to difficulties in determining which conservation actions to take and where they should be implemented (Kark et al., 2015; Sample et al., 2020). In addition to frameworks for international coordination, effective conservation of migratory species requires ecological information about the species throughout the annual cycle (Faaborg et al., 2010; Maxwell et al., 2015; Reynolds et al., 2017). Research on the full annual cycle of migratory populations has received growing attention in the literature (Hostetler et al., 2015). Such studies have examined how climate (Wilson et al., 2011; Zipkin et al., 2012), land use (Oberhauser et al., 2017; Robinson et al., 2016), or both (Brown et al., 2017; Rushing et al., 2016) affect population demographics. Many works, however, have analyzed either breeding or non-breeding (including wintering) areas (but see Howard et al., 2020), with primarily theoretical rather than empirical parameter estimates (Hostetler et al., 2015). Considerably less attention has been paid to integrating information from long-term field studies (e.g., on demographics, movement, and ecotoxicology) among many countries and throughout the annual cycle (Millon et al., 2019; Rushing et al., 2017; Sergio et al., 2019b). Such integration while examining international strategies for conserving migratory species in the face of global change (Pecl et al., 2017; Scheffers and Pecl, 2019) is particularly needed.

The red kite (*Milvus milvus*) is a migratory raptor and facultative scavenger warranting the attention of conservation scientists and practitioners for the following reasons: (1) relatively small geographic range that is currently restricted to Europe yet spans many countries, (2) associated with moderate climatic regimes, and (3) believed to be especially vulnerable to global change (Huntley et al., 2007; Wormworth and Mallon, 2006). This species often scavenges food sources generated by agriculture (e.g., livestock carcasses and animals killed during crop harvest), meat processing industries, and urban areas (Carter, 2007). Red kites emerge therefore as a focal species for examining responses to changing climate and land-use across international borders. Despite a large body of literature on the red kite (Aebischer, 2009; Aebischer and Scherler, 2021; Carter, 2007), along with widespread and regionally focused conservation efforts (Knott et al., 2009), a comprehensive description on how this migratory species can be conserved across its geographic range is lacking. Detailed understanding of its ecological requirements and life history along with threats to population viability among regions is needed for effective conservation of this species under global change.

Our aim is to synthesize lessons drawn from ecological investigations and actions for conserving the red kite to outline an integrated conservation strategy across the species range while accounting for global change. We place special emphasis on international coordination of conservation and monitoring among many countries, which has yet to be addressed in the literature on conservation of migratory species. This effort builds from a meeting of more than 20 experts on red kite biology and management from ten European countries at the "Red Kite Symposium" held in Valsaín (Spain) in December 2018 (Table S.1).

2. Methods

We conducted a literature review and synthesis in several steps. First, we updated and summarized the available knowledge on the population status and empirical evidence for main drivers of population dynamics in red kites. This was based on summarizing literature found through searches in the Web of Knowledge (www.webofknowledge.com) database, Google Scholar (scholar.google.com) database, along with unpublished reports in our own bibliographic databases. When searching literature databases, we used various combinations of the keywords "red kite", "*Milvus milvus*", in addition to the common name used in other languages (e.g., "Rotmilan" in German). This search resulted in 263 literature sources. Second, we used this information to examine management actions that have been implemented to conserve this migratory species. This laid a foundation for identifying major challenges for red kite conservation across its entire range along with the main opportunities for effective transboundary collaboration in both the scientific and management arenas. Finally, we provided recommendations that are sufficiently general such that they can be adapted to inform conservation of other species distributed across geopolitical areas.

3. Distribution and status of breeding individuals

The red kite distributes over >3 million km^2, currently breeding in 28 European countries (Fig. 1). The global breeding population consists

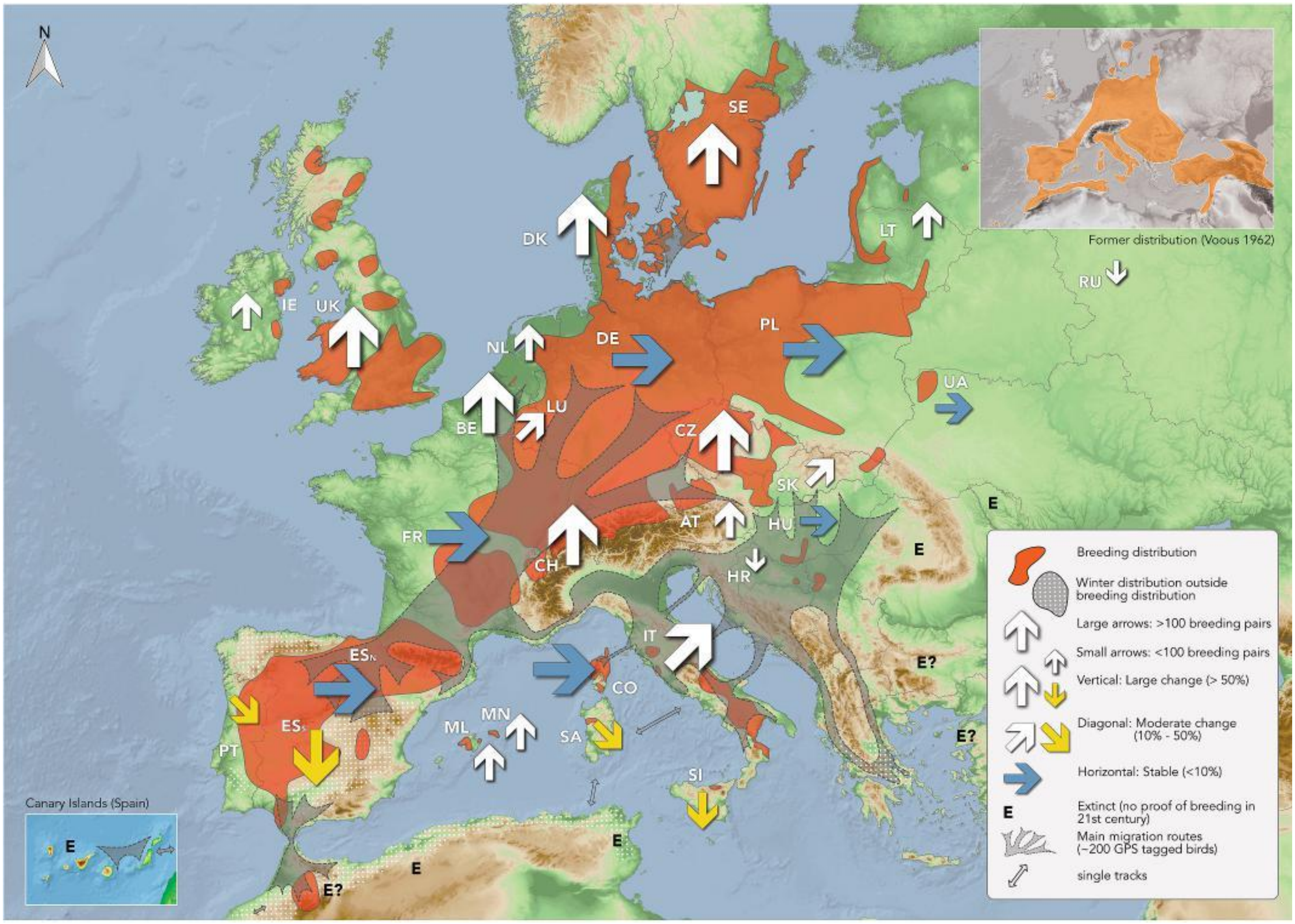

Fig. 1. Current and former breeding range of the red kite along with country-specific trends in breeding pairs. Trends were determined by comparing the two most recent estimates within the last 35 years (arrows). For almost all countries, the most recent trend was based on comparing estimates from the late 1990s–2000s and 2010 to 2018. Annual estimates and literature sources are provided in Table S.2. Trends are distinguished within Spain (ES) to highlight the strong decline in the southern third of the country. Occupied countries without a trend arrow have reported <100 breeding pairs and lack sufficient information to determine a trend. Question marks indicate that data are insufficient to conclude whether the species continues to breed in the respective countries. The gray shading connecting breeding and wintering areas represents the two major flyways based on satellite telemetry and migration surveys (Maciorowski et al., 2019; Raab et al. & Rösner et al. in Annex S4). The inset map is adapted from Voous (1962) and shows the former breeding distribution. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

of 32,000 to 38,000 pairs (Table S.2). Only 14 countries harbor more than 100 pairs each, and >90% of the population is concentrated within six countries (i.e. Germany, United Kingdom (UK), Sweden, Switzerland, France and Spain). Based on current evidence, the species no longer breeds in Africa and has been extirpated from 18 countries (Table S.2). The last confirmed breeding record in Morocco is almost 20 years old (Bergier and Thévenot, 2010; Bergier pers. comm.; Radi et al., 2020), and the species disappeared from Algeria in the 19th century (Isenmann and Moali, 2000) and from Tunisia before 1960 (Isenmann, 2005). In Europe, breeding red kites also disappeared from Romania in 1912 (though very few pairs may have bred irregularly there in the 1990s; Daroczi and Zeitz, 2003), from Moldova in the 1960s (Zubcov, 2001), and from the Canary Islands in the 1970s (Martín and Lorenzo, 2001). Extinction can also be assumed for the southernmost red kite occurrences on the Cape Verde Islands (Hazevoet, 2014; Hille and Collar, 2011). Red kites on these islands were originally thought to be the sole and endemic subspecies (*M. m. fasciicauda*) besides the nominate form (Hille, 1998), but phylogenetic analyses did not support this belief (Johnson et al., 2005).

Considering the current lack of evidence for breeding on other continents, the red kite is one of the few migratory bird species believed to breed exclusively in Europe (Fig. 1). Despite its wide-ranging movements and flexible diet (Carter, 2007; Mougeot et al., 2011), the red kite experienced important population changes over the last few decades. After a sharp decrease and range contraction over Europe up to the first half of the 20th century associated with legal persecution of raptors (Aebischer, 2009), the red kite population recovered in most European countries at different times during the second half of that century (Table S.2). This recovery is attributed to the implementation of raptor protection laws (Aebischer, 2009; Carter, 2007; Stevens et al., 2019; Aebischer and Scherler, 2021; Fig. 1; Table S.2) and concomitantly reduced mortality, as reported for other migratory raptors in Europe (De Pascalis et al., 2020). In particular, it has recolonized or even slightly expanded along the northern edges of its original range (Carter and Powell, 2019, Fig. 1).

During this recovery, however, the red kite continued receding from the southern edge of its original occupied range (Sergio et al., 2019a). Negative population trends persist in southern Spain and Portugal while some of the formerly occupied areas remain deserted, particularly in the southern and southeastern edges of the original range (Fig. 1 and Table S.2) (Carter and Powell, 2019; Molina, 2015; Sergio et al., 2019a). Within Serbia (Puzović et al., 2003) along with the islands of Sicily and Sardinia (Cillo and Laterza, 2014), abundance sharply decreased without subsequent recovery. A likely explanation for these disappearances is persecution before protection laws were implemented (Aebischer and Scherler, 2021). Declines have continued in the southern part of the range even after the species was protected (Table S.2), and little is known about causes of extinction after protection laws were implemented. By contrast, recent population recoveries on the Balearic Islands and Corsica are attributed to a successful conservation program and particularly good ecological conditions for the species, respectively (De Pablo, 2015; Mougeot and Bretagnolle, 2006; Muntaner, 2019). See Annex S1 for more details on red kite populations on islands.

Recovery of the global breeding population has led to updating the conservation status of red kites from “Near threatened” to “Least concern” in the last evaluation of its global conservation status. This altered status was based on IUCN criteria and expert consultation (BirdLife International, 2020). The decision however acknowledges ongoing and emerging threats within regions (see Annex S2). Expert contributions for the decision highlighted continued depletion of breeding populations in parts of Spain and Italy, but loss of breeding individuals within northern Africa and Asian countries was not considered. The decision also ignored long-term decrease in juvenile survival rates across Germany (Katzenberger et al., 2019). Ignoring this decreased survival in the youngest age class could constrain recovery efforts due to an estimated 50% depletion of floaters (i.e., the non-breeding fraction of the population) despite moderate changes in the number of breeding pairs over last decades (Katzenberger et al., 2021). As advocated by the latter authors, IUCN should consider such demographic modeling when estimating changes in raptor populations. Indeed, floaters are critically important in compensating for losses of adult territorial birds (Ferrer et al., 2004).

Furthermore, the decision did not mention the potential for climate change as a likely factor limiting the recovery in these southern areas. This contrasts with a call for halting range contraction in the south as one of the priorities in the European action plan for the red kite when they were listed as near-threatened (Knott et al., 2009), and such range contraction was recognized as an important concern by many attending the 2018 Red Kite Symposium in Valsaín (Annex S4). Climatic factors were indirectly referenced by the decision in a comment regarding increased residency within northern parts of Europe, and otherwise climate change was not considered. One study recently asserted that IUCN criteria should be improved to better account for climate change in red list evaluations, particularly in the case of migratory birds (Zurell et al., 2018).

Last, while some countries have well developed monitoring programs of breeding red kite populations at national or regional levels (e. g., France, Germany, Italy, Spain, Switzerland, and the UK), for many others we have only rough estimates of breeding pairs (Table S.2). This is of high concern for several countries along the southern and eastern edges of the current range (i.e., Bulgaria, Morocco, Serbia, and Turkey), where confirmed breeding records of the species are >10 years old and where last known breeding populations had undergone severe declines. Reasons for these declines have yet to be determined. Identifying the few remaining breeding pairs along these edges of the current distribution is crucial for targeting conservation actions to halt ongoing range loss.

4. Migratory patterns and winter status

The red kite exhibits multiple migratory strategies across its range, including long-distance migration, short-distance migration, and residency (Aebischer, 2009; Literák et al., 2022). Recent work based on monitoring of birds with satellite transmitters has provided new information revealing a high variability in migration strategies between and within populations, along with variation between years in the same individuals (Garcia-Macia et al., 2022,b; Literák et al., 2019,2020,2022; Maciorowski et al., 2019; Panter et al., 2022; Urios and García-Macía, 2022; Vidal-Mateo et al., 2021). Reported strategies of migration from these studies included direct flights to or from wintering areas with no stopovers, migrations with one or more stopovers lasting multiple days, and using consecutively in the same season two separate wintering areas in France and Spain. In addition to birds stopping over in eastern Germany en route to breeding sites in Poland (Maciorowski et al., 2019), Vidal-Mateo et al. (2021) noted two stopover areas in Mediterranean countries: one in southern France between the Central Massif and the Pyrenees; and another in the Spanish Vasque Country just after crossing Pyrenees.

These recent telemetry studies have also confirmed two major flyways across Europe (Fig. 1). The largest breeding populations north of the Alps (i.e., Sweden, Germany, France and Switzerland) follow the western flyway toward wintering grounds in southwestern Europe. Individuals migrating toward wintering grounds in north Africa and Spain fly over Pyrenean passes, with the highest concentration migrating over the western portion of this mountain range (Aebischer, 2009; Hiraldo et al., 1995; Maciorowski et al., 2019; Rösner et al. and Raab et al. in Annex S4; Urios and García-Macía, 2022; Vidal-Mateo et al., 2021). Comprising the eastern flyway, many individuals breeding northeast of the Alps overwinter in Italy and countries in southeastern Europe (Literák et al., 2019; Maciorowski et al., 2019; Raab et al. in Annex S4; Raab et al., 2017; Tomik et al., 2019). This eastern flyway spans a wide front through southeastern European countries. En route toward wintering areas, red kites cross the Adriatic Sea and other narrow tracts of

Mediterranean Sea to reach Italy, the Mediterranean islands and north Africa along with the southern face of the Alps to reach southern France and eastern Spain (Literák et al., 2020; Raab et al., 2017).

During the past several decades, an increasing number of red kites in central and northern Europe have ceased to migrate (Garcia-Macia et al., 2022; Vidal-Mateo et al., 2021). Instead, they remain year-round in or near breeding areas, particularly where food availability is high and reliable during winter (Carter and Powell, 2019; Evans and Pienkowski, 1991). Winter numbers constantly increased over the last decades in Switzerland, Germany, and Denmark, and over last half century in Sweden (Table S3). Reliable information about abundance during nonbreeding is available for a limited number of countries, and trends accounting for changing survey effort have not been determined in many of them (Table S.3). Spain holds most of the European wintering population, followed by France, and then lower numbers in Switzerland, Sweden, Italy and Germany (Table S.3).

5. Main threats for range-wide conservation

Markedly low productivity may have contributed to long-term and slow declines in the few remaining populations of red kite along the southern edge of Europe (Sergio et al., 2019a; Godino et al., 2020; Godino & Pinilla in Annex S4). As an extremely long-lived species (maximum age >30 years; Bird et al., 2020) with relatively low annual offspring production, however, adult and subadult mortality has been clearly shown to be a more important demographic driver than reproduction (Sergio et al., 2021). A recent analysis of a 50-year data set of red kites ringed across Germany indicated a consistent long-term reduction in survival for this population, particularly for younger-age classes (Katzenberger et al., 2019). This decline in survival rate is in line with the marked reduction in the number of non-breeding birds predicted by demographic modeling (Katzenberger et al., 2021). Similar results were found for Doñana National Park in southwestern Spain, where high mortality in birds younger than seven years was a major driver of long-term population decline (Sergio et al., 2021).

Several factors have been identified as driving red kite population declines, mainly through increased mortality (Knott et al., 2009, Table 1; Fig. 2; Annex S2). Given their tight association with human settlements and rural economic activities (Orros and Fellowes, 2015), red kites are highly sensitive to a wide range of emerging anthropogenic threats associated with global change. Poisoning is outstanding as a major cause of mortality across the species range, including primary (i. e., direct consumption of poisoned bait) and secondary (i.e., feeding on poisoned animals) poisoning (Badry et al., 2021; Annex S2; Berny, 2007; Coeurdassier et al., 2014; de la Bodega et al., 2020; Hirschfeld et al., 2017; Katzenberger et al., 2019; Mateo-Tomás et al., 2020; Molenaar et al., 2017; Mougeot et al., 2011; Panter et al., 2022; Smart et al., 2010). Poisoning is the only known threat shown to be associated with red kite abundance at a national scale (Spain) and over a long period (1994–2014; Mateo-Tomás et al., 2020). This finding, combined with its continent-wide distribution and observability, highlights the potential of red kites as a good sentinel species for wildlife poisoning (Mateo-Tomás et al., 2020). This also highlights the need to evaluate in other breeding areas to what extent poisoning is the main threat and a relevant demographic driver of abundance across the entire range (Table 1; Badry et al., 2021; Berny and Gaillet, 2008; Deak et al., 2020). Evaluating causes of mortality in a large number of GPS-tagged birds over all the range is urgently needed to examine this possibility.

Besides poisoned baits and rodenticides (Berny and Gaillet, 2008; Mateo-Tomás et al., 2020), red kites may also be frequently exposed to diverse contaminants: herbicides used as plant protection products in agriculture (Badry et al. In press); barbiturates used as euthanasia agents for domestic animals and livestock (Herrero-Villar et al., 2021); lead from hunting ammunition (Berny et al., 2015; Descalzo et al., 2021); along with other widespread contaminants such as polychlorinated biphenyls, organochlorine pesticides (Gomara and Gonzalez, 2006; Gomara et al., 2008; Monclus et al., 2018), and polycyclic aromatic hydrocarbons (Morin-Crini et al., 2022). These findings support the postulation that red kites are good sentinels of contamination risk for raptors (Badry et al. In press).

Habitat loss through agricultural intensification and concomitant reduced food availability is also recognized as an important limiting factor for reproduction in red kite populations across Europe (Huyghe et al., 2015; Knott et al., 2009; Maciorowski and Urbańska, 2013; Mammen, 2000; Nachtigall et al., 2010; Nicolai et al., 2017; Sergio et al., 2019a; Viñuela et al., 1999). Reductions in the availability of

Table 1
Most important anthropogenic causes of mortality for the red kite in European and north African countries where data were available. When information about mortality reasons was sufficient, a ranking of importance (with 1 indicating strongest impact) based on literature, symposium presentations in Annex S4, and judgement of the coauthors is provided. An ‘x’ indicates that insufficient information was available for the ranking.

						Collisions with human-made structures			
Country	Poisoned baits	Secondary poisoning	Illegal trapping and shooting	Electrocution	Disturbances near nests	Cables	Vehicles	Wind turbines	Literature
Austria	1		2					3	Raab et al. (2017)
Belgium		x			x				Voskamp and van Rijn (2010)
Czech Republic	1	2	3	3	4	4	3	4	(Vyhnal in Annex S4)
Denmark	x		x						Grell (2003)
France	1	2	2	x			x	1	(Caupenne et al., 2015; David et al., 2012)
Germany	2	2	3	2	2	2/3	1	1	(Bellebaum et al., 2013; Brune and Hegemann, 2009; Katzenberger et al., 2019; Mammen et al., 2014)
Italy	4	3	5	2				1	Allavena et al. (2006)
Luxembourg		x		x	x				Biver (2013)
Morocco				x					IUCN (2020)
Netherlands	x	x							van Rijn (2018)
Poland	1			1		2			Maciorowski and Urbańska (2013)
Portugal	x		x	x					ICNF (2012)
Slovakia	x		x						B. Maderič, pers com.
Spain	1	2	4	3	7	8	5	6	Viñuela et al. (2021)
Sweden		3	5			4	2	1	Stolt et al. (1986)
Switzerland		1			3		2		Aebischer (2009)
United Kingdom	1	3	2	7	4		5	6	(Sansom et al., 2016; Smart et al., 2010)

Fig. 2. Anthropogenic sources of mortality for red kites: (a) and (g) consumption of poisoned baits; (b) collisions with power lines; (f) electrocution at electric pylons; (c), (d), and (h) collisions with vehicles; (e) collisions with wind turbines. Photos by S. Rösner.

human-mediated food, including livestock carcasses and other waste, could induce declines in reproduction during the breeding season and elevated mortality during the non-breeding season (Blanco, 2014; Blanco et al., 2017; Fulco et al., 2015; Pitarch et al., 2017). Disturbances around nests and habitat destruction might cause severe impact in local populations through reduced reproduction or reduction in the number of breeding territories (Carter, 2007; Davis and Davis, 1981; Seoane et al., 2003; Viñuela et al., 1999), which may be partly attributed to high breeding fidelity (e.g., using the same territory for up to 18 consecutive years; Ortlieb, 1989).

Specific pathways of human-caused mortalities in red kites other than poisoning include electrocution in addition to collisions with wind turbines, power lines, vehicles, and trains (Bellebaum et al., 2013; Crespo-Luengo et al., 2020; Kolbe et al., 2019; Mougeot et al., 2011). Red kites are one of the bird species most commonly found dead under wind turbines (Annex S2; see also Fig. 2), and this may become a major cause of mortality in the near future given the expected increase in wind energy development in Europe (e.g., 100% by 2028 in France and 300% increase by 2030 in Spain, the latter including solar plants; Serrano et al., 2020).

Predation of nests by invasive species poses a new challenge for the conservation of red kites. The introduced North American raccoon (*Procyon lotor*) may locally affect some red kite populations in Germany through nest predation (Fischer et al., 2020; Mammen et al., 2014) and is present in other red kite European strongholds such as Spain (Salgado, 2018).

Dependence of breeding populations of migratory species on conditions during the non-breeding season has been demonstrated in the black kite (*Milvus migrans*) (Sergio et al., 2019a), a trans-Saharan migrant, and has yet to be shown in red kites. Nonetheless, contrasting trends between red kite populations with differing migratory strategies indicate that threats acting on wintering grounds may be crucial drivers of the species demography elsewhere (Annex S2). For example, red kite populations breeding in northern Europe (e.g., Germany) and wintering in southwestern Europe (e.g., Spain) have shown worse trends than more sedentary populations such as those in the UK, Switzerland, Sweden, and Italy (Fig. 1) (Carter, 2007; Katzenberger et al., 2021; Stevens et al., 2019). These contrasting trends may be related to mortality caused by large-scale and intensive rodenticide use in the main wintering area of Spain and in the middle of western flyway in France along with other threats involved in southern declines (e.g. other sources of poisoning and illegal shooting; Annex S2). Modeling exercises using available knowledge about seasonal and spatial variation in demographic parameters is a crucial research line to determine relative importance of environmental drivers and human threats in breeding and wintering areas for population dynamics across the entire range (Katzenberger et al., 2021).

6. Regional-scale conservation

Diverse actions have been implemented for red kite conservation across its distribution range, including mitigation of major threats (e.g. poisoning and electrocution; Table 2) and reintroductions. These actions are supported by several international policies and legislations (Table S.4; Annex S3). In contrast to reintroduction, population reinforcement, and supplementary feeding, there is scarce evidence assessing effectiveness of efforts to mitigate collisions, poisoning, and nest predation by invasive mammals (Table 2). Successfully accounting for or mitigating anthropogenic mortality is important, however, before using the former interventions (IUCN/SSC, 2013).

Correction of power lines and careful placement of wind farms are frequently used approaches for mitigating red kite mortality through collision and electrocution (e.g., in Czech Republic, Germany Portugal, and Spain; Hernandez-Lambrano et al., 2018). Trained dogs to locate poisoned baits and integrated pest management to reduce the use of pesticides have also been deployed in many parts of the range to reduce the risks associated with poisoning (Table 2; Deak et al., 2020; Jacquot et al., 2013; Knott et al., 2009). Such dog units were successfully deployed in Sardinia and in the Italian peninsula through two recent EU LIFE projects (LIFE13 NAT/IT/000311; LIFE14 NAT/IT/000484). Mitigation measures for rodenticide application (i.e., restricting quantity of poisoned bait used by farmers and promoting alternative pest control techniques) seem to have largely reduced red kite mortality in France (i.e., 5- to 10-fold lower numbers of red kites found poisoned

Table 2
Examples of conservation actions for red kites and their effectiveness. Note that monitoring actions such as censuses or telemetry are not included here as direct conservation actions. Information was retrieved from a Scopus search for "red kite" AND "conservation" in the title, abstract and keywords until March 1, 2019 along with presentations at the Red Kite Symposium in Segovia, Spain in December 2018.

Conservation action	Region(s)	Objective	Effectiveness	References
Agricultural measures	Germany	Increase natural food availability during the breeding season to counteract food shortages by cultivation and suitable management of agricultural measures (e.g. fallows, extensively used grasslands, alfalfa/ field fodder)	Increase in prey abundance (e.g., small mammals, birds) by 50–200%, increase in use of managed plots by red kites by 200% (without agricultural operations) up to 1000–2000% during mowing	Karthäuser et al. (2019)
Reintroduction	Scotland, England, Northern Ireland (United Kingdom)	Recover extinct populations	1450% increase in United Kingdom population between 1995 and 2016.	(Evans et al., 1999; Wotton et al., 2002; Orr-Ewing in Annex S4)
	Tuscany (Italy)		Increase from 0 to 30 breeding pairs between 2007 and 2018	(Ceccolini et al. in Annex S4)
Captive breeding	Aragón (Spain)	Recovery and reinforcement of populations	95 red kites bred in captivity during 2011–2020. Breeding of released birds in the wild confirmed.	(Ginés and Cortés in Annex S4 and pers.comm)
Rehabilitation	Madrid (Spain)	Recovery of individuals	31.3% of rehabilitated birds out of 8 admitted. 45.8% of the rehabilitated birds survived the first year after release (n = 24 GPS tagged birds)	(Fregenal, 2020; Díaz et al. in Annex S4)
	Aragón (Spain)	Recovery of individuals	62% of birds rehabilitated out of 30 admitted (1994–2020)	(Ginés and Cortés in Annex S4 and pers.comm)
	Scotland and southern England (United Kingdom)		66.7% of birds rehabilitated out of 6 admitted during 1989–1994	Evans et al. (1999)
Supplementary feeding	Denmark, Spain, Sweden, Tuscany (Italy), United Kingdom, Germany	Supporting reintroduction programs and recover threatened populations. Counteract possible food shortages for avian scavengers. Provide safe food without poison. Public viewing of red kites	Possible increase in productivity, immature survival, and reduced dispersal. Increased red kite abundance (~50% of expected values) in residential areas with supplementary feedin	(Christie, 2007; Orros and Fellowes, 2015; Åkesson, Ceccolini et al. and De la Puente et al. in Annex S4; Tenan et al., 2012)
Habitat protection	Sachsen-Anhalt (Germany)	Reduce mortality and avoid habitat deterioration	14 protected areas declared free of wind farms. No other assessment available	(MULELSA, Ministerium für Umwelt, 2018; Rösner et al. in Annex S4)
	Austria, Czech Republic, France, Luxembourg, Poland, Slovakia	Declared Special Protection Areas for red kite breeding grounds under EU Birds Directive (2009/147/EC)	No assessment available	Knott et al. (2009)
Power line correction	Czech Republic, Spain, Portugal, Slovakia	Reduce mortality by electrocution	No assessment available	(Knott et al., 2009; De la Puente et al. and Vyhnal in Annex S4)
Dog units	Czech Republic, Spain	Prevent poisoning	No assessment available	(De la Puente et al. and Vyhnal in Annex S4)
Outreach and raising awareness	Belgium, Czech Republic, Denmark, Hungary, Italy, Slovakia, Spain, United Kingdom	Prevent/minimize illegal killing	Positive impact recognized but no assessment available	(Evans et al., 1999; Knott et al., 2009; Vyhnal in Annex S4; van der Wal et al., 2015)
Mitigation measures for rodenticide application (e.g., restrict the quantity of poisoned bait used by farmers and promoting alternative pest control techniques)	Franche-Comté (France), United Kingdom	Lower ecological impacts of bromadiolone treatments	Decreased mortality in non-target wildlife species from 541 (33 red kites) during 1997–1998 to 20 (3 red kites) during 2009–2012 in France.	(CRRU UK, 2021; Jacquot et al., 2013)
Payments for landowners to protect red kites	Wales (United Kingdom)	Minimize persecution of red kites	From 6 individuals to 50 breeding pairs between 1903 and 1978[a]	Christie (2007)

[a] Other conservation actions were implemented in addition to the focal one.

after management interventions; Coeurdassier et al., 2014).

With an aim to mitigate nest predation, plastic belts to exclude mammalian predators from climbing nest trees had variable success in Germany (Fischer et al., 2020). This approach was particularly effective in areas with large raccoon populations (Nachtigall et al., 2020). In other areas these actions are less effective, as predatory mammals rarely climb nesting trees of birds of prey (Schütz et al., 2020), and the losses of young birds in the nests are mainly caused by goshawks (*Accipiter gentilis*; Gottschalk et al., 2019). The effectiveness of education and outreach campaigns has not been measured beyond counting the number of events and participants (e.g., Vyhnal in Annex S4). Such public engagement has likely been critical to ensure acceptance of conservation efforts and the recovery of populations that are most affected by human-induced mortality.

Once the risk of anthropogenic sources of mortality have been addressed as much as possible, reintroductions and population reinforcements have been implemented to ensure successful recovery following population depletion. Since the first reintroductions in 1989, by hacking with fledglings removed from nests in Spain and Sweden, the red kite population in the UK increased by 1450% from 415 to 6000 breeding pairs in 2017 (Orr-Ewing in Annex S4). The UK currently hosts ~16% of the global population (Table S.2), and this has been recognized as one of the most successful reintroduction programs of any species in the world (Carter and Powell, 2019). The reintroduction of 106 red kites in Tuscany (Italy), using fledglings translocated from nests in Corsica (France) and Fribourg Canton (Switzerland) from 2007 to 2014, resulted in the successful reestablishment of the species, with 30 breeding pairs in 2018 (Ceccolini et al. in Annex S4). Captive breeding and rehabilitation of injured red kites at recovery centers support many of these programs by providing birds for reintroduction. Maintaining such programs allows for assessing the effectiveness of ex situ and in situ actions for red kite conservation (Table 2; Ginés & Cortés in Annex S4).

Until hacked juveniles can hunt for natural prey, reintroductions and reinforcements of existing red kite populations were successfully supported with supplementary feeding in the UK and Italy (Carter, 2007; Ceccolini et al. Annex S4). Providing supplemental food in this context aims to ensure sufficient survival rates for population growth (Schabo et al., 2017) through, for example, limiting mortality during winter (Blanco, 2014; Cortes-Avizanda et al., 2016). Increasing availability of safe food has been shown to mitigate this risk of poisoning (Tenan et al., 2012). A risk of supplementary feeding is releasing poor-quality individuals from selective pressure along with overpopulation and competition with other raptors or scavengers (Orros and Fellowes, 2015). Evidence suggests that foraging activity by red kites increases in areas where food is regularly provided by humans (Cereghetti et al., 2019; Orros and Fellowes, 2015). Although this attraction to supplemental food can buffer effects of poisoning on population viability, it can also increase other risks related to human-mediated food. Supplemental feeding may induce sanitary and toxicological problems when improperly managed (Blanco et al., 2017; Pitarch et al., 2017), and foraging in areas dominated by humans can pose additional risks such as collisions or electrocutions to energy and transport infrastructures (Hill et al., 2019a, b). Successful supplemental feeding of red kites depends on a tailored design for this species that accounts for the risks associated with this management practice (Oro et al., 2008; Orros and Fellowes, 2015) and reduces competition with larger scavenging species such as vultures (Cortes-Avizanda et al., 2016; Viñuela et al., 1999).

7. The emerging threat of climate change

During the 1990s, the Spanish breeding population of red kites was the second largest in Europe (Viñuela, 1996). Today it is the sixth largest, after breeding populations in Germany, UK, Sweden, Switzerland, and France (Fig. 1; Table S.2). This expansion in the northern portion and simultaneous retraction in the southern part of its original range matches range shifts of many European terrestrial birds in the 20th century that are associated with climate change (Newton, 2003; Pautasso, 2012). The shifting range of the red kite is also consistent with model predictions that highlight this species as being highly vulnerable to climate change (Huntley et al., 2007; Wormworth and Mallon, 2006).

Predicted effects of climate change on red kites vary across the geographic range. Hot summer temperatures and increasing amount of annual precipitation have been associated with the absence of red kites in large areas of Spain (Seoane et al., 2003). By contrast, models have shown that climatic parameters only weakly affected their habitat suitability and distribution in Germany (Heuck et al., 2013; Katzenberger, 2019) — the core of its current breeding range (Fig. 1). In Switzerland, increased reproductive output was associated with elevated temperatures during spring (Nägeli et al. In press). The authors suggested that such elevated reproduction could explain the upward expansion within the alpine region and the notable population growth in Switzerland during last decades. It remains unclear why climate does not seem to affect red kite distribution or abundance in Germany, while it appears to be a main factor in Spain. We therefore propose the following non-exclusive hypotheses:

Hypothesis 1. Climate variability is lower in Germany than in Spain. In Germany, average monthly temperature from 1990 until 2020 varied between 0.9 °C (January) and 18.7 °C (July) and average accumulation of monthly precipitation ranged between 41.6 mm month^{-1} (April) and 82.2 mm month^{-1} (July). In contrast, average monthly temperature in Spain measured in the same time period varied between 6.2 °C (January) and 23.2 °C (July) and average sum of monthly precipitation ranged between 17.4 mm/month (July) and 73.6 mm/month (October; World Bank Group, 2021).

Wet and cold climates – similar to central Europe – can occur in northwestern Spain (i.e., Galicia), along the northern edge of the country, and in mountainous regions. Most red kite populations are found in mid-elevation areas in Spain (Seoane et al., 2003). Climatic zones more similar to northern Africa occur in the southeastern part of the country. Interestingly, red kites in Spanish mountains mainly occur within the "oak floor" (i.e., deciduous trees of genus *Quercus*, mainly *Q. pyrenaica* and *Q. robur*), which are forests below areas where coniferous trees dominate and above where evergreen oaks dominate. Most land currently occupied by red kites in central Europe has similar oak forest types as the climax vegetation, although these forests are strongly altered by human use for forestry, agriculture, and livestock. In Wales, a remnant population of red kites persisted in a landscape with large oaks and livestock (Carter, 2007). Most of central Europe is within the optimal climatic range for red kites, but only a fraction of Spain offers this within a narrow elevation band in mountainous regions (Seoane et al., 2003; Viñuela et al., 1999).

Hypothesis 2. Within the range of any species, optimal environmental and climatic conditions are usually found at the core of the range (Telleria et al., 2021). Abundance typically reaches a maximum in this core, while along range edges environmental conditions are poor and abundance is lower. We therefore expect stronger effects of climate on distribution and abundance along range edges compared to the core of range (e.g., Cuervo and Moller, 2013; Garcia and Arroyo, 2001; Pironon et al., 2017).

Models for examining the effect of climate change on distribution of bird species predict a dramatic loss of range in the southern portion and expansion in the northern portion for the red kite (Huntley et al., 2007). Large-scale changes in red kite range observed over the last century clearly concur with this prediction (Fig. 1), while during recent decades a global increase of 10% in range has been reported due to expansions in northern areas overcompensating for contractions in the southern portion (Keller et al., 2020). Thus despite loss of range and near extirpations in southern Europe, the overall range has expanded due to recolonization of regions in central and northern Europe (Table S.2).

Red kites are not strictly dependent on forests but require large open areas as foraging grounds in their breeding territories (Carter, 2007; Viñuela et al., 1999). Further northward expansion could therefore be constrained by habitat wherever large continuous and thick boreal forest prevails, which is the case in much of Scandinavia and Russia. However, breeding populations of red kites have increased naturally along northern edges of their range in continental Europe including the Netherlands and southern Scandinavia (Fig. 1; Table S.2).

Strong empirical evidence is lacking to determine whether and how climate change affects extensive range loss in the southern portion and restricted expansion in the north. Shifts in rainfall patterns (i.e., heavy precipitation events and droughts) can affect nestling survival (Gottschalk et al., 2015; Sergio, 2003). The few populations of red kites remaining in southernmost latitudes (i.e., southern Spain, Sardinia, and Sicily; Fig. 1) are at the brink of extirpation, as they are formed by single isolated birds or small groups of breeding pairs (Molina, 2015; Sarà et al., 2009; Annex S2). Populations at the edge of distribution ranges may have lower density and productivity, and these marginal populations may therefore be more sensitive to climate change than those at the core of the range (Cuervo and Moller, 2013; Maiorano et al., 2013).

One of the lowest reported reproductive rates and levels of genetic diversity of the red kite were documented at its southernmost distribution in Europe (i.e., Doñana National Park in southwestern Spain; Roques and Negro, 2005; Sergio et al., 2019a). The 47-year average of <1 fledgling per breeding pair (i.e., 0.82) in this population is almost half the average reproductive rate documented across other European regions (i.e. 1.5) and declined slowly during this period (Sergio et al., 2019a). Likewise, genetic variation measured as nucleotide diversity was also low in this region (0.0016) compared to central European populations 0.0053 (Roques and Negro, 2005). Shifting climatic conditions may have created a north-to-south gradient from moderate to low rates of reproduction, which may partly explain population declines in the southern parts of their range (Sergio et al., 2019a). More research is however needed to understand the functional link between red kite population declines, range shifts, and climate change, which is the case for most bird species (Dunn and MØller, 2019).

8. Integrated conservation of a migratory species under global change

Reports on the global status of biodiversity under global change call for more effective conservation actions (e.g., Almond et al., 2020). These actions should be grounded on the scientific evidence available regarding the major threats and their impacts on nature along with monitoring the effectiveness of management (Williams et al., 2020). Considerable progress must be made in conservation to integrate disciplines besides ecology or biology, especially economics, political sciences, and law while coordinating actions across countries (Fisher et al., 2009).

In the following sections, we identify outstanding challenges to conserve red kite across their range under global change (Fig. 3), depicting thus the basis of an integrated strategy to conserve other wide-ranging species in transboundary contexts. As such, this strategy builds upon information presented in the previous sections regarding the status and conservation of red kites across Europe. We pay special attention to the need for transboundary and multisectoral coordination among conservation practitioners to: i) account for the impacts of global change at multiple scales, ii) complement the existing network of protected areas with conservation on private lands, iii) recover depleted populations, and iv) monitor not only individuals of the target species (e.g., via satellite telemetry) but also the implemented actions to inform ongoing conservation decisions.

8.1. International coordination to account for global change at multiple scales

Transboundary and multisectoral coordination among policy-makers and conservation practitioners have critical importance for the effective protection of most species (Kark et al., 2015; Knott et al., 2009; Mateo-Tomás et al., 2018). Conservation of a migratory species typically requires international collaboration, but this approach has been developed and tested in only a limited number of cases (e.g., Gallo-Cajiao et al., 2019; Runge et al., 2017). In the red kite such international collaboration has been limited to reintroduction programs (Ceccolini et al. in Annex S4; Carter and Powell, 2019). Such international coordination involves communication and agreements regarding legal frameworks and coordination of multiple on-ground actions (Scheffers and Pecl, 2019).

In the case of the European Union (EU), transboundary coordination

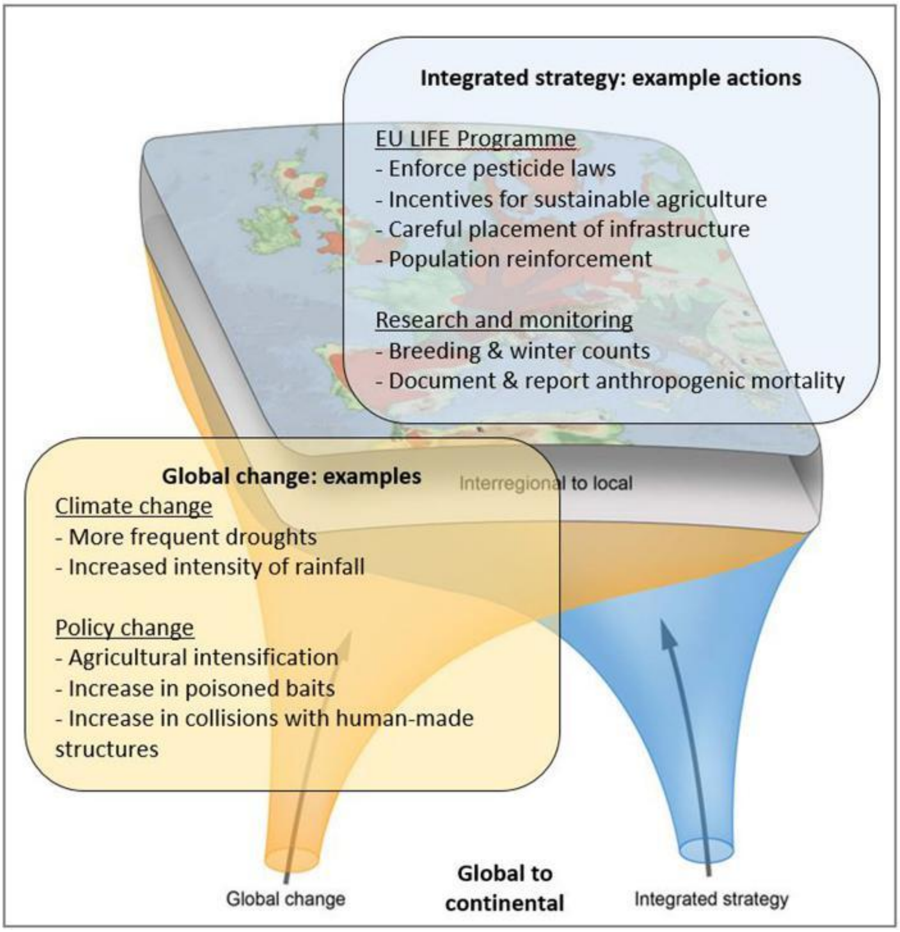

Fig. 3. Example drivers under global change (yellow) and subset of activities within an integrated strategy (blue) to conserve a partially migratory species across scales and flyways. Orange and gray shading respectively indicate the current breeding range and main migratory routes of the red kite throughout its current range including Europe and northern Africa. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

of conservation efforts aimed at migratory species may be facilitated by Natura 2000) (N2000) sites designated under the Birds Directive (2009/147/EC) and Habitats Directive (92/43/EEC) (Leibenath et al., 2005; Nilsson et al., 2019). The Birds Directive, for example, specifies that Special Protection Areas (SPAs) must be established for each species listed in Annex I to ensure that their habitat requirements are met throughout the annual cycle. Across Europe, these N2000 sites form the nodes in a network that can provide the basis of an international conservation strategy for highly mobile species such as the red kite through providing refuges for migration and breeding across European SPAs. As another example, protected areas in the northern part of the range could serve as source populations for reinforcing or reestablishing populations in more southern latitudes. Furthermore, lessons learned about scavenger-friendly management practices (de la Bodega, 2014) and reintroduction efforts (e.g., Evans et al., 1999) can be transferred between practitioners working in SPAs in different countries. Such knowledge transfer would not only inform conservation actions but also enhance the accumulation of evidence regarding their effectiveness (Williams et al., 2020).

The role of global change for determining species distribution and demographics must be considered together with more local impacts related to, for example, persecution (Pecl et al., 2017). Many threats to population viability of the red kite (e.g., poisoning, persecution, electrocutions, collisions; Table 1) act at the local scale and are driven by international, national, and regional policies that affect land management (Fig. 3; Annex S3). Moreover, climate change is a global process that affects species and ecosystems from continental to regional scales (IPCC, 2014) and could constrain recovery of red kite breeding populations in southern Europe and northern Africa (Fig. 1). However, forecasting the effects of conservation actions for red kites and other migratory species across space and time while accounting for global change across scales remains an enormous challenge (Belsky and Joshi, 2018; Murray et al., 2018; Rushing et al., 2016).

A flyway approach to conserving migratory species involves coordinating among jurisdictions used by individual animals throughout their annual cycle, including breeding, wintering, and migration (Boere and Piersma, 2012; Boere and Stroud, 2006). For example, this approach helps ensure sufficient food resources (Zhang et al., 2018) while minimizing persecution (Deniau et al., 2022) as individuals move between breeding and overwintering habitats. The flyway approach was adopted by the 1995 Agreement on the Conservation of African-Eurasian Migratory Waterbirds under the CMS and focuses on conservation and management of waterbird species across nearly 70 countries (Boere and Piersma, 2012). This approach has yet to be applied to migratory taxa other than waterbirds within this flyway, but this is likely needed to effectively conserve red kites and other neglected land birds. All countries within the current range of the red kite, including migratory routes, are parties to the CMS (Art. I (1) (f)). This international policy framework could be utilized for developing and using a flyway approach to conserve the red kite along with other migratory species. International and multisectoral collaboration along red kite flyways (Fig. 1) is required to maintain critical habitats connected by migration along with translocations for population reinforcements. This coordination is likely essential to mitigate effects of global change on this species.

8.2. Beyond protected areas

Protected areas (PAs) such as those in the N2000 network are key to preserve species and ecosystems (Sanderson et al., 2016), but in the face of rapid global change major gaps exist regarding biodiversity conservation both within and outside PAs (Hilborn and Sinclair, 2021; Runge et al., 2014; Sergio et al., 2019a; Tyrrell et al., 2020). Specific benefits of these PAs include protecting forests and extensive agriculture (Navarro and Pereira, 2015), which are critical for the life cycle of red kites. Greater occurrence probability of red kites in N2000 sites and other protected areas compared to non-protected areas in Germany indicated positive effects of these designations (Frank et al. In preparation; Katzenberger, 2019).

Despite its demonstrated benefits, the effectiveness of N2000 for continental-scale conservation of European birds has been repeatedly questioned (Albuquerque et al., 2013; Burns et al., 2021; Nilsson et al., 2019; Palacin and Alonso, 2018). Effects of N2000 on red kite populations have yet to be rigorously examined across Europe, although some evidence exists pointing toward ineffectiveness. The abundance of red kites continues to decline or is not recovering to former levels in some regions (Table S.2) and within Natura 2000 sites (Table S.5). The current N2000 appears to cover an insufficient portion of the range for it to be effective. For example the 77 SPAs in France harbor only about 15% of the national red kite breeding population, with only 19 SPAs hosting more than 5 breeding pairs each (David et al., 2012). In Germany, SPAs host 18% of the breeding population in this country (Gerlach et al., 2019). In the case of Spain, 22% of 706 red kite nests were located inside 44 SPAs, of which only six held 5 or more nests (SEO/BirdLife unpub. data). The latter is probably an overestimation of the real proportion of birds breeding inside SPAs, because population monitoring is more common inside these protected spaces.

In addition to conservation actions to enhance the effectiveness of conservation within PAs, engaging stakeholders operating beyond PAs (e.g., landscape-based conservation approach; Sayer et al., 2013) will likely become increasingly important in the context of climate change driving shifts in distribution of many species (Mattsson and Vacik, 2018; Snäll et al., 2016). The utility of PAs for long-term conservation of wide-ranging species like red kites (i.e., long-distance dispersive and vagrant movements as juveniles) may be limited. This limited utility was clearly shown for Doñana National Park in southwestern Spain, the last stronghold of the species in southern Europe, where population declines persist due to threats outside of the PA (Sergio et al. 2005, 2019a, 2021).

In 1991, the Standing Committee of the Bern Convention adopted Recommendation No. 25 (1991) on the conservation of natural areas outside legally PAs. This recommendation asserted that species conservation is possible only in the context of regional planning. Private land conservation or stewardship through agreements with landowners has been effectively used for conservation of highly endangered species such as the Iberian lynx (*Lynx pardina*) (Figueiredo et al., 2019), the Spanish imperial eagle (*Aquila adalberti*) (Ferrer et al., 2018), and migratory waterfowl in North America (Anderson and Padding, 2015). Although conservation practices on private lands have been described for migratory raptors (Bergmanis et al., 2019; Santangeli and Laaksonen, 2015; Annex S4), their effectiveness has yet to be fully investigated.

Private land conservation could be particularly effective for conserving the red kite due to its association with agricultural areas and human settlements (Orros and Fellowes, 2015), which may not reach the standards to be designated as PAs. A primary mechanism for private land conservation to protect species occurring in agricultural areas across Europe is the Common Agricultural Policy (CAP). This policy covers all countries in the EU while allowing for conservation practices tailored for characteristics in each region (European Commission, 2019a). Planning is underway to streamline approaches for nature conservation and climate adaptation under the CAP, offering new opportunities for effective conservation action (European Commission, 2019b). The “eco-scheme” concept of the post-2020 CAP, now in the process of development in EU member countries, is a central strategy to improve biodiversity conservation in agrarian land. This new concept would replace the greening element of Pillar 1 in the CAP and would give EU member states more autonomy to tailor incentives for implementing biodiversity-friendly farming. This new concept adopts an integrated vision of management in specific agrosystems (e.g. pasturelands or extensive cereal cropping) aimed to preserve and promote biodiversity. For example, tailoring the new CAP to reduce the application of ro-denticides would mitigate risks of secondary poisoning in red kites and other wild species (Coeurdassier et al. 2012, 2014; Olea et al., 2009). This mitigation would be consistent with recommendations from the

European Parliament (2019) regarding implementation of the EU Directive on the Sustainable Use of Pesticides.

8.3. Recovering depleted populations

Climate mitigation efforts including habitat restoration and, as a last resort, translocation have been forwarded as critical for conserving species vulnerable to climate change (Secretariat of the CBD, 2009). Management based on reintroduction or population reinforcement is currently considered as a fully developed, successful, and well-regulated approach for counteracting extinction risk and promoting population recovery (Seddon et al., 2007). Successful reintroduction programs have in fact allowed the recovery of the red kite in several European regions, including the UK (Carter and Powell, 2019) and Italy (Ceccolini et al. in Annex S4; Table S.2). Furthermore, the current European legal framework makes reintroductions or translocations mandatory whenever necessary to conserve populations of protected species (López-Bao et al., 2018; Annex S3). Thus, combining supplementary feeding with population reinforcement or reintroduction should be implemented where necessary to halt or recover red kite population declines in the southern part of the range. Providing food may be especially effective to compensate for increased risk of predation by expanding populations of goshawks and eagle owls (*Bubo bubo*), which may have constrained efforts to recover small populations of red kites in southern Spain (Sergio et al., 2019a).

Population reinforcement and reintroduction should be conducted in a stepwise manner beginning with stakeholder engagement (e.g., hunters and farmers) to minimize anthropogenic sources of mortality, producing robust viability plans following IUCN guidelines (IUCN/SSC, 2013), and hacking of fledglings to improve probability of natural settlement by breeders in the release area. The goal of such release programs is to achieve self-sustaining populations that can persist without translocation or release of captive juveniles. Release areas should be chosen using a science-based approach along with a well-designed plan for monitoring of released birds (e.g., via satellite tracking). Releases should follow an adaptive management approach based on predictive models while following animal ethics protocols (Seddon et al., 2007; Thulin and Rocklinsberg, 2020).

The question remains about when or where population reinforcement and reintroduction must be applied to expand or at least maintain remnant populations (Box 1). Success of the conservation program in the Balearic islands, beginning with a depleted population of <10 pairs and release of 5 juvenile red kites (De Pablo, 2015; Muntaner-Yangüela, 2015; Table S.2; Annex S2), was partly enabled by strict isolation of this population. This isolation confines potential dispersal within the islands and reduces threats to a restricted number of territories where management can be easily implemented. By contrast, juveniles in continental populations spend weeks or months as vagrants while dispersing thousands of square kilometers during their first year of life (Literák et al., 2020; Sergio et al., 2021; Raab et al. in Annex S4). During these wandering phases, young individuals encounter multiple threats to their survival (e.g., poisoning and collisions with human-made structures) and may preclude successful management (Iglesias et al., 2015; Sergio et al., 2021).

Monitoring in conjunction with conservation measures is important for protecting or recovering threatened populations. Monitoring by itself, however, causes at least some disturbance that could outweigh the benefits of information gains while further threatening isolated pairs or small populations in the final stage before extinction after long-term fragmentation. Risks are greatest when involving capture, manipulation, and tagging of the few birds remaining in the wild, which may be of concern in a highly philopatric species quickly losing range. Under these conditions, the information obtained (e.g., regarding mortality causes) would be restricted to a small sample of individuals and would likely not warrant the costs and risks of monitoring. Such an approach may only confirm the cause of final extinction of the few birds remaining, for example in a poisoning event involving most of the remaining population (Mateo-Tomás et al., 2020). In conclusion, this is a clear case in which a reintroduction program including mitigation of poisoning risk for breeding birds is more ethically sound than monitoring the remaining birds (Thulin and Rocklinsberg, 2020).

Thus, to avoid range loss and secure these highly endangered populations, a strategy that combines population reinforcement and securing safe food sources would help ensure successful recovery of these extremely endangered populations. Successful experiences of population reinforcement by releasing birds from rehabilitation or captive-breeding centers support this view (Díaz et al. and Ginés & Cortés in Annex S4). Beyond the main goal to initiate the recovery of southern populations, released birds could also attract potential colonizers from surrounding regions in this facultative colonial species (Carter, 2007). Monitoring of translocated young is expected to provide information about local causes of mortality, which is of crucial

Box 1

Contrasting examples regarding the use of population reinforcement for the recovery of depleted populations.

Doñana National Park

A conservation program using supplementary feeding and satellite telemetry without population reinforcement was recently proposed for Doñana National Park. The aim of this effort is to improve survival of red kites in the first years of life, which was implicated along with low productivity as causing long-term decline in abundance within the PA (Sergio et al. 2019a, 2021). The demographic model indicated that releasing young birds is not currently the most advisable technique there due to low survival in this age class. Young birds are inexperienced and especially vulnerable to anthropogenic risks including poisoning and electrocution. However, Doñana National Park is unique as the only locality in the southern edge of continental Europe still holding a significant breeding population (i.e., 37 pairs in 2017). So, the conservation plan with no releases may be adequate to recover that population under current conditions.

Other areas of southern Spain

In contrast to Doñana National Park, red kites within the remaining southern third of Spain are currently found as small and isolated groups of pairs or even as isolated single pairs (Molina, 2015). Population reinforcement to recover depleted populations of red kites has been initiated through EU LIFE projects in Calabria of southern Italy (i.e., 15–20 pairs across 2000 km^2; Ceccolini in Annex S4) and in western Sierra Morena of southern Spain (i.e., 8 pairs across 3000 km^2; Godino et al., 2020; Raab, 2022; Annex S7). Population reinforcement or reintroduction is likely needed to avoid extinction of these remnant populations.

importance to avoid extinction (Sergio et al., 2021). Population reiforcemnent must however be considered as a last resort and only adequate in extreme situations, such as those found in the southern and southeast edges of the current breeding range of red kites.

Reintroducing red kites at the southernmost edge of their original range (i.e., the Canary Islands), presents a particularly promising opportunity to address legal and ethical duties regarding the conservation of this species (Annex S1). These efforts not only would avoid range loss or recover from past range loss, but also would provide critical information for understanding the effectiveness of techniques to mitigate species range loss in the face of global change. Population reinforcement can also improve knowledge about functional links between climate change and range loss in birds, which is a critical knowledge gap for understanding global change (Dunn and MØller, 2019).

Detailed monitoring of populations may allow for identifying ecological factors that explain range loss in the southern part of the range. For example, it is suspected that southern populations may have low breeding performance, but for reasons poorly known. Acquiring data from the few pairs currently remaining would probably be insufficient to confidently link climate factors to breeding ecology. Examining other drivers (e.g., anthropogenic mortality and supplemental feeding) limiting the creation of a self-sustaining population following reintroductions or reinforcements should be carried out in a way that does not hinder the success of these programs (IUCN/SSC, 2013).

8.4. Targeted monitoring and research

Systematic monitoring of species responses to conservation actions is highlighted as a major need to halt biodiversity loss (Williams et al., 2020). Regarding the conservation of migratory species like the red kite, coordinating monitoring among scientists and conservation practitioners (e.g., government authorities, environmental consultants, and non-government organizations) across the species range would allow robust comparisons to inform management under changing environmental conditions (Derlink et al., 2018). Reconciling transboundary differences in methodologies for monitoring population demographics and threats is an outstanding need to inform red kite conservation. For example, coordinated and periodic counts of red kites across Spanish regions have been very useful to understand the importance of poisoning on the species breeding population (Mateo-Tomás et al., 2020). Upscaling this method to internationally coordinated counts of red kites at winter roosts would allow for more comparable estimates of red kite abundance among countries during this season (LIFE EUROKITE, 2021).

Satellite tracking technologies have emerged as consistent means to study movements, mortality, and causes of mortality across flyways used by raptors including red kites (Panter et al., 2022; Raab et al., 2017). For example, this technology was recently applied to identify areas undergoing unsustainable mortality in black kites (Sergio et al., 2019b) and determining space use of red kites during the breeding season (Spatz et al. In press; Spatz et al., 2019). Owing to its scavenging feeding behavior along with being perceived as a competitor for small game, the red kite is a good sentinel of poisoning and other forms of wildlife persecution (Derlink et al., 2018; Mateo-Tomás et al., 2020). Thus, improved monitoring of red kite distribution and demographics would inform conservation and management of this and other illegally persecuted species. Likewise, documenting mortality caused by electrocution or collisions with infrastructure can inform decision-makers about design of wind farms along with marking or burying of power lines (Bernardino et al., 2018; May et al., 2020).

Conservation of red kites and other species affected by climate change would also benefit from increasing the understanding of the species responses (i.e., physiological, behavioral, demographic) to climate change. These investigations should provide estimates at multiple spatial scales, from local to intercontinental, paying special attention to migratory connectivity and dispersal. Transboundary collaboration among conservation practitioners would facilitate this task through, for example, comparison of red kite populations at different latitudes. Monitoring changes in distribution and abundance is particularly important in areas where the breeding range is expanding in northern Europe (e.g., Sweden and Baltic countries) and contracting along the southern edge of Europe (i.e., southern Spain and some Mediterranean islands; Fig. 1). These data are important for addressing questions about continent-wide impacts of global change (e.g., Huntley et al., 2008) and for informing long-term conservation of this species.

9. Conclusion

Shifts in the geographic range and migration patterns of red kites and other wildlife species are expected under global change (Huntley et al., 2008; Munstermann et al. In press; Scheffers and Pecl, 2019), but the functional reasons behind shifts in these species are still poorly understood (Dunn and MØller, 2019). Achieving conservation goals therefore likely depends on improving predictions about how abundances will change as a function of management of different threats (Mateo-Tomás et al., 2020; Mattsson et al., 2020). Red kites are subject to diverse threats (Table 1) and experience disparate population trajectories across their geographic range despite a high degree of migratory connectivity between regions (Fig. 1). Achieving goals for conserving migratory populations is more likely when actions are based on the best available knowledge regarding the ecology of the species, considering the full annual cycle and global change impacts (Belsky and Joshi, 2018; Murray et al., 2018; Rushing et al., 2016). Nonetheless biodiversity continues to decline despite the increasing availability of scientific evidence on how the main threats affect species and ecosystems, which indicates that additional steps should be taken (Williams et al., 2020).

As an illustrative example, using models to predict areas with high risk of primary (Mateo-Tomás et al. 2012, 2020) and secondary (Imholt et al., 2015; Jacob et al., 2014) poisoning could inform spatiotemporally explicit efforts to mitigate negative impacts on red kites and other flesh eaters. Such measures could include incentives for farmers to reduce their use of toxic pesticides (Jacquot et al., 2013), providing safe food alternatives for carnivorous wildlife (Karthäuser et al., 2019; Orros and Fellowes, 2015), and increased enforcement and outreach to reduce persecution (Christie, 2007).

Our findings emphasize the need to strengthen international coordination among all conservation practitioners to advance scientific knowledge - on both the species biology across the full annual cycle and the outcomes of conservation actions across space and time - as a basis for effective conservation of the species. Compared to the current approach of conserving many migratory species characterized by independent work among groups, linking international coordination of conservation actions informed by systematic monitoring of the outcomes from local to global scales is likely to be more successful (Nita et al., 2016). Continuing with the previous example, efforts to mitigate poisoning could be allocated toward wintering areas used by the majority of individuals from critical breeding areas to help ensure their ongoing contribution to population viability (Sample et al., 2020).

We therefore recommend that successful conservation of red kites and other migratory species will be based on adaptive management, information sharing, and coordination between scientists, conservation practitioners, policymakers, and local communities across the entire species range. Based on experiences from adaptive management for sustainable harvest of waterfowl populations across countries in Scandinavia (Madsen et al., 2017) and North America (Nichols et al., 2007), this can yield great benefits in terms of conservation outcomes, learning, and stakeholder engagement after only a few years of planning that precede implementation. Extending this to species occupying many countries of Europe, however, represents a new challenge.

The EU LIFE Programme offers an opportunity for such international coordination in the adaptive management of migratory species. The current LIFE EUROKITE project (2020─2027) is establishing a network of communication among conservation practitioners while collecting data on reproduction, movement, and mortality of red kites across many of their core breeding and wintering areas (LIFE EUROKITE, 2021). The next step will be coordinating management actions based on model predictions of associated changes in abundance from regional to inter-regional scales, made possible by a parallel research project that is being planned. Ongoing interactions between modelers and conservation practitioners along with targeted monitoring are essential for adaptive management to be successful (Williams and Brown, 2014). Developing funding mechanisms that link LIFE to the EU Framework Programme for Research and Innovation would help enable the implementation of adaptive management. If successful, we expect that tailoring international-scale implementation of adaptive management for red kites will generate important lessons for integrated conservation of other species occupying many countries, particularly of migratory ones. These include birds and bats that occupy multiple countries as they move between wintering and breeding areas during the annual cycle.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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