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Review Paper

Mitigation and management plans should consider all anthropogenic disturbances to fauna

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A B S T R A C T

The direct impacts of anthropogenic habitat loss on fauna have attracted considerable global research focus. However, it is not only these overt impacts of human activities that are contributing to the global biodiversity crisis. Other disturbances, such as artificial light, anthropogenically generated noise, dust, vibrations, and physical visual disturbances (e.g., foreign objects such as Unmanned Aerial Vehicles - UAVs) may be subtle or indirect, yet capable of creating significant impacts to fauna. These disturbances have previously been termed 'enigmatic impacts', suggesting they may be difficult to quantify or address. While there has been little research focus towards the mitigation or remediation of these impacts in conservation and restoration planning, a growing body of literature demonstrates that they can be disruptive and damaging to animal populations at multiple spatial and temporal scales. Here, we present a global review of the empirical evidence for disturbances (excluding direct habitat loss) that result from anthropogenic activities, developments, and industries, which are deleterious to the natural ecology of fauna species or communities. Although the impacts of disturbances such as vibrations and visual disturbances on fauna have attracted little research focus, disturbances created by human activities are clearly capable of causing significant disruptions and adverse impacts to fauna. Understanding how such disturbances impact fauna is critical to returning functional and biodiverse fauna communities to landscapes and environments that have been impacted or degraded by human activities.

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1. Introduction

Anthropogenic activities have affected over 75% of the world's terrestrial ecosystems and few areas remain ecologically pristine (Sanderson et al. 2002; Watson et al. 2016). The continued, and rapidly increasing, use of natural resources is resulting in significant environmental change and habitat destruction globally (Dobson et al. 1997; Tilman et al. 2001; Sanderson et al. 2002; Sih et al. 2010; Watson et al. 2016; Cross et al. 2020). Habitat loss is a leading global threat to biodiversity, driving substantial rates of species extinctions (May and Tregonning, 1998; Kerr and Deguise 2004; Fischer and Lindenmayer 2007). Habitat and landscape alteration have been the focus of much conservation research (Fazey et al. 2005; Fischer and Lindenmayer 2007), and their impacts on fauna have been well studied across a range of ecosystems (Fardila et al. 2017). However, it is not only these overt impacts of human disturbances that are threatening ecological functioning and biodiversity. Human activities affect ecosystems at vastly broader scales than the immediate removal of vegetation from landscapes for infrastructure or agricultural and urban development (e.g., Coffin 2007; Balmford et al. 2009; Kight and Swaddle 2011).

Human activities inevitably create other types of disturbances that may be subtle, indirect, and unintentional, yet are capable of propagating over large spatiotemporal scales to represent significant impacts for faunal populations and communities (Raiter et al. 2014). Such disturbances encompass a diverse array of effectors including anthropogenic noise, artificial light, vibrations, visual disturbance (e.g., from foreign objects), dust, and contamination (Kight and Swaddle 2011; Manfrin et al. 2017; Fettermann et al. 2019; McClelland et al. 2019). These can result in a range of cryptic, complex, and potentially cascading impacts to ecosystems (Keller and Largiadèr 2003; Dixon et al. 2007; Raiter et al. 2014). For example, noise pollution generated by vehicle traffic and heavy machinery use can disrupt communication and mating behaviour (e.g., Verzijden et al. 2010; Injaian et al. 2018a), and light pollution can disrupt activity periods and foraging behaviour of a range of fauna (e.g., Titulaer et al. 2012; Lewanzik and Voigt 2017). Dust deposition and heavy metal contamination of soil and water through run-off can result in bioaccumulation of heavy metals in animals through consumption of contaminated plants or other animals, significantly impacting fitness, physiology, and eliciting stress responses (Green and Larson 2016; Shah et al. 2018; Caballero-Gallardo et al. 2018). These may even arise from direct disturbances to ecosystems, for example a loss of genetic connectivity and diversity through fragmentation and habitat loss. These not only directly impact habitats immediately surrounding disturbances, but likely cause significant adverse impacts at considerable distances from anthropogenic activities (Vistnes and Nellemann 2001; Benítez-López et al. 2010). Furthermore, impacts can potentially erode populations subtly until they reach a threshold beyond which they are no longer viable and rapidly decline.

These disturbances have previously been termed 'enigmatic impacts', as they may be difficult to detect, quantify, or attribute, and their effects may be cumulative, offsite, or cryptic (Raiter et al. 2014). Such terminology implies difficulty in their interpretation, and Raiter et al. (2014) suggest that these disturbances are subsequently likely to 'slip under the radar' in environmental impact assessments. While, as Raiter et al. (2014) propose, these disturbances may be poorly considered in a restoration and conservation context, a growing body of literature demonstrates how the drivers and consequences of these disturbances can disrupt the diversity, abundance, fitness, and behaviour of numerous fauna (e.g., Choi et al. 2009; Thomas et al. 2016; Cabrera-Cruz et al. 2019). Furthermore, expanding research has demonstrated that the deleterious results from disturbances stem from sources already understood in a conservation context, including population genetics, animal physiology, and ecotoxicology (Köhler and Triebskorn 2013; Hing et al. 2016). While the mechanisms and outcomes are often familiar, the stimuli that trigger these responses tend to be poorly researched, lending the unexpected nature to these effects.

Here, we present a global review of the empirical evidence for anthropogenic disturbance that affect the behaviour, physiology, mortality, genetics, abundance, or diversity of vertebrate and invertebrate fauna. For the purposes of this review, we include any anthropogenically generated disturbance (excluding direct habitat loss) where the industry resulting in the disturbance is stated. We aim to determine whether, i) these disturbances generated by industry or developments have been empirically detected and quantified in terms of their impact to fauna, ii) whether there is evidence that these types of disturbances individually or interactively damage fauna communities, and iii) whether current research considers mitigation and management of secondary disturbances.

2. Methods

2.1. Literature search

We conducted a comprehensive search of the peer-reviewed literature assessing the impacts of any form of disturbance generated by anthropogenic activities on fauna globally. We excluded studies of the direct effects of habitat loss, but included those assessing the secondary impacts resulting from habitat loss (e.g., genetic isolation through habitat fragmentation). Separating the two, however, is difficult as both are contributory to the other (Ewers and Didham 2006). For example, contamination of watercourses with heavy metals or petrochemicals might represent a direct habitat loss for aquatic biota, as those watercourses may no longer be capable of supporting aquatic fauna communities. To terrestrial fauna communities, however, a reduction of the quality of water resources, rather than a complete loss of habitat, might be considered a secondary impact. For the purposes of this review, we included all literature assessing a form of anthropogenic disturbance (excluding direct habitat loss) where the industry or development resulting in the disturbance was reported. Other forms of anthropogenic ecosystem degradation that impact fauna, but do not directly state the industry generating the disturbance were excluded (e.g., marine plastic pollution: Galgani and Loiselle 2021). We used three databases to compile the literature: Google Scholar (last searched October 31st· 2020), Scopus (all documents including secondary documents, last searched October 31st· 2020), and Web of Science (all databases and years (1972–2020), last searched October 31st· 2020). We obtained additional references from the bibliographies of published literature. All empirical, peer-reviewed journal publications were included, while review papers were excluded after the inclusion of relevant primary literature from bibliographies. The final database comprised 449 publications.

To understand the entirety of how a disturbance threatens fauna, it is critical to determine the mechanism of the threat (e.g., type of disturbance), and the source of the disturbance (Balmford et al. 2009). As such, our literature search was constructed to incorporate three broad criteria. The first criterion was a broad context that sought to capture only research into degradation resulting from human activity (search terms comprised any combination of 'anthropogenic', 'enigmatic', or 'indirect', AND 'impact', 'disturbance', or 'effect'). The second attempted to capture the broadest array of potential effectors of such impacts on animals (encompassing the terms 'noise', 'dust', 'light', 'vibration', 'contamination', or 'habitat fragmentation', AND 'animal', 'fauna', 'vertebrate', or 'invertebrate'). Finally, the third aimed to expand the array of applied contexts and effectors under whose auspices the research may have been conducted or published (including the terms 'agriculture', 'urbanisation', 'mining', 'tourism', 'fishery', 'marine', 'aviation', 'roads', 'wind turbines', 'factory', 'forestry', or 'construction'). Literature were sorted by publication date, origin of study, target taxa, type of industry, and type of disturbance (e.g., noise, air/dust, contamination, vibration, visual interference-foreign objects, light, or secondary habitat loss).

Finally, we attempted to identify whether the existing literature addresses the importance of considering these disturbances in mitigation and management planning. Successful conservation hinges both on understanding how anthropogenic disturbances impact fauna, and understanding the goals of conservation, the actions required to meet goals, and how conservation outcomes can be improved (Salafsky et al., 2002). While complex, understanding these issues at the highest feasible level will assist in the design, development, and implementation of successful mitigation and conservation efforts (Margoluis et al. 2009).

As such, publications were assigned one of three study classes: 'research only', those that reported research findings with no commentary on management or conservation implications; 'management needed', those that identified a need for conservation, management, or mitigation strategies from research findings; and 'management proposed', those that examined or proposed methods of management or mitigation of the studied disturbances. The discussion section of all papers was searched for the keywords 'mitigation', 'management', 'conservation', 'restoration', or 'rehabilitation'. Publications were assigned 'research only' if searches returned no results, 'management needed' if the publication discussed or mentioned a need for mitigation, conservation, or management strategies, and 'management proposed' if the publication proposed or presented examples of one or more methods for mitigation and management of disturbances.

Studies were first grouped based upon their geographic location (both continent and regional location), industry, and type of disturbance, to identify any regional or industry-type biases. We then grouped studies based upon the target fauna group and taxa to identify the extent to which assessments of the impacts of disturbances on ecosystems considered fauna. Finally, we assessed whether publication date, study location or industry exhibited any association with type of disturbance, target fauna groups or taxa. Eight variables were included in analyses: (1) publication date, (2) continent of study, (3) origin of study (countries or oceans), (4) target group (vertebrate, invertebrate, or both), (5) target taxa, (6) type of industry, (7) type of disturbance, and (8) type of study (e.g., behaviour, physiology and fitness, genetics). Studies assessing the impact of air quality or particulate matter (dust) were grouped into the disturbance category 'air/dust', and those assessing any form of contamination by heavy metal (i.e., through runoff or contamination of water sources) were grouped into 'contamination'. Publications assessing any impact on the physiology or health of fauna, including studies of bioaccumulation, contamination, or mortality, were grouped into one category (mortality and physiology). All anthropogenically made linear structures such as roads and railways were assigned to the group 'linear infrastructure'. Wind farms were included in the industry type group 'energy production'. Publications were grouped by decade (1971–1980, 1981–1990, 1991–2000, 2001–2010, and 2011–2020) to determine if there were any differences in publication output over time. Pearson's Chi-square tests were employed to analyse differences between all categorical variables, using the R3.4.4 statistical environment (R Core Team 2016)..

3. Results

3.1. Overview

The 449 included publications presented the impacts of disturbances on fauna from 11 industry or development types, most commonly urbanisation (121 publications, 26.9%), linear infrastructure (105 publications, 23.4%), and marine industries (80 publications, 17.8%). The impacts from multiple industries were presented in 27 publications (6%). Studies reported seven effectors of disturbance, most commonly the impact of anthropogenic noise (188 publications, 41.8%), followed by secondary habitat loss (92 publications, 20.5%), artificial light (82 publications, 18.3%), contamination (40 publications, 8.9%), visual interference (e.g., foreign objects such as UAVs or anthropogenic structures; 14 publications, 3.1%), dust or air pollution (14 publications, 3.1%), and vibration (2 publications, 0.4%). The response of fauna to multiple effectors were considered in 17 publications (3.8%). Of those that assessed multiple forms of disturbance, most assessed the impacts of two disturbances (15 publications), with six publications assessing the impact of both noise and vibration, five assessing anthropogenic noise and artificial light, and one each assessing vibration and contamination, air pollution and noise, light and secondary habitat loss, and noise and secondary habitat loss. The remaining two studies assessed three effectors each: contamination, noise, and light, and noise, light, and secondary habitat loss.

Studies presenting behavioural responses of fauna to disturbance were over-represented in the database (235 publications, 52.3%, $\chi2 = 260.51$, *d.f.* = 3, $P < 0.001$), with fewer studies assessing mortality or physiological responses (98 publications, 21.8%), changes in species abundance, richness, or density (78 publications, 17.4%), and impacts upon genetics (8 publications, 1.8%). The remaining 27 studies assessed multiple types of responses (6%), with 21 assessing physiology/mortality and behaviour, five assessing physiology/mortality and species diversity/abundance, and one study assessing both behaviour and species diversity/abundance. The majority of publications presented data on vertebrates (393 publications, 87.5%), predominantly mammals (164 publications) and birds (122 publications). Only slightly over 10% of studies (50 publications) presented data on invertebrates, and only six publications (1.3%) considered both invertebrates and vertebrates.

3.2. Year and origin of publication

Nearly three-quarters of all studies had been published within the last decade (326 publications, $\chi2 = 848.47$, *d.f.* = 4, $P < 0.001$; Fig. 1a), and publication output increased steadily over that period (Fig. 1b). Publications originated from 65 regional locations (e.g., countries, islands or oceans), with representation from all seven continents (Fig. 2). Only three publications presented data from multiple continents. Excluding publications not stating a specific study location (six publications), there was a strong geographic bias toward Europe and North America ($\chi2 = 401.68$, *d.f.* = 6, $P < 0.001$). The majority of North American literature originated from the United States (108 publications). Almost half (30 locations, 46.2%) of all recorded study locations resulted in only a single report assessing the disturbances of anthropogenic activities on fauna, with just 11 locations producing 10 or more publications (16.9%).

Disturbances generated by urbanisation (121 publications, 26.9%), linear infrastructure (105 publications, 23.4%), and marine industries (80 publications, 17.8%) were the primary focus of the literature ($\chi2 = 480$, *d.f.* = 10, $P < 0.001$; Table 1). Publications were significantly more likely to assess the impacts of anthropogenic noise on fauna than any other disturbance effector (188 publications, 41.8%, $\chi2 = 419.44$, *d.f.* = 6, $P < 0.001$), with the impacts of secondary habitat loss (92 publications, 20.5%) and artificial light (82 publications, 18.3%) on fauna the next most common forms of disturbance assessed. Few publications assessed the impacts of visual disturbances such as foreign objects (14 publications, 3.1%), or vibration (2 publications, 0.4%) on fauna.

3.3. Fauna

Publications predominantly reported responses of vertebrate fauna to disturbances (393 publications, 87.5%; $\chi2 = 461.99$, *d.f.* = 1, $P < 0.001$). Only 50 (11.1%) publications assessed invertebrate responses, and six (1.3%) publications assessed the responses of both vertebrate and invertebrate fauna. Much of the literature for both invertebrate ($\chi2 = 41.10$, *d.f.* = 5, $P < 0.001$) and vertebrate studies ($\chi2 = 335.37$, *d.f.* = 6, $P < 0.001$) originated from Europe, and vertebrate fauna were equally

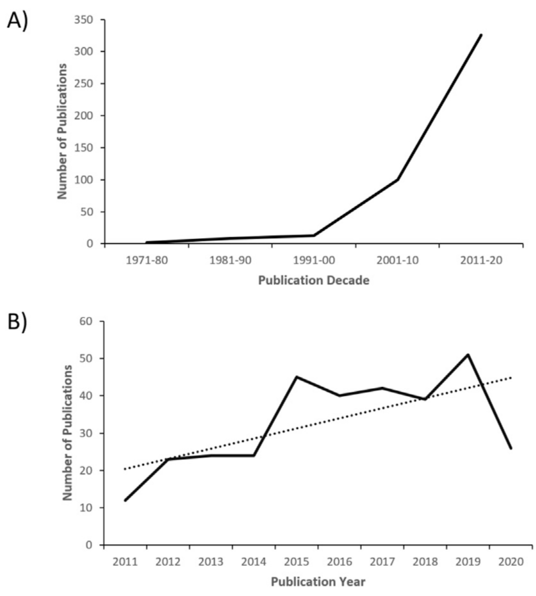

Fig. 1. Number of publications assessing the impacts of disturbances on fauna (invertebrates and vertebrates) by publication decade (A; $n = 449$) and by year within the last decade (B; $n = 326$). The dotted line in Fig. 1b represents the linear trend line fitted to publication output over time.

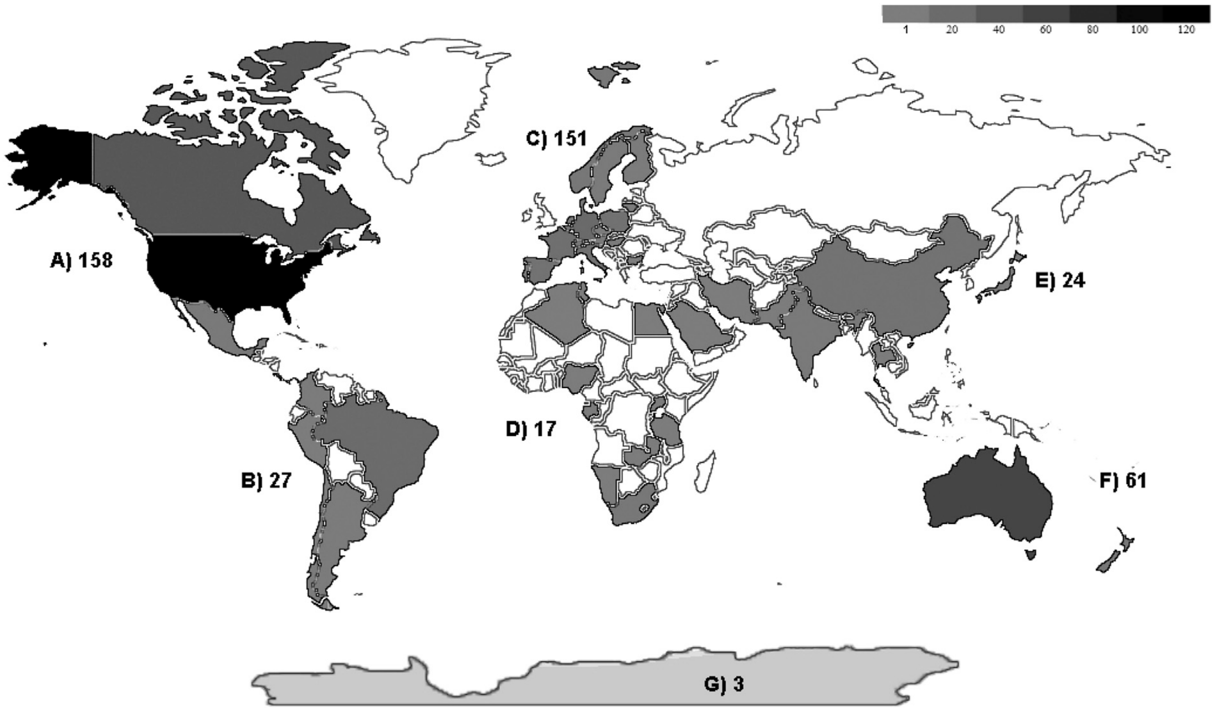

Fig. 2. Heat map of publications presenting data from terrestrial biomes assessing the disturbances of anthropogenic activities on fauna. Total publication numbers by continent are shown for A) North America, B) South America, C) Europe, D) Africa, E) Asia, F) Australasia (including New Zealand), and G) Antarctica. Source industry and disturbance effectors.

common targets in North American studies. Globally, insects were the primary focus for invertebrate publications (16 publications, 38.1%), and assessments of vertebrate responses favoured mammals (169 publications, 40.3%) and birds (122 publications, 30%). Mammals and birds were the primary focus for assessments across all industries and disturbance types, apart from those assessing impacts generated by the forestry industry ($\chi2 = 14$, *d.f.* = 11, $P = 0.233$), or those assessing the impacts of vibration on fauna ($\chi2 = 10$, *d.f.* = 11, $P = 0.530$), which had small sample sizes ($n = 4$ and $n = 2$, respectively). A summary of the literature for impacts to fauna resulting from each type of disturbance can be found in Table S2 (Supplementary Material).

3.4. Research objective

Almost half of all publications reported empirical evidence without direct mention to conservation, management, or mitigation implications (216 publications, 48.5%). Over half of the remaining studies (122 publications) provided one or more suggestions for mitigation or management strategies for the particular disturbance assessed (Table 1), while 107 publications (46.7%) recognised there was a need for management or mitigation. Of the research that offered potential management and mitigation solutions, the majority focused upon linear infrastructure (37 publications, 30.3%), urbanisation (31 publications, 25.4%), and marine industries (16 publications, 13.1%; $\chi2 = 158.85$, *d.f.* = 10, $P < 0.001$).

Papers that provided management implications were biased towards the impacts of secondary habitat loss (46 publications, 37.7%), noise (44 publications, 36.1%), and artificial light (25 publications, 20.5%; $\chi2 = 133.095$, *d.f.* = 5, $P < 0.001$). These papers overwhelmingly favoured assessments for vertebrate responses (114 publications, 93.4%; $\chi2 = 92.10$, *d.f.* = 1, $P < 0.001$), with mammal (48 publications, 45.3%) and bird species (36 publications, 34%) the main target of studies ($\chi2 = 72.58$, *d.f.* = 4, $P < 0.001$), excluding those assessing multiple targets. Few studies offering management or mitigation strategies targeted invertebrate species (8 publications, 0.7%), and there was no apparent bias towards a particular group ($\chi2 = 2.29$, *d.f.* = 4, $P = 0.683$). The majority of the literature which sought to provide suggestions for management or mitigation strategies originated in North America (46 publications, 37.7%), Europe (36 publications, 29.5%), or Australasia (23 publications, 18.9%; $\chi2 = 81.20$, *d.f.* = 5, $P < 0.001$).

4. Discussion

Sufficient evidence is available in the literature to identify that the impacts of anthropogenically generated disturbances are not poorly understood (although some disturbances are clearly better understood than others are), nor are their impacts

Table 1
Number of publications assessing the impact of disturbances generated by human development and industries on fauna. Number of study continents, animal groups, and publications providing research only, detailing the need for conservation and management, or providing methods for mitigation and management are given for each disturbance and industry. Publication totals exclude papers for which studies originate from multiple regions, or those assessing multiple animal groups. A full list of the publications used in this review are provided in Tables S1 and S3 (Supplementary Material). *Indicates that papers are a subset of those that indicate a need for conservation or management strategies. **Indicates a category containing one or more papers where article access was unable to be gained.

Effectors	Industries	No. Publications	No. continents	No. Animal groups	Research Only	Management needed	Management proposed*
Air/Dust (***n*** **= 14, 3.1%)**	Factory/Construction	1 (7.1%)	1	1	0	1	0
	Linear Infrastructure	1 (7.1%)	1	1	1	0	0
	Mining/Metal works	8 (57.1%)	4	4	8	0	0
	Urbanisation	3 (21.4%)	2	1	3	0	0
	Multiple	1 (7.1%)	1	1	1	0	0
Contamination (***n*** **= 38, 8.5%)**	Agriculture	4 (10.5%)	3	3	2	2	0
	Energy production	2 (5.3%)	2	1	2	0	0
	Linear Infrastructure	4 (10.5%)	2	4	3	1	0
	Mining/Metal works	15 (39.5%)	6	6	12	3	1
	Munitions	1 (2.6%)	1	1	0	1	1
	Urbanisation	10 (26.3%)	4	5	9	1	0
	Multiple	2 (5.3%)	2	1	2	0	0
Light (***n*** **= 82, 18.3%)**	Agriculture	2 (2.4%)	2	1	1	1	0
	Energy production	1 (1.2%)	1	1	0	1	1
	Linear Infrastructure	1 (1.2%)	1	1	0	1	1
	Marine	2 (2.4%)	1	1	2	0	0
	Urbanisation	73 (89%)	6	9	39	34	21
	Multiple	3 (3.7%)	3	2	0	3	2
Noise (***n*** **= 188, 41.8%)**	Aviation	7 (3.7%)	4	2	2	5	3
	Energy production	15 (8%)	3	2	10	4	3
	Factory/Construction	12 (6.4%)**	3	3	2	8	6
	Linear Infrastructure	43	6	4	19	23	9
	Marine	(22.9%)**	5	7	37	36	15
	Mining/Metal works	74	3	3	4	2	0
	Tourism	(39.4%)**	3	2	0	4	2
	Urbanisation	6 (3.2%)	4	5	11	7	3
	Multiple	4 (2.1%)	3	3	4	5	3
		18 (9.6%)					
		9 (4.8%)					
Secondary Habitat Loss (***n*** **= 92, 20.5%)**	Agriculture	3 (3.3%)	3	2	2	1	1
	Aviation	1 (1.1%)	1	1	0	1	1
	Energy production	3 (3.3%)	2	2	2	1	0
	Forestry	4 (4.3%)	3	3	3	1	1
	Linear Infrastructure	54 (58.7%)	6	5	10	44	27
	Marine	3 (3.3%)	2	3	0	3	1
	Mining/Metal works	1 (1.1%)	1	1	0	1	1
	Tourism	3 (3.3%)	2	2	0	3	2
	Urbanisation	10 (10.9%)	4	3	2	8	6
	Multiple	10 (10.9%)	3	3	1	9	6
Vibration (***n*** **= 2, 0.5%)**	Factory/Construction	1 (50%)	1	1	0	1	1
	Multiple	1 (50%)	1	1	1	0	0
Visual (***n*** **= 14, 3.1%)**	Aviation	14 (100%)	4	2	8	6	3
Multiple (***n*** **= 20, 4.5%)**	Energy production	3 (15%)	2	1	1	2	0
	Factory/Construction	3 (15%)	1	3	2	1	0
	Linear Infrastructure	2 (10%)	1	1	0	2	0
	Marine	1 (5%)	1	1	1	0	0
	Mining/Metal works	3 (15%)	2	2	3	0	0
	Urbanisation	7 (35%)	4	4	5	2	1
	Multiple	1 (5%)	1	1	1	0	0

on fauna unquantifiable. We identified 469 publications from ecosystems on all seven continents assessing the impact of some form of anthropogenically generated disturbance on fauna. Many provide empirical evidence that these disturbances have numerous and significant influences on the abundance, physiology, fitness, behaviour, and species composition of fauna communities. However, a clear bias is evident in the international literature towards the study of anthropogenic noise and artificial light on fauna behaviour, primarily in the context of urbanisation and vehicle traffic along linear infrastructure and shipping routes. Concerningly, the impacts on fauna of these disturbances appear to be largely overlooked in the context of environmental restoration and conservation, as was proposed by Raiter et al. (2014). Additionally, comparatively few studies examining disturbances address the need for conservation or management strategies, providing no or few suggestions for potential mechanisms by which their impacts on fauna might be mitigated or managed. Generally, mitigation and management mechanisms were proposed largely in the context of linear infrastructure, urbanisation, and marine industries, and overwhelmingly to address the impacts of secondary habitat loss, noise, and artificial light.

Anthropogenic noise and artificial light are pervasive sources of disturbance in urban areas, and pose considerable threats to fauna in these environments (Newport et al. 2014). Over half of the world's population live in urbanised environments, with development and supporting transport infrastructure expanding rapidly and continuously to accommodate population growth (Turner et al. 2004; Garden et al. 2006). Indeed, the urban environment is one of the few environments expanding globally (Miller and Hobbs 2002; Dearborn and Kark 2010). With continued urban growth and infrastructure development, it is unsurprising that the impact of urban disturbances on fauna has received considerable research interest. However, despite there being evidence for other effectors of anthropogenic disturbances such as contamination, foreign objects, and vibration having clear and significant impacts on fauna physiology, behaviour, and mortality (e.g., Roux and Marra 2007; Wang et al. 2014; Caballero-Gallardo et al. 2018; Rümmler et al. 2018; McClelland et al. 2019), these disturbances have received comparatively little research focus. Generally, however, it is noteworthy that the output of studies assessing disturbances of human industries on fauna has increased rapidly within the last decade.

4.1. Dominant vectors of secondary disturbances

Anthropogenic noise was the most broadly and commonly studied category of impact vector. Anthropogenically generated noise represents a global threat to fauna (Slabbekoorn and Ripmeester 2007; Kight and Swaddle 2011; Newport et al. 2014), being typically much louder and occurring with greater rate than natural noises from wind or water (Kight and Swaddle 2011; Newport et al. 2014). Particularly, we found many studies assessing road noise in urban areas (e.g., Yoshida et al. 1997; Li et al. 2002; Murthy et al. 2007), reporting diverse impacts on mating, communication, and foraging behaviour (Verzijden et al. 2010; Kern and Radford 2016; Injaian et al. 2018), species diversity and abundance (Wiącek et al. 2015; Khanaposhtani et al. 2019), and fitness and physiology (Crovo et al. 2015; Injaian et al. 2018). Traffic networks are vast and growing globally, and are a significant source of anthropogenic noise (Siemers and Schaub 2010).

Noise pollution is not limited to linear infrastructure and vehicle traffic, however. For example, boating noise has attracted increasing attention and has been tentatively linked to the disruption of migratory behaviour of marine mammals (Nowacek et al. 2007). Research is lacking into the impacts of noise on fauna from other industries that also generate substantial noise pollution, such as mining or oil and gas extraction (Rylander et al. 1974; Blickley et al. 2012; Shannon et al. 2016), and aviation (Newport et al. 2014). Noise from extractive or aviation industries is clearly capable of significantly disrupting the behaviour and activity of numerous fauna taxa (e.g., Burger 1981; Wolfenden et al. 2019), and greater study of the impacts from these industries could yield valuable data. Similar future study should better elucidate the impact of vibrations on fauna. Vibration and noise are intrinsically linked, as vibrations themselves can create airborne noise (Talty 1998), and there is evidence that vibrations from human activities may significantly influence fauna behaviour and physiology, particularly those relating to auditory senses and acoustic behaviours (Wang et al. 2014; Caorsi et al. 2019).

Artificial lighting is ubiquitous throughout urbanised landscapes, with usage rapidly growing globally (Hölker et al. 2010; Davies et al. 2013; Robert et al. 2015). The majority (66%) of literature examining artificial light did so in the context of urban environments. Artificial light can impact the behaviour of bird species by altering sleep patterns (Raap et al. 2015, 2018), activity periods (Borchard and Eldridge 2014), and changing foraging behaviours (Dupont et al. 2019), and can trigger changes to breeding biology including breeding site selection, breeding periods and success, and hatchling behaviour (Raap et al. 2016; Russ et al. 2017). Furthermore, the spatial scale of light pollution can be difficult to quantify because it potentially affects fauna by linking at a global scale. Many animal migrations are undertaken nocturnally (e.g., Able 1970; Feng et al. 2006; Alerstam et al. 2011), and although visual cues are clearly important it remains unclear exactly what navigational cues are required (Warrant and Dacke 2010). Where migrations take place at a global scale, light pollution may be influential across a large number of jurisdictions, and may cause effects in ecosystems far beyond the source of the effector if, for example, a species critical to the seasonal patterns of the ecosystem does not arrive reliably (e.g., Gibson et al. 2018). Despite the overwhelming focus on noise impacts from urban areas, many industries are likely responsible for analogous impacts with which they are currently unfamiliar.

Habitat loss and land use change not only directly affects ecosystems through removal of habitat for fauna, but also have numerous secondary impacts such as a loss of genetic diversity or connectivity through decreased ability for animals to disperse across landscapes (Keller and Largiadèr 2003; Ewers and Didham 2006; Dixon et al., 2007). Fragmentation of habitats may also increase mortality risks of animals attempting to cross between habitat patches separated by roads or development (Cuyckens et al. 2016; Delgado et al. 2018; Hastings et al., 2019), or contribute to population reductions through facilitating illegal poaching and greater wildlife trade through increased access provided by road networks (Raiter et al. 2014). Fragmentation may also exaggerate or facilitate the impacts of predator species (Dawson et al. 2018), and habitat fragmentation may be particularly deleterious for rare species and short-range endemics which are typically restricted to specialised habitats and may face higher risks of extinction (Işik 2011; Spinozzi et al. 2012; Cross et al. 2020). Similar to patterns in the literature assessing the impacts of noise and light, the majority of studies examining secondary impacts of habitat loss on fauna were undertaken in the context of linear infrastructure or urbanisation. While the intertwined effects of habitat loss and habitat fragmentation are complex and difficult to disentangle (Mortelliti et al. 2010, 2012), we propose future studies should attempt to consider their impacts in a much broader range of ecological contexts.

The ecological impacts of dust and air quality on vegetation are relatively well studied. For example, particulate matter generated by human activities can reduce the photosynthetic ability of plants, erode leaf cuticles, and increase leaf necrosis (e.g., Farmer 1992; Rahul and Jain 2014), and dust deposition can negatively influence productivity of plants through contamination (Kovář 1990). However, comparatively little is known about how dust impacts upon fauna communities. Airborne, soil-borne and water-borne contaminants likely pose significant risks to the fitness and physiology of fauna communities, via ingestion of contaminated vegetation or water, inhalation of particulates, or bioaccumulation through trophic levels (Erasmus and De Villiers 1982; Dogra et al. 1984; Llacuna et al. 1993; Zocche et al. 2010; Lettoof et al. 2020). Bioaccumulation and contamination by heavy metals may be chronically deleterious to wildlife, altering physiology, elevating stress, and ultimately resulting in increased mortality or a reduction of fitness in numerous fauna species (e.g., Lourenço et al., 2011; Green and Larson 2016; Lettoof et al. 2020). These effects can be realised over very large spatio-temporal scales; for example, air-borne particles of up to 30 μm can be dispersed distances of up to 3000 km from the source disturbance (Tsoar and Pye 1987; Field et al. 2010).

A source of contamination and bioaccumulation that was surprisingly absent from studied literature was that of toxins released into the environment by agriculture. Despite several well-known examples of population decline and ecological cascades resulting from agricultural pest control or veterinary agents such as DDT (e.g., Carson 1962) or diclofenac (e.g., Oaks et al. 2004), contamination and bioaccumulation of these toxins appears to have received little research attention as a vector of secondary effect. Given the broad use of similar chemical agents outside of agriculture (i.e. glyphosate herbicides in weed management; Giesy et al. 2000), we suggest this is likely an important disconnect for future studies to remedy.

One notable emerging disturbance not considered by Raiter et al. (2014) are visual disturbances from non-natural objects such as Unmanned Aerial Vehicles (UAVs). UAVs likely disrupt the behaviours of many marine, terrestrial, and avian fauna (e.g., Lyons et al. 2017; Fettermann et al. 2019; Brunton et al. 2019), although the type and intensity of these disruptions appears to be highly idiosyncratic. Studies provide evidence of direct impacts from UAV operation to animal mortality and to altered behaviours (e.g., Dolbeer 2010; Lyons et al. 2017; Fettermann et al. 2019; Brunton et al. 2019), but it remains unclear how pervasive these effects are and the quantitative conservation threat they represent in different ecosystems and at various spatiotemporal scales.

5. Conclusions

The impact of anthropogenically generated disturbances on fauna has attracted considerable research attention, particularly in terms of the impacts of noise and artificial light. These impacts have been studied across a range of industries and fauna, across numerous contexts, although some impacts, such as vibrations or visual disturbances, remain largely understudied. However, disturbances clearly are capable of creating significant adverse impacts to community dynamics, behaviour, and physiology of diverse fauna from a range of trophic levels (e.g., Roux and Marra 2007; Slabbekoorn and Ripmeester 2007; Kight and Swaddle 2011; Wang et al. 2014; Lacoeuilhe et al. 2014; Robert et al. 2015). There does not appear to be a knowledge gap on these topics, although mechanisms for their mitigation and remediation appear infrequently considered.

If no knowledge gap exists, then why is there a perception of difficulty in the detection or quantification of these disturbances? Firstly, it is clear that many effectors have been well-studied in the context of one particular avenue of impact (i.e., the impacts of light pollution being overwhelmingly studied in the context of urbanisation). The other element that our literature review identified was how these disturbances are poorly understood in a restoration and conservation context. It is unclear whether this stems from a lack of realisation of the potential disturbances created by anthropogenic activities, a lack of funding, or as proposed by Raiter et al. (2014), because it may be 'convenient or politically expedient to ignore them from a development perspective'. Understanding how these disturbances impact fauna is critical, both to effectively conserving biota in remnant ecosystems and to returning functional and biodiverse fauna communities through ecological restoration to landscapes and environments that have been impacted or degraded by development (Raiter et al. 2014). Many of the effects identified in the literature illuminate the mechanisms by which the disturbances influence processes dictating the structure and function of animal population and communities, yet few offer specific suggestions for their mitigation or management. Failure to recognise the ecological impacts resulting from human development and industry risks creating complex, lasting deleterious impacts on the integrity, resilience and functioning of natural ecosystems. These impacts will likely accelerate the already alarming rates of species declines and extinctions being witnessed globally. Our review supports the apparent disconnect between those examining the impacts stemming from anthropogenic activity and communication of the implications of these impacts to industry and land managers responsible for their mitigation and management (Robinson 2006; Cook et al. 2013). In a world where the human impacts of climate change, land use change, and biodiversity loss are accelerating, delays in the communication of understanding to regulators, policy makers, and practitioners are unaffordable (Martin et al. 2012). It is critical we continue to expand empirical research into the diverse and complicated disturbances of human influence on animal populations, and on ecosystems more broadly, but it is vital that these findings are presented clearly and pragmatically so they may be better incorporated into ecological restoration and conservation biology.

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

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gecco.2021.e01500.

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