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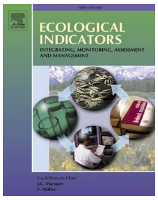

Birds as bioindicators of river pollution and beyond: specific and general lessons from an apex predator

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ABSTRACT

Birds can be impacted by pollution but are seldom used as bioindicators. One exception involves the Dippers *Cinclus* spp., a genus of five passerines adapted uniquely to swim and dive in rivers on five continents to feed on aquatic invertebrates and small fishes. Here, we review the effectiveness of Dippers as pollution indicators while identifying further opportunities, caveats and uncertainties that are transferable to other indicator organisms.

Dippers have been used as biodindicators i) through relationships linking their distribution, breeding performance and behaviour to river pollution through effects on prey quality and quantity; ii) where contaminants occur in their eggs, tissues, faeces or regurgitates, notably metals (Hg, Se), persistent pollutants (e.g. PCBs, PBDEs, DDE, HEOD) and microplastics. Most data are from *C. cinclus* in Europe and *C. mexicanus* in North America.

While some pollution effects on Dipper distribution or fitness are well-evidenced, particularly acidification, the resulting impairments are not sufficient to diagnose the source of impact without additional data on water quality or prey abundance. Dippers in these cases provide a general rather than definitive indication of pollution.

For contaminants, Dippers have revealed the distribution of specific pollutants at scales ranging from point-sources and regions to different continents. Influences of land use, trophic pathways, diet-shifts, contaminant transport, intergenerational transfer and trends through time have all been identified and supported by detailed knowledge of prey use, territoriality, dispersal, migration, life history, isotopic signatures and energetics.

We suggest opportunities to expand the role of Dippers as bioindicators into other locations (Asia and South America), other influences on water quality (e.g. agriculture, wastewater), other contaminants (e.g. PFAs, pharmaceuticals) and through developments in modern biology such as ‘omics. Initial data also show that Dippers could integrate the effects on rivers of habitat modification, flow modification and climate change by indicating effects both directly and through interactions with other multiple stressors. This group of birds illustrates how fundamental ecological information aids the development of bioindicators but reveals the importance of using complementary environmental data when diagnosing bioindicator response. We suggest these are important lessons for ecological indicators more generally.

1. Introduction

Bioindicators can be defined as individuals, populations or communities of organisms whose response to ecosystem character provides useful information about the state of the environments with which they interact (Dmowski, 1999; Bryce, 2006; Parmar et al., 2016). For individual species, potential bioindicator uses can reflect either distribution, life history and behaviour in relation to environmental character, or physiological responses such as ecotoxicity, cellular modification, biomarker signals and contaminant burdens (Burger, 2006). This means that their biodindicator value depends on some combination of whether they (1) are typical of the ecosystem under study; (2) are ubiquitous and abundant; (3) are easy to identify and sample; (4) are able to bioconcentrate exobiotic substances; (5) are able to survive high concentration of toxic substances; (6) have a distribution or life history features that can be related clearly to aspects of environmental quality (Ormerod and Tyler, 1993a; Gragnaniello et al., 2001). Biodindicators should also be able to reveal trends in environmental quality both through degradation and recovery (Pharaoh et al., 2023).

A wide array of organisms have been used as bioindicators, involving

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many taxonomic groups across the major kingdoms of microbes, plants and animals (Parmar et al., 2016). Despite the fact that mammals and birds often represent higher trophic levels that integrate ecosystem processes, however, they are underrepresented among the most widely used bioindicators (Burger, 2006). This is surprising for birds in particular because they satisfy the characteristics required to be effective bioindicators while their charisma often generates substantial public interest. Birds are often easy to see and hear, and therefore easy to count and monitor (Egwumah et al., 2017). Well-trained professionals and amateurs are able to identify birds, thus facilitating surveys of individuals, populations and life-history traits, for example through nest recording. Both through their species diversity and life history expression, birds can respond behaviourally and ecologically to short- and long-term environmental variations, both at the species and community levels. This includes species at a range of trophic positions from primary consumer to top predator which can reveal or bioaccumulate pollutants in their tissues throughout their life in ways that reflect food-web processes (Amat and Green, 2010). In combination, these features mean that there is a long history of professional and citizen science involving birds that has allowed a greater availability of information on their density and distribution without the need to invest large financial resources or require constant scientific and administrative support to obtain standardized data (Fernández et al., 2005).

The bioindicator value of birds has been a particular focus in freshwater systems - where a range of pressures affect ecological conditions to the point that rivers, lakes and streams are now considered to be in need of urgent conservation action (Tickner et al., 2020; Haase et al., 2023). These pressures range from pollution, climate change and habitat impairment to the effects of barriers to movement, invasive non-native species and water withdrawal for supply. While there are clear challenges in using birds to indicate such a wide array of effects, one monogeneric family, the Cinclidae, stands out for its diverse uses in assessing the ecological quality of streams and rivers. Each of the world's five species of Dippers (*Cinclus* spp) is almost completely dependent on aquatic macroinvertebrates and small fishes, and as a result, they occupy a key position in riverine food webs in which they feed simultaneously as secondary and tertiary consumers (Ormerod, 1996). Their prey preferences as apex predators are well quantified, meaning that contaminant transfers to Dippers and relationships with factors affecting prey communities are well understood (Gutiérrez-Cánovas et al., 2021). Additionally, their occurrence along territories of 300–2000 m means that their distribution, nutrient sources for egg-formation and routes of pollutant exposure can be linked to local conditions. Furthermore, patterns of dispersal and migration are sufficiently well understood to account for any larger-scale influences on their contaminant burden or response to environmental conditions. Although there is some variation in the knowledge of the five *Cinclus* species, their ecology is extremely well described to the point that habitat requirements and global distribution patterns are clearly defined (Tyler and Ormerod, 1994; Morrissey et al., 2004; Morrissey et al., 2010a). The five species are distributed throughout extensive areas of the world, except for Oceania, Antarctica, Africa south of the Sahara and North America east of the Rockies where barriers to dispersal have prevented range expansion over evolutionary timescales (Buckton and Ormerod, 2002; Ormerod and Tyler, 2005).

For all the above reasons, we postulate that Dippers provide a well-understood example of a bioindicator of the quality of streams and rivers both through their distribution and life history, and through their links with the food-web transfer of pollutants. This understanding is now so well advanced that they act as model organisms through which impacts on stream ecosystems can be demonstrated theoretically (Rowland et al., 2023). The aim of this review is to evaluate the use of Dippers as bioindicators of water quality through a systematic review of published and peer-reviewed scientific literature. Although our starting point was water quality and pollution, at the suggestion of the referees we also evaluate some unexploited potential in the use of Dippers in the ecological assessment of river quality more generally to support areas of policy and management such as physical habitat quality, flow modification and climate change. At the same time, however, there are some constraints and uncertainties in the use of Dippers as bioindicators that provide important generic lessons. We therefore attempt to draw wider conclusions gained over four decades of research on this group of birds that are relevant to the use and development of bioindicators more widely.

Ormerod and Tyler (1993a) previously reviewed the general role of freshwater birds as bioindicators of water quality, but a considerable volume of research has been added in the 30 years since this earlier assessment.

2. Methods

2.1. The ecology of Dippers: An outline

Dippers (*Cinclus* spp) are medium-sized (55–75 g) passerines of the family Cinclidae, closely linked to permanent, upland rivers and shallow streams generally with clean, well-oxygenated water flowing over stony beds (Ormerod and Tyler, 2005). This genus represents the only passerines capable of diving into the water to search for prey for which they are highly adapted in morphology, physiology and behaviour (Murrish, 1970). Their key prey – mostly immature Ephemeroptera, Plecoptera and Trichoptera along with some small fishes - are also recognised for their association with clear, well-oxygenated conditions (Thut, 1970; Feck, 2002; Chiu et al., 2009). This distributional link between Dippers and unpolluted water has resulted in their proposed value as bioindicators of water quality (Feck, 2002; Sorace et al., 2002). In addition, the direct association with the river corridor and obligate use of the river channel makes Dippers easy species to identify and monitor, since they are tied to watercourses at all stages of their lives except during brief periods of inter-basin dispersal and migration (Bent, 1948; Sunquist, 1976; Ormerod and Tyler, 2005; Chiu et al., 2013a,b; Flores Bedregal et al., 2015).

A wide range of organisms has been recorded in the prey spectrum of Dippers, including molluscs, crustaceans, worms, salmonid eggs (Moreno-Rueda, 2016), small fishes (Santamarina, 1993), dead fish (Moreno-Rueda, 2016) and frog larvae (*Ascaphus truei*; Morrissey and Olenick, 2004). For the most part, however, prey use in Dippers follows a clear and consistent pattern of highly selective foraging that reflects the different phases of their annual cycle (Ormerod and Tyler, 1991). Increased energetic requirements prior to breeding mean that males and females focus on large Trichoptera and small fishes, such as cottids and salmonid fry. Additionally, the demands for calcium in the egg-laying female are met by feeding on fish, benthic molluscs and crustaceans such as gammarids. Nest provisioning involves a progressive shift from small invertebrates (e.g. baetid or heptageniid mayflies or leuctrid stoneflies) to larger prey such as hydropsychid and limnephilid caddis as the energetic demands of the brood increase. Successfully fledged young Dippers then concentrate on easily captured prey such as simuliid larvae or small mayflies (Yoerg, 1994). The precision with which these dietary changes have been identified has been key to understanding relationships with water quality as well as tracing the energetic pathways along which contaminants are transferred (Ormerod et al., 1986; Sorace et al., 2002; Chen et al., 2010). All of these points informed the literature search that follows.

2.2. Literature search

We conducted a quantitative literature review based on the Preferred Reporting Items for Systematic Review Recommendations (PRISMA; Moher et al., 2009, Fig. 1). Research articles were obtained by searching three major online databases (*Web of Science, Google Scholar* and *ResearchGate*) in November 2022 using the following string (("Dipper" OR "*Cinclus*") AND ("water quality" OR "biological quality" OR "microplastics" OR "pollution" OR "Contamination" OR "polluted" OR

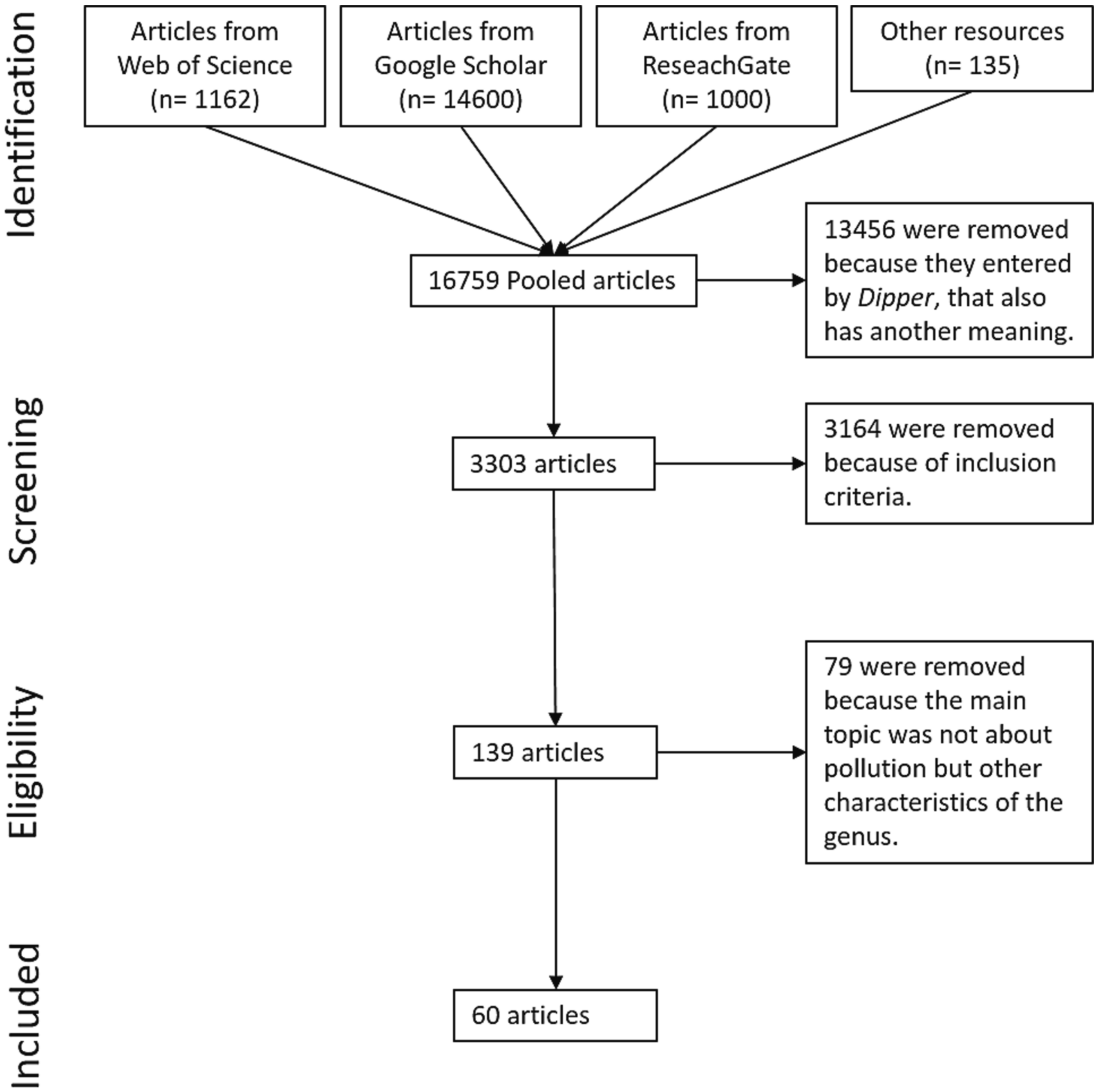

Fig. 1. PRISMA literature search flow diagram (Moher et al., 2009): The number of studies that were located, retained, and discarded is shown at each stage of the process.

"unpolluted" OR "water acidity" OR "acidification" OR "acid-stress" OR "Bioindicator" OR "Herbicide" OR "Selenium" OR "mercury" OR "chemicals" OR "endocrine-disrupting" OR "organochlorines" OR "drugs" OR "pharmaceuticals" OR "Hormones" OR "Organic Wastewater" OR "organohalogenated" OR "metal exposure" OR "plastic waste" OR "biological indicator" OR "wastewater" OR "heavy metal pollution" OR "exposure")).

We initially obtained a large number of articles (Fig. 1) which were then refined using inclusion criteria through which i) the word "Dipper" referred solely to the bird of interest and the research had specifically involved *Cinclus* species; ii) selected articles evaluated some aspect of the biology or distribution of Dippers in relation to water pollution or water quality; and iii) the article was accessible with a reasonable search. We also used the literature cited in the most relevant articles to find other useful references for this review. Finally, 60 articles were included in this systematic review (the complete list of references is reported in Appendix S1 in the online supplementary material). At the suggestion of the referees, we also undertook a subsequent search for literature that linked the ecology of Dippers to other stressors on rivers – specifically habitat modification, flow modification and climate change.

3. Results

3.1. Trends in time and space

Although studies of the biology of Dippers have a history extending well over 100 years (Tyler and Ormerod, 1994), detailed assessments of their relationships with water quality began in the 1980s (Fig. 2). Since then, pollution has remained one of the most important research topics for this genus, supported by expanding fundamental knowledge. So far, the research effort has concentrated on the nominate *Cinclus cinclus* in Europe (72.6 % of papers) and *C. mexicanus* in North America (27.4 %) with most articles arising from the UK, Canada, the USA and Norway (Fig. 3). The Brown Dipper *C. pallasii* has featured to lesser extent among a suite of river birds used as indicators of habitat quality in the Himalayan Mountains (Manel et al., 2000; Sinha et al., 2019). This raises a clear deficit outside Europe and N. America especially for the three *Cinclus* species in Asia and South America where water quality problems are widespread.

3.2. Dippers and general indices of water quality

Birds have been involved in several different quality indices that

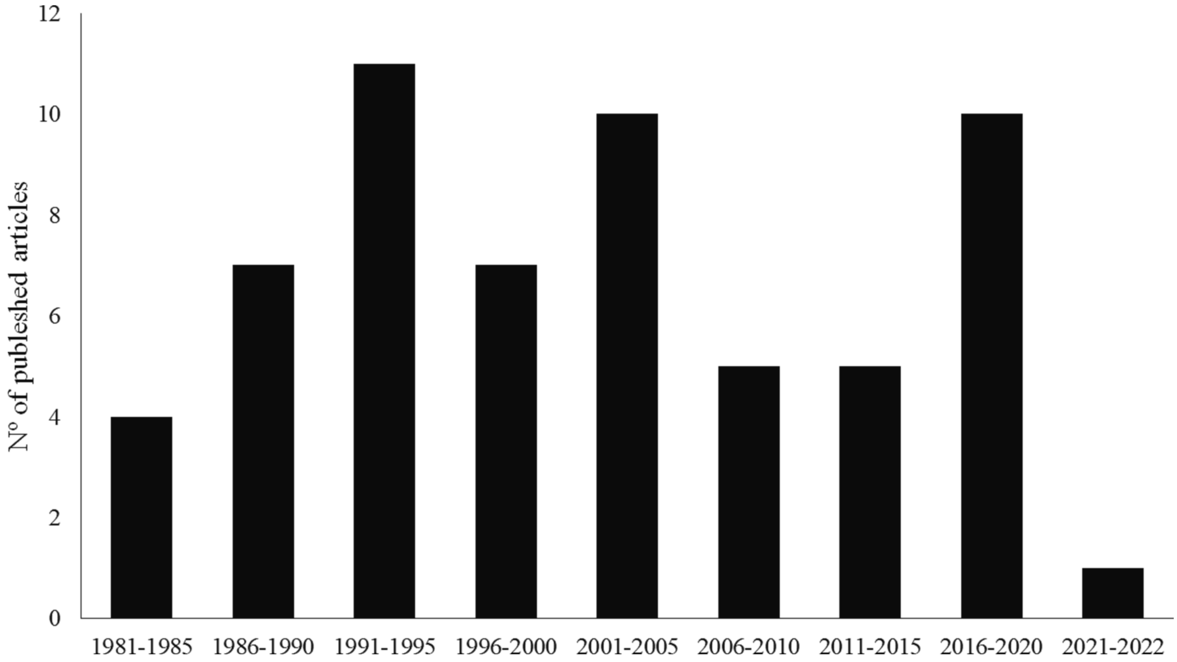

Fig. 2. Number of articles included in the review grouped by year of publication.

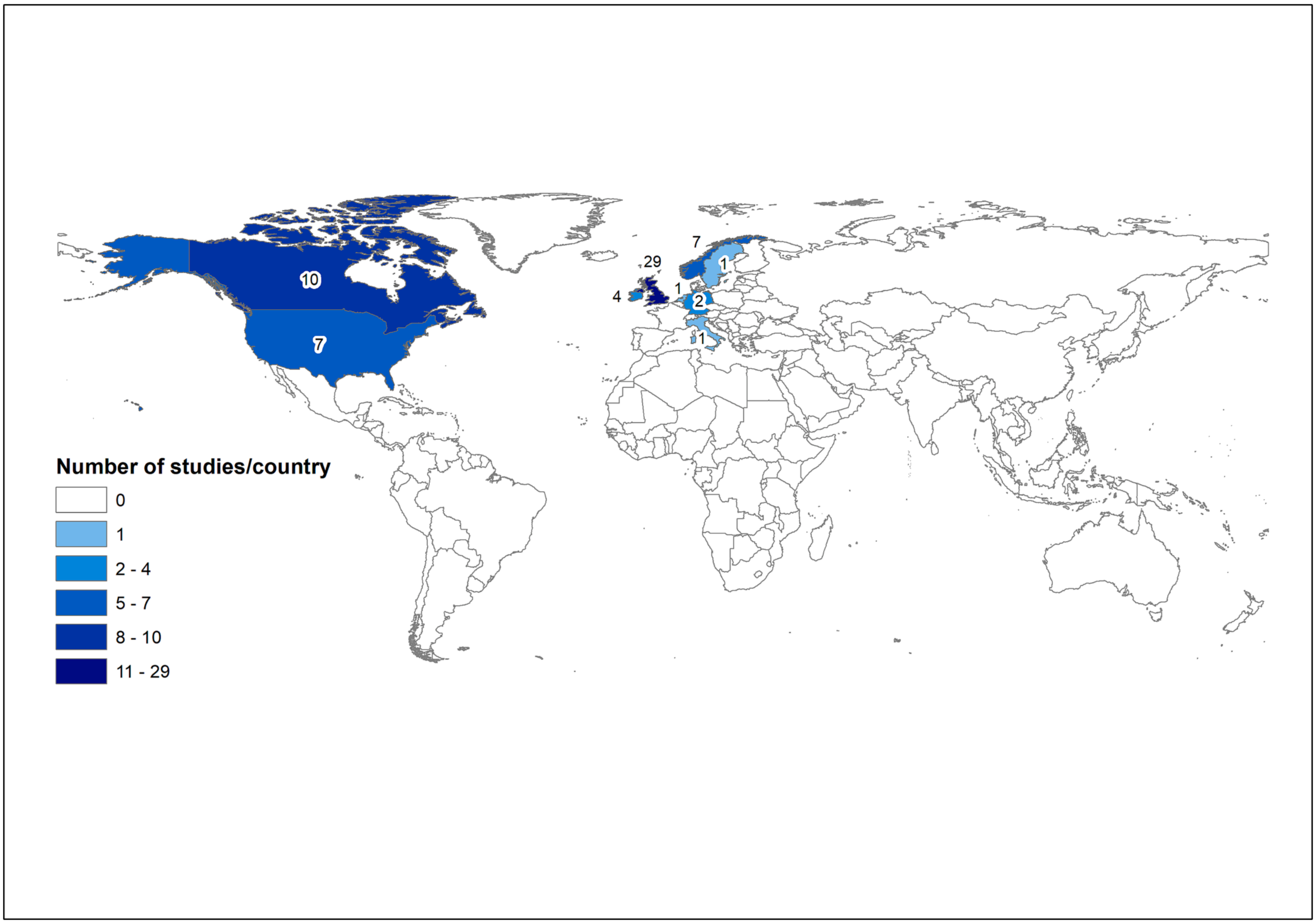

Fig. 3. Worldwide distribution of published articles on the relationship between Dippers and water quality by country. The number of articles published by country is shown and a colour is assigned based on the established colour scale.

relate their distribution and abundance either directly or indirectly to the state of river ecosystems. For example, the Bird Integrity Index (BII; Bryce et al., 2002) putatively assessed human impact on the riparian zones of rivers using birds from a range of guilds. However, very few of the target bird species involved in this work were tied specifically to freshwater ecosystems or linked in any obligate way to freshwater production. The Index of Biotic Integrity (IBI) was focussed more specifically on the wetted river channel, and calculated from the river macroinvertebrate community. Feck and Hall (2004) used this index to interpret the presence of *Cinclus mexicanus,* but showed that Dipper numbers were related more clearly to taxa that figured specifically as prey – notably aquatic limnephilid caddis and heptageniid mayflies – than to the abundance of all freshwater invertebrates. This interesting result confirms the importance of basic knowledge of resource use by Dippers when interpreting links with river quality.

This same need to understand fundamental aspects of Dipper ecology was amplified further in understanding links with water quality in European rivers. Both Ormerod et al. (1985a,b) and Peris et al. (1991) related Dipper abundance to the richness and density of aquatic macroinvertebrates that are part of the diet of both chicks and adults – mediated in some circumstances by the geomorphological characteristics of the river environment such as river gradient (Ormerod et al., 1985a,b). These relationships with prey abundance underpin some of the uses of Dippers as bioindicators discussed below, for example, in relation to stream acidification, heavy metals and chlorinated hydrocarbons (Lachenmayer et al., 1985; Monig, 1985; Nybø et al., 1996). Even in the absence of direct measurements of river invertebrate abundance or water quality, the presence or absence of Dippers has been used as a rapid means of water quality assessment (Sorace et al., 2002). The latter authors observed that dippers were exclusively present in unpolluted streams that either had high Extended Biotic Index values (EBI; Ghetti, 1997) or were close to other higher-quality streams.

Table 1
An overview of the main research topics, pollutants, species and locations of water quality studies involving *Cinclus* spp.

Pollutants	Number of articles reviewed	Species	Countries	Key references
Acidity	19	*C. cinclus*	Norway UK,	Nybø et al., 1997 Ormerod and Tyler, 1989 Vickery, 1992 Logie, 1995 Ormerod & Durance, 2009
Mercury	16	*C. mexicanus*	Canada USA	Morrissey et al., 2010b Henny et al., 2005
		C. cinclus	UK Ireland Norway	Ormerod and Tyler, 1992 O'Halloran et al., 2003 Pedersen et al., 2020
Aluminum	2	*C. cinclus*	Norway	Pedersen et al., 2020
Selenium	5	*C. mexicanus*	Canada	Harding et al., 2005 Wayland et al., 2006 English et al., 2022
Other heavy metals (lead, cadmium, copper and zinc)	3	*C. cinclus*	Germany Norway	Lachenmayer et al., 1985 Nybo et al. 1996
		C. mexicanus	USA	Storm et al., 2002
Organochlorines	18	*C. mexicanus*	Canada	Morrissey et al., 2010b Morrissey et al., 2014
		C. cinclus	Germany Ireland	Monig, 1985 Ormerod and Tyler, 1992 O'Halloran et al., 1993
			UK	Ormerod and Tyler, 1993b Ormerod et al., 2000 O'Halloran et al., 2003
Microplastics	1	*C. cinclus*	UK	D'Souza et al., 2020
Water quality and Biological Indicators	9	*C. mexicanus*	USA	Feck and Hall, 2004
		C. cinclus	Italy UK	Sorace et al., 2002 Ormerod et al., 1985a,b

While these generic responses to river quality are helpful in understanding the bioindicator value of Dippers, rivers and streams are affected by a wide variety of different pollutants from agriculture, urban wastewater or industry (Table 1). This raises two important questions. First, is there evidence that Dippers respond in specific ways to specific pollutants? Second, is the distribution, abundance or life history of Dippers alone sufficient to diagnose the effects of pollution without additional chemical or biological data? We develop these themes in the sections that follow.

3.2.1. *Acidification*

Studies of the distribution and abundance of Dippers in relation to the acid-base status of Welsh streams were the first to reveal how pollution reduced prey availability to this species with consequences for most aspects of their life history (Tyler and Ormerod, 1992). Extensive evidence revealed how acid rain and forest management combined to acidify base-poor streams over large areas (Ormerod and Tyler, 1989; Ormerod and Durance, 2009). About half the entire stream length of 24,000 km in Wales was affected, reducing pH values either chronically or episodically to values of ∼ pH4-6. These same effects were reflected in increased concentrations of aluminium in acidified waters, which in various states of speciation had markedly toxic effects on fish and sensitive freshwater invertebrates at pH values around pH 5.

Evidence began to emerge during the 1980s that Dippers were not only in significantly reduced numbers along acid streams across Wales, but also that populations had declined along acidifying rivers (Ormerod et al., 1985a,b; Ormerod and Tyler, 1987; Buckton et al., 1998). Along the same acidified streams, important Dipper prey were in substantially reduced numbers – especially small Ephemeroptera, energy-rich Trichoptera and calcium-rich taxa (Ormerod and Tyler, 1991). Where Dippers attempted to breed along acidified streams, territory lengths increased, abundances declined (Ormerod et al., 1985a,b), eggshells were thinner (Ormerod et al., 1988), clutch and brood-sizes were reduced, nestling growth was retarded (Ormerod et al., 1991) and daily activity patterns reflected greater foraging intensity to maintain energy balance by comparison with circumneutral streams (O'Halloran et al., 1990). These effects were supported by physiological measurements that showed impaired calcium metabolism in Dippers along acidified streams (Ormerod et al., 1991).

Acidification was not just a local phenomenon, affecting large areas of Europe and North America where acid rain fell over base-poor rocks and soils (Muniz, 1990; Herrmann et al., 1993). Contemporary and subsequent research on Dippers and their prey in these other areas confirmed many of the same effects of acidification that had been observed in Wales. In western Scotland, for example, acidified streams had reduced densities of Dippers alongside reduced egg mass, shell-thickness, clutch size, brood size, rates of brood provisioning and reduced chick survival (Vickery, 1991; 1992; Logie, 1995). Importantly, Logie et al. (1996) related acidification effects on Dippers to 'critical load exceedance' through which rates of atmospheric deposition of sulphur and nitrogen oxides – as acid rain – were greater than could be buffered by local geochemical processes. In Norway, Jerstad (1991) detected reduced productivity in Dippers along acidified streams while Nybø et al. (1997) demonstrated a 6 % thinning in their eggshells linked to the scarcity of calcium-rich prey. These authors also proposed an 'Eggshell Index' as an indicator of acidification. There was some debate at this time about whether aluminium or its hydroxides might be directly implicated in eggshell anomalies by interfering with calcium and/or phosphorus metabolism, although clear evidence was never found other than through impacts on Dipper prey (Diamond, 1989; Pedersen et al., 2020).

Three important corollaries to these Welsh, Scottish and Norwegian studies were first, that acidification effects on Dippers were reproducible regionally. Second, they had clear public, cultural significance – for example in Norway where the Dipper is the national bird. Third, the effects helped to bring about Europe-wide policy tools aimed at controlling the acidifying emission and deposition of combustion products from fossil fuels. At the same time, however, there was a caveat. Despite the clarity or effects and processes through which Dippers responded consistently to acidification in different locations, the interpretation of this relationship required additional data on stream chemistry and acid sensitivity. This meant that measurements of breeding performance, territory length or Dipper abundance alone would be insufficient to diagnose the cause among different competing explanations. This is a common and widespread problem with biological indicators based on distribution and life history in that they often reveal an environmental impact, but seldom diagnose the processes responsible (Jones et al., 2023).

3.2.2. *Metals*

The food-web transfer of metals to birds has been a well-recognised area of bioindicator activity in metal contaminated environments, through the methylation of mercury, or through associations with other processes such as acidification as reviewed above (Cristol et al., 2008). In Dippers, a range of light and heavy metals has been investigated, including lead (Strom et al., 2002), cadmium, copper and zinc, but most attention has fallen on aluminium, mercury and selenium (Nybø et al., 1996).

For aluminium, early speculation was that phosphorus and calcium metabolism might have been affected by aluminium exposure in acidified environments (Scheuhammer, 1987; Diamond, 1989) but Pedersen et al. (2020) have since concluded that evidence for the biological transfer of this metal is limited. Most evidence is that aluminium *per se* is not particularly toxic to birds, which can absorb small proportions of this element through the diet without significant impact on fitness (Diamond, 1989). Any role for aluminium in the effects of acidification on Dippers was therefore more likely to reflect effects on aquatic prey.

For Mercury, a range of passerines have been used to indicate occurrence and impairment of the nervous system (Scheuhammer, 1987), breeding performance (Jackson et al., 2011a,b), survival (Hallinger and Cristol, 2011), endocrine and immune functions (Hawley et al., 2009; Wada et al., 2009) and behaviour or cognition (Hallinger et al., 2010; Swaddle et al., 2017; Greene et al., 2018; Wolf et al., 2017). However, relationships with mercury sources reflect a complex blend of ecosystem processes affecting methylation, movement patterns or food-web position in target species and choice of tissues used in measurement (Diamond, 1989; Bodaly et al., 2004; Silverthorn et al., 2017; Cristol and Evers, 2020). Some evidence also suggests antagonistic, enzymatic effects against mercury toxicity from other metals – notably Selenium (Potter and Matrone, 1974; Chang, 1977). Some of these complexities apply to Dippers, in which mercury is detectable at concentrations in eggs that are low but sufficient to reveal differences between regions linked probably to differences in atmospheric deposition (Ormerod and Tyler, 1992; O'Halloran et al., 2003; Henny et al., 2005; Pedersen et al., 2020). In an inter-continental comparison, two different *Cinclus* species (*C. cinclus* and *C. mexicanus*) were used during a larger study of scale-dependent effects on contaminant patterns supported by stable isotopic analysis (Morrissey et al., 2010b). Mercury was the only contaminant at greater concentrations in Dippers in Canada than in Europe probably reflecting local trophic pathways where American Dippers fed on the eggs of migrating Pacific salmon which vectored contaminants of marine origin (Morrissey et al., 2004).

Although apparently mitigating the effects of mercury, selenium can be toxic in its own right to birds and fish even at relatively low environmental concentrations (Harding et al., 2005). Selenium bioaccumulated in tissues can affect growth, reproduction, metabolism and embryo survival, although effects vary across locations and species (Adams et al., 1998). In aquatic birds such as waterfowl, however, apparent bioindicator value arises from evidence that selenium concentrations in eggs can reflect concentrations in local freshwater ecosystems (Ohlendorf et al., 1993; Adams et al., 1998; Skorupa, 1998). This appears also to be the case in Dippers, but with some equivocation. A study in the Gregg River catchment of Canada showed elevated selenium concentrations in the prey and eggs of American Dippers in areas affected by coal mining (Wayland et al., 2006, 2007). However, similar studies near to coal mines on British Columbia's Elk River revealed elevated Selenium concentrations in American Dipper prey, but they were not translated into elevated levels in the birds' blood, feathers or eggs. Nor was there any effect on clutch size or hatching rate (English et al., 2022).

3.2.3. *Organic pollution and urban wastewater*

Urban wastewater is a major source of water pollution globally and is detectable from water quality samples, from aquatic organisms such as invertebrates, and from stable isotopic signatures that can be reflected in the eggs of Dippers (Morrissey et al., 2013a; Morrissey et al., 2013b). In the UK and more widely across Europe, legislation in the early 1990s led to a progressive reduction in insanitary pollution, and this in turn created opportunities for clean-water organisms to recolonise some rivers that were once classed as grossly polluted (Vaughan and Ormerod, 2012; Pharaoh et al., 2023). This included invertebrates used typically as prey by Dippers – Ephemeroptera, Plecoptera and Trichoptera – which in Britain has also allowed widespread re-establishment of breeding Dipper populations along formerly polluted rivers, at least where habitat is suitable (Beckett, Ormerod et al. unpubl data). Although Dippers have yet to be evaluated formally as an indicator of wastewater pollution, their re-establishment in previously polluted catchments raised the possibility that they could now be used to indicate the presence of legacy or emerging contaminants in these locations. This includes substances such as polychlorinated biphenyls (PCBs), polybrominated diphenyl ethers (PBDEs), pesticides, plastic polymers and other complex substances that occur in these waters as well as in some agricultural catchments (Kolpin et al., 2002; Wilson et al., 2005; Jackson and Sutton, 2008, Phillips and Chalmers, 2009; Barber et al., 2011; Morrissey et al., 2013b). We evaluate interactions between these substances and Dippers in the sections that follow.

3.2.4. *Complex organic pollutants*

Persistent or complex organic pollutants are organic compounds with many derivatives and formulations that arise from agricultural, urban and industrial sources (Dewailly et al., 1989; Morrissey et al., 2005). Many are legacy chemicals which have now been removed from production or legal use in most nations, but can persist for decades as parent compounds or their residues in environmental circulation or in wildlife. They include DDE (1,10- (2,2-dichloroethenylidene) bis (4-chloro)-benzene), TDE (1,10- (2,2-dichloroethylidene) bis (4-chloro)-benzene), DDT (1,1,1-Trichloro-2,2-bis(4-chlorophenyl), HCB (hexachlorobenzene), gHCH (1,2,3,4,5,6-hexachlorocyclohexane, Gamma isomer) (lindane), HEOD (1,2,3,4,10,10-hexachloro-6,7-epoxy-1,4,4a,5,6,7,8,8a-octahydro-*exo*-1,4-*endo*-5,8-dimethanonaphthalene) (aldrin and dieldrin), PCBs with their wide range of congeners (polychlorinated biphenyls) and PBDEs. In several instances, the ecotoxic effects of these compounds is well known, reflecting bioaccumulation, biomagnification along the food web, maternal transfer, embryo toxicity and endocrine disruption. DDT, for example, reduced eggshell thickness, breeding performance and population in a range of terrestrial and aquatic bird species during the 1960s and 1970s (Pearce et al., 1979; Hernández et al., 1988). PCB residues at sufficient concentrations are believed to disrupt behaviour and normal reproduction in birds, even at sub-lethal levels (Barron et al., 1995). While many previous studies of the effects of organic pollutants involved raptorial species, passerines have also been used to assess spatial patterns and temporal trends on contaminant concentrations (Custer et al., 1998; Bishop et al., 1999). Moreover, persistent pollutants are widespread in rivers, potentially even impairing recovery from historical gross pollution in rivers now occupied by Dippers (Windsor et al., 2019a). Indeed, persistent organic chemicals are present in Dipper eggs but at sub-lethal levels that create the opportunity for a local, territory-specific, indication of contamination (Ormerod and Tyler, 1992; Kallenborn et al., 1998).

Persistent pollutants in Dipper eggs were first assessed in the late 1980s and early 1990s to eliminate the possibility that these chemicals were responsible for shell-thinning observed along acidified streams (see Ormerod et al., 1988). Subsequent data from fresh, deserted and addled eggs illustrated how the concentrations of PCBs, DDE, HEOD and other compounds varied regionally across the UK and Ireland, and locally between catchments in different land use, also producing some of the first data on specific PCB congeners as wildlife contaminants (Ormerod and Tyler, 1992; Ormerod and Tyler, 1993b; O'Halloran et al., 1993). Further work has since shown how Dipper eggs could reveal spatial contaminant patterns ranging from localised point sources (Ormerod et al., 2000), differences between continents (Morrissey et al., 2010b), influences of urban land use (Morrissey et al., 2013b), trophic position in food webs (Morrissey et al., 2004), contaminant pathways linked to migratory salmonids (Morrissey et al., 2012), and trends within locations through time (O'Halloran et al., 2003). Although the patterns detected have often been clear from spatial analysis, interpretation was aided by other analysis including spatial ecology, food-web analysis, stable isotopic assessments, measurements in other media such as blood cells or plasma, and appraisal of dietary shifts (Morrissey et al., 2010b; Morrissey et al., 2013a; Windsor et al., 2020).

Throughout these studies, evidence for ecotoxic effects on Dippers was equivocal, with some of the data suggesting that elevated PCBs had no effect on breeding performance or post-fledging survival (Ormerod et al., 2000) while Morrissey et al. (2014) recorded inferior body condition in nestlings, altered chick sex ratios and apparent changes in thyroid hormone homeostasis at PBDE-contaminated urban sites in Wales. Ormerod and Tyler (1992) speculated that, given their trophic position as predators, effects on Dippers might have been more substantial during the 1960s/70s when organochlorine insecticide use was sufficient to affect other predators. Currently, however, the fact that Dippers can persist in locations affected by legacy chemicals is one of the reasons for their ability to reflect the presence and spatio-temporal pattern among these compounds. There is potential for further similar uses with these or other bioaccumulating chemicals, for example PFAS (Per- and polyfluoroalkyl substances), that might have effects on other river organisms or processes.

3.2.5. *Microplastics*

Concern about the occurrence of plastics as pollutants in freshwaters is well established (Moore et al., 2011; Imhof et al., 2013; Jambeck et al., 2015), and predictions suggest that exports through rivers into the world's oceans are likely to grow substantially (Borrelle et al., 2020). Much of the work on rivers has focussed on microplastics - defined as plastic particles <5 mm (GESAMP, 2015; Avio et al., 2017; De Souza Machado et al., 2018; McNeish et al., 2018; Nelms et al., 2018), but there is still debate and uncertainty about potential impacts on animals. Initial work has investigated possible physiological (Holland et al., 2016; Horton et al., 2017; Windsor et al., 2019b) or molecular effects but field data are equivocal (De Souza Machado et al., 2018; McNeish et al., 2018). So far, only around a quarter of all freshwater studies have involved animal exposure of which assessments in birds have been a small minority (Muller et al. in review). However, work has included the White-throated Dipper in one of the first ever studies to illustrated the food-web transfer of microplastics in free-living birds.

Alerted by data indicating that around half of their invertebrate prey were contaminated (Windsor et al., 2019b), D'Souza et al., (2020) assessed the possible food-web transfer of microplastic to Dippers along the formerly polluted but recovering rivers of south Wales. Faecal and regurgitate analysis showed that adults had ingested microplastics, mostly as fibres, at 14 of the 15 sites surveyed, with concentrations increasing at more urbanised locations. Faecal analysis from altricial young also illustrated the inter-generational transfer of microplastic during nest provisioning. Important additional work used Fourier transform infrared spectroscopy to identify the multiple polymers present which included polyester, polypropylene, polyvinyl chloride and vinyl chloride copolymers, in turn linked to potential sources such as textile fibres from washed clothes. Aided again by previous fundamental studies on Dippers during the 1980s, D'Souza et al. (2020) were able to use energetic models derived from double-labelled water to calculate likely rates of plastic intake (Bryant and Tatner, 1988). Calculations suggested that adults were likely to ingest ~200 microplastic particles daily, while chicks were probably fed several thousand particles between hatching and fledging, but most of these were also voided by regurgitation or defecation (D'Souza et al., 2020).

Evidence of adverse effects from these loadings has not been documented. As with persistent pollutants reviewed above, therefore, the bioindicator value of Dippers in this case is to reveal the presence and food-web transfer of pollutants through freshwater ecosystems rather than clear eco-toxic effects. There is obvious potential for this same bioindicator function to be employed in other parts of the range of all five *Cinclus* spp. where microplastic contamination may vary (Muller et al. in review).

4. Beyond water quality: habitat quality, flow modification and climate

Beyond the effects of water quality and pollution, river ecosystems and their biodiversity are under pressure from other global changes that are recognised increasingly as interacting, multiple stressors (Ormerod et al., 2010; Birk et al., 2020). Understanding and diagnosing their effects is an important aspect of modern management responses aimed at slowing or reversing biodiversity decline – for example by addressing climate change, flow modification and habitat impairment (Tickner et al., 2020). Ecological indicators potentially have an important role, but how effectively might rivers birds such as Dippers contribute? We suggest two roles.

The first is in their response to stressors other than pollution. For example, the life histories of all five species of Dippers is closely related to geomorphological conditions along rivers, in particular through their distribution along high gradient streams where riffles and clear water provide access to foraging conditions and invertebrate prey (Ormerod et al., 1985a,b; Chen and Wang, 2010; Aragón et al., 2015). Habitat selection also involves features that are often modified by human activity such as riparian tree cover, nest sites and substratum conditions at risk from anthropogenic sedimentation (Buckton and Ormerod, 1997; Vaughan et al., 2007; Larsen et al., 2010). The potential effects of such modifications have been quantified on different continents using standardised hydro-morphological recording methods that show how Dippers and other river birds could act as indicators of anthropogenic habitat impairment at the channel, riparian and catchment scales (Manel et al., 2000; Sinha et al., 2019; Tamang et al., 2023). Vaughan et al. (2007) suggested that indicator development using Dippers and other river birds for these pressures could have value to public communication as well as biodiversity conservation because of the wider public interest in birds generally. At the same time, indicator approaches need careful development to separate anthropogenic from natural effects on distribution and abundance.

The distribution of river birds, including Dippers, has also been linked widely to hydrological regimes in rivers through effects of both extreme events and average conditions that affect geomorphological structure and prey dynamics (Royan et al., 2013). Dippers throughout their range are postulated to synchronise their life-cycle events, especially breeding, to variations in the annual hydrograph. However, evidence of effects of modified flow patterns through energy generation or abstraction is scarcer (Silverthorn et al., 2018). There is some debate about whether the effects of modified flows on Dippers might be positive (e.g. through flow stabilisation and enhanced foraging opportunity) or negative (e.g. through increased predation risk and reduced foraging opportunity), and more data are needed (D'Amico et al., 2000).

Changing discharge patterns also figure strongly in the effects of climate change on stream and river organisms. The array of climate change pressures is complex, involving changing flow, impacts on resource availability, changing thermal regimes and altered oxygen solubility. In temperate regions the effects appear to be negative, though patterns differ in other biogeographical regions (Durance and Ormerod, 2007; Pye et al., 2023; Larsen et al., 2023). Dippers appear to respond to climatic effects directly, for example through advanced laying at higher temperature (Nilsson et al., 2020), but also indirectly, through changes in prey abundance. Long-term evidence shows that inter-annual survival in Dippers at temperate latitudes declines at higher discharge which can reduce prey numbers and also disrupt breeding onset (Marzolin, 2002; D'Amico et al., 2003; Chiu et al., 2013a,b). Royan et al. (2015) have predicted that these climatic effects on discharge could reduce the occurrence of Dippers in the temperate UK, with both low flows and flow magnitude involved. In contrast, studies at higher sub-arctic latitudes suggest that increased discharge promotes earlier breeding, although the mechanism appears to be linked to ice-free conditions and access to prey supplies (Nilsson et al., 2020). Also at northern latitudes in Scandinavia, increasing temperature and higher river flows mediated by climate change has been shown to increase both survival and population size in Dippers (Nilsson et al., 2011, 2019; Saether et al., 2000). In combination, these effects imply that Dippers could provide valuable indications about the ecological effects of climate change, but the patterns may be context-specific depending on whether changes in temperature, flow and prey abundance are negative or positive under local conditions. Some of the observed effects of discharge and temperature on Dippers and their prey also reflect quasi-natural variation in climate caused by oceanic systems such as the North Atlantic Oscillation (Nilsson et al., 2019; Larsen et al., 2023). Further developments in the use of Dippers as climate change indicators would this require separation of such effects from direction climate change.

A second role for the use of Dippers in indicating non-chemical stressors is in identifying confounding factors or improving indicator models by accounting for other influences on distribution or fitness. Examples include separating the effects of altitude and land use on Dipper distribution in the Himalayan mountains (Manel et al., 2000), accounting for altitude when assessing climatic effects on fitness (Nilsson et al., 2019, 2020) and accounting for altitudinal migration when assessing contaminant burdens (Morrissey et al., 2004). Specifically with respect to water quality, distribution models for Dippers were most effective when measures of habitat quality and acid-base status were included simultaneously (Brewin,Buckton and Ormerod, 1998). The implication in all these cases is that multi-variate measurements or models incorporating physical data can enhance bioindicator value.

5. Conclusions, future directions and caveats

Much of the above work reveals how Dippers, particularly from the two species present respectively in Europe and N. America, have been revealed as valuable bioindicators in river ecosystems. Following observations during the early 1980s that Dippers were influenced by prey abundance and water quality, they have now been used to reveal pollutants either indirectly through their abundance and fitness, or directly through contaminant measurement. Initial assessment of the effects of stream acidification and eggshell thinning led not only to the need to understand prey use, but also to eliminate the possibility that other contaminants might have confounded acidification effects thus paving the way for many subsequent studies. These have ranged from assessing relationships with other pollution effects on invertebrate numbers, measuring chemical contaminants with clear risks to wildlife or assessing the food-web transfer of emerging pollutants, such as microplastics. Spatial patterns relating contaminant burdens to putative sources have sometimes been equivocal, for example for selenium. In other cases, however, variations have been identified that range from the detection of point sources of PCBs to large scale differences in persistent pollutants shown by comparing two Dipper species with near-identical links to freshwater ecosystems on two continents.

In addition to these established uses of Dippers as bioindicators, we suggest that there are further potential developments, especially i) in other parts of the range of the well-studies species (e.g. Mexico for *C. mexicanus* and Southern Europe or North Africa for *C. cinclus*); ii) as the effects of global change interact increasingly with existing pressures through habitat modification, flow modification and altered temperature and iii) in other Dipper species distributed in South America and Asia. Opportunities also are available to assess other pollutants that might either occur in tissues (e.g. PFAs) or affect their prey (e.g. pharmaceuticals, agricultural chemicals, urban wastewater). In some of these cases, for example climate change, effects will be context specific and require bespoke local indicator methods.

Finally, we emphasise that there are caveats and uncertainties in the use of Dippers as indicators that might offer lessons about the development of biological indicators more generally. In some cases, Dippers have provided generic rather than specific indications of water or habitat quality in which additional environmental data were required to aid the diagnosis of causes and effects. Moreover, throughout all the uses of Dippers as bioindicators so far, fundamental ecological studies of associated life history patterns have aided interpretation. Examples include assessments of prey use, territoriality, dispersal, migration, breeding performance, isotopic signatures and energetics. We expect that new developments in ecology and biology will expand fundamental understanding further, for example through molecular studies such as the expanding uses of 'omics and modern uses of ecological genetics.

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CRediT authorship contribution statement

Vera N. Maznikova: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization. **Steve J. Ormerod:** Conceptualization, Investigation, Data curation, Writing – original draft, Writing – review & editing, Supervision. **Miguel Ángel Gómez-Serrano:** Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration.

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.

Data availability

No new data were used for the research described in the article.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2023.111366.

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