

Assessing the ecological and societal impacts of alien parrots in Europe using a transparent and inclusive evidence-mapping scheme

Rachel L. White^{1,*}, Diederik Strubbe^{2,3,4}, Martin Dallimer⁵, Zoe G. Davies⁶, Amy J.S. Davis², Pim Edelaar⁷, Jim Groombridge⁶, Hazel A. Jackson⁶, Mattia Menchetti^{8,9}, Emiliano Mori¹⁰, Boris P. Nikolov¹¹, Liviu G. Pârâu¹², Živa F. Pečnikar¹³, Tristan J. Pett^{6,19}, Luís Reino^{14,15}, Simon Tollington^{6,16}, Anne Turbé¹⁷, Assaf Shwartz^{18,*}

1 School of Pharmacy and Biomolecular Sciences, University of Brighton, Brighton, UK **2** Terrestrial Ecology Unit (TEREC), Ghent University, Ghent, Belgium **3** Center for Macroecology, Evolution and Climate, Natural History Museum of Denmark, University of Copenhagen, Copenhagen, Denmark **4** Evolutionary Ecology Group, University of Antwerp, Antwerp, Belgium **5** Sustainability Research Institute, School of Earth and Environment, University of Leeds, Leeds, UK **6** Durrell Institute of Conservation and Ecology, School of Anthropology and Conservation, University of Kent, Canterbury, UK **7** Department of Molecular Biology & Biochemical Engineering, University Pablo de Olavide, Seville, Spain **8** Dipartimento di Biologia, Università degli Studi di Firenze, Sesto Fiorentino (Firenze), Italy **9** Institut de Biologia Evolutiva (CSIC-UPF), Passeig Marítim de la Barceloneta 37, 08003 Barcelona, Spain **10** Dipartimento di Scienze della Vita, Università degli Studi di Siena, Siena, Italy **11** Institute of Biodiversity and Ecosystem Research, Bulgarian Academy of Sciences, Sofia, Bulgaria **12** Institute of Pharmacy and Molecular Biotechnology, Biology Department, Heidelberg University, Heidelberg, Germany **13** Faculty of Mathematics, Natural Sciences and Information Technologies, University of Primorska, Koper, Slovenia **14** CIBIO/InBIO-Centro de Investigação em Biodiversidade e Recursos Genéticos, Universidade do Porto, Vairão, Portugal **15** CEABN/InBIO-Centro de Estudos Ambientais 'Prof. Baeta Neves', Instituto Superior de Agronomia, Universidade de Lisboa, Tapada da Ajuda, 1349-017 Lisboa, Portugal. **16** The North of England Zoological Society, Chester Zoo, Chester, UK **17** Independent Researcher, Chicago Boulevard, 32000 Haifa, Israel **18** Human and Biodiversity Research Lab, Faculty of Architecture and Town Planning, Technion, Haifa, Israel **19** Earthwatch Europe, Mayfield House, 256 Banbury Road, Oxford, OX2 7DE, UK

Corresponding author: Rachel L. White (r.white2@brighton.ac.uk)

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* These authors contributed equally to this work.

Abstract

Globally, the number of invasive alien species (IAS) continues to increase and management and policy responses typically need to be adopted before conclusive empirical evidence on their environmental and socioeconomic impacts are available. Consequently, numerous protocols exist for assessing IAS impacts and differ considerably in which evidence they include. However, inclusive strategies for building a transparent evidence base underlying IAS impact assessments are lacking, potentially affecting our ability to reliably identify priority IAS. Using alien parrots in Europe as a case study, here we apply an evidence-mapping scheme to classify impact evidence and evaluate the consequences of accepting different subsets of available evidence on impact assessment outcomes. We collected environmental and socioeconomic impact data in multiple languages using a “wiki-review” process, comprising a systematic evidence search and an online editing and consultation phase. Evidence was classified by parrot species, impact category (e.g. infrastructure), geographical area (e.g. native range), source type (e.g. peer-review), study design (e.g. experimental) and impact direction (deleterious, beneficial and no impact). Our comprehensive database comprised 386 impact entries from 233 sources. Most evidence was anecdotal (50%). A total of 42% of entries reported damage to agriculture (mainly in native ranges), while within Europe most entries concerned interspecific competition (39%). We demonstrate that the types of evidence included in assessments can strongly influence impact severity scores. For example, including evidence from the native range or anecdotal evidence resulted in an overall switch from minimal-moderate to moderate-major overall impact scores. We advise using such an evidence-mapping approach to create an inclusive and updatable database as the foundation for more transparent IAS impact assessments. When openly shared, such evidence-mapping can help better inform IAS research, management and policy.

Keywords

evidence base, impact assessment, invasive alien species, monk parakeet (*Myiopsitta monachus*), ring-necked parakeet (*Psittacula krameri*), Psittaciformes

Introduction

The number of human-mediated species introductions has been increasing worldwide (Seebens et al. 2017), with invasive alien species (IAS – the subset that cause negative impacts) identified as a significant environmental, societal and economic threat (Pimentel et al. 2005; Vilà et al. 2010; Bellard et al. 2016; Paini et al. 2016; Bacher et al. 2018). As an international response, Aichi Biodiversity Target 9 of the Convention on Biological Diversity (CBD) states that, by 2020, IAS and their pathways should be identified and prioritised and priority species controlled or eradicated (CBD 2010). Legal instruments have been established to meet this target, including European Union (EU) legislation (Regulation No. 1143/2014). This regulation aims to set a common standard for combatting IAS across political jurisdictions at a multinational scale, underpinned by a list of IAS of Union Concern (Tollington et al. 2017; Carboneras et al. 2018). Robust prioritisation tools are therefore essential to target the limited available resources towards the most relevant species (i.e. those that are or will likely become invasive). Consequently, the last decade has seen the development of a diverse range of IAS risk assessment protocols which, collectively, evaluate entry, establish-

ment, spread and impact – differing considerably in their scope, approach, strengths and limitations (Roy et al. 2018).

Quantifying the magnitude of IAS impacts remains particularly challenging for various reasons (see Jeschke et al. 2014; Courchamp et al. 2017; Bartz and Kowarik 2019). In practice, most impact assessment protocols rely on searching for evidence of previous records of invader impacts. However, one important, but arguably under-recognised, way in which available protocols differ is in the type of evidence they consider. Firstly, in some protocols impact evidence needs to originate from the invaded area under assessment, but in other protocols can also be derived from other non-native ranges, species' native ranges, or even from captivity/cultivation. Secondly, some protocols only accept peer-reviewed evidence, whereas others allow inclusion of grey literature or expert opinion. Thirdly, study design is rarely differentiated, risking largely anecdotal observations to be considered as equally informative as experimental studies. Finally, although impacts of IAS can be positive or negative (Ricciardi et al. 2013, Simberloff et al. 2013), the fact that a noticeable change has occurred is often viewed negatively. Accordingly, most protocols focus on deleterious impacts and only few acknowledge so-called 'beneficial impacts' (Bartz and Kowarik 2019), despite their importance for making informed management decisions (Schlaepfer et al. 2011; Branquart et al. 2016). Efforts are therefore being made to produce standardised and globally applicable impact assessment protocols; e.g. Environmental Impact Classification of Alien Taxa, EICAT (Blackburn et al. 2014). Although available protocols increasingly require assessors to carefully document which studies are selected to provide information for impact assessments (e.g. Hawkins et al. 2015), limited attention has been paid to developing strategies for collating, organising and structuring this evidence in a transparent, openly accessible, inclusive and standardised manner.

An assessment of the consequences of accepting different types of evidence data on impact assessment outputs has yet to be conducted. However, the current disparity in accepted evidence potentially leads to ambiguous, difficult-to-repeat and even contested impact assessment outcomes (Kumschick et al. 2017; Matthews et al. 2017), when instead, it is vital that IAS management and policy decisions are underpinned by a robust and transparent impact assessment (Courchamp et al. 2017; Vanderhoeven et al. 2017). This would, for example, help minimise stakeholder and societal conflicts arising from IAS control actions and is especially important for managing charismatic invaders (IAS with widespread popular appeal), such as many pet bird species, given the often strong public objection against their control (Crowley et al. 2019). Consequently, we suggest the implementation of a general scheme that allows for an inclusive, transparent and reproducible mapping and appraisal of the evidence entering any IAS impact assessment (Table 1, Suppl. material 1: Fig. B1). Briefly, this scheme arranges the evidence along four different axes of variation. First, it discriminates the geographical relevance of the area from which the evidence is taken ("geographical area"). Second, evidence is classified according to where it is published

Table 1. Impact evidence variables and metadata recorded for each evidence entry in this study. When assignment to a single category is difficult, this can be flagged in the comments column or the entry can be given a dual coding.

Impact evidence variable	Levels	Description
Species	11 parrot species	Any one of the 11 parrot species designated “alien” status in Europe by EASIN (see Table 2).
Impact category	GISS categories (see Suppl. material 1: Appendix B3 for descriptions)	Environmental: (1) competition, (2) transmission of diseases or parasites, (3) herbivory and (4) impacts on ecosystems. Socioeconomic: (5) agricultural production, (6) animal production, (7) forestry production, (8) human health, (9) human well-being, and (10) human infrastructure and administration.
Geographical area	European	Evidence from Europe (see Suppl. material 1: Appendix B2 for definition)
	Other non-native range	Evidence from any other non-native range
	Native range	Evidence from native range
	Captive	Evidence from captivity (regardless of country)
Actual / potential impact	Actual	Evidence from within assessment area (here: Europe).
	Potential	Evidence from native range, other non-native range or captivity.
Source type	Peer reviewed	Peer-reviewed publications, academic books and book sections.
	Not peer-reviewed (grey literature)	PhD/Master’s thesis, governmental/NGO reports, conference proceedings, magazine/newspaper article, webpage.
	Unpublished data	Personal communication, personal observation, unpublished data.
Study design	Experimental	Qualitative/quantitative study using a qualitative/quantitative experimental manipulation of the mechanisms by which the invader is presumed to have an effect (allows inference on magnitude and causality of impact).
	Non-experimental	A study that uses a qualitative/quantitative, but non-experimental, scientific sampling design (allows inference on magnitude but not causality of impact).
	Anecdotal	Casual observation acquired without a sampling design (only allows inferences on presence/absence of impact, not on magnitude or causality).
	Indirect report	Impact not observed by person reporting it or sources that do not report primary data (impacts cannot be verified).
Impact direction	Deleterious	Evidence entry explicitly reports deleterious impact.
	Beneficial	Evidence entry explicitly reports beneficial impact.
	No impact	Covers cases where no impact is explicitly reported.
Metadata	Source identifier; Evidence entry identifier (for entries coming from a source containing multiple pieces of evidence); Year in which evidence was made available; Source language; Geographical region; Country; Detailed location of reported impact (e.g. nearby city or coordinates); Full bibliographic reference of source; Expert assessor name; and a short written description of relevant evidence.	

(“source type”), in order to provide some structure along the gradient of reliability of sources. Third, it distinguishes the methodological approach that was used to obtain the impact evidence (“study design”), since these differ in what types of inferences

can be made with respect to causality and magnitude of impact. Finally, the scheme records whether the impact is deleterious, beneficial or no impact detected (“impact direction”). Such an initial classification of reported impacts subsequently allows stakeholders to apply different assessment protocols or other criteria to the evidence and then to evaluate how this affects the final impact scoring. Here, we explore the utility of classifying the evidence base in this manner using alien parrot species (Psittaciformes) within Europe.

Parrots are amongst the most prominent pet birds worldwide and the large volume of pet-trade driven exports followed by escape and release has resulted in the establishment of numerous alien populations worldwide (Reino et al. 2017). Alien parrots have repeatedly been listed as a cause for concern; e.g. the ring-necked parakeet (RNP, *Psittacula krameri*) is considered amongst the 100 worst IAS in Europe (DAISIE 2009). Parrots are also a charismatic species group and since alien parrots currently mainly concentrate in urban areas where they were first introduced (Pârâu et al. 2016; Mori et al. 2019), they are often encountered by the general public – attracting both concern and support. Thus, alien parrots represent a complex socio-environmental conflict (Luna et al. 2019).

The European Alien Species Information Network (EASIN) recognises 11 alien parrot species in the EU (Table 2) and only two of these species are currently listed as having “high impact” (RNP and monk parakeet: MP, *Myiopsitta monachus*), with the remainder designated “low/unknown impact”. Across Europe, the RNP has a minimum of 90 established breeding populations and has grown from several tens of individuals in the 1970s to at least 85,000 birds in 2015 (Strubbe and Matthysen 2009; Pârâu et al. 2016). The MP is found in 179 municipalities across Europe, with its stronghold in Madrid and Barcelona. The current population of 23,000 individuals originates from a few tens of individuals recorded breeding in the mid-1970s (Strubbe and Matthysen 2009; Postigo et al. 2019). There have been a number of studies which have assessed alien parrot impacts alongside other species (e.g. Evans et al. 2016) and several additional studies have reviewed (but not quantified) impacts of alien parrots (e.g. Menchetti and Mori 2014). The findings of these studies (Suppl. material 1: Table A2) demonstrate substantial uncertainties and conflicting results regarding the environmental and socioeconomic impacts of alien parrots, partly due to differing protocols and evidence bases.

Alien parrot species thus represent an excellent group to explore the added value of the above-mentioned evidence-mapping scheme for conducting impact assessments (Table 1 and Suppl. material 1: Appendix B1). Here, we conduct a systematic and comprehensive assessment of existing evidence of environmental and socioeconomic impacts by alien parrots, on a continental scale. The resulting evidence base was subsequently used to (1) provide insights on how the evidence-mapping scheme can be used to further improve impact assessments and (2) identify the main types of alien parrot impacts, whilst evaluating the quantity, quality, spatial distribution and severity of the underlying evidence.

Table 2. Current status of the 11 alien parrot species within Europe (as recognised by EASIN; <https://easin.jrc.ec.europa.eu/>). Information obtained from GAVIA database (Dyer et al. 2017) unless otherwise stated. Only countries where species have been assigned “Breeding” or “Established” status are included under “Other alien range”, whereas countries assigned “Unknown” or “Died Out” status are also included for European range.

Species name	Native range	Alien European range (<i>Unknown, Died out</i>)	Europe populations (size)	Other alien range: breeding/ established	Impact status (EASIN)
Yellow-collared lovebird (<i>Agapornis personatus</i>)	Tanzania	France, Spain	Unknown	Burundi, Kenya	Low/ unknown
Turquoise-fronted amazon (<i>Amazona aestiva</i>)	Argentina, Bolivia, Brazil, Paraguay	Italy, Spain (<i>Germany, Switzerland</i>)	Genoa, Milan, Valencia (Mori et al. 2013, 2017)	USA	Low/ unknown
Yellow-crowned amazon* (<i>Amazona ochrocephala</i>)	Central and South America	(<i>Germany, Italy</i> : Mori et al. (2013, 2017))	Genoa, Milan, Stuttgart (50 since 1984) (Mori et al. 2013, 2017)	Barbados, Cayman Islands, Mexico, Netherlands Antilles, Puerto Rico, Trinidad, USA	Low/ unknown
Blue-crowned parakeet (<i>Araucaria acuticaudata</i>)	South America	Spain, (<i>UK, Italy</i> : Mori et al. 2013)	Barcelona (8 pairs/25 birds) (Anton et al. 2017), Sabadell, Valencia. Less than 200 birds across Europe	USA	Low/ unknown
Red-masked parakeet (<i>Araucaria erythrogenys</i>)	Ecuador, Peru	Spain	Barcelona, Seville, Valencia	Cayman Islands, USA,	Low/ unknown
Mitred parakeet (<i>Araucaria mitrata</i>)	Argentina, Bolivia, Peru	Spain	Barcelona (100–150 birds) (Anton et al. 2017), Valencia, Mallorca.	Puerto Rico, USA	Low/ unknown
Budgerigar (<i>Melopsittacus undulatus</i>)	Australia	Greece (<i>Germany, Spain, Turkey, Austria, Belgium, Italy</i> (Biondi et al. 2005), <i>UK</i>)	Unknown	Cayman Islands, Dominican Republic, Guadeloupe, Hong Kong, Jamaica, Japan, Mexico, Namibia, Oman, Puerto Rico, Qatar, Spain (Canary Islands), Taiwan, USA, Venezuela	Low/ unknown
Monk parakeet (<i>Myiopsitta monachus</i>)	Argentina, Bolivia, Brazil, Paraguay, Uruguay	Austria, Belgium, Czech Republic, France, Germany, Italy, Netherlands, Portugal, Spain, UK (<i>Denmark, Slovakia</i>)	30 established populations. More than 22,000 individuals across Europe (Postigo J-L, pers. comm. 2018).	Australia, Canada, Cayman Islands, Chile, Dominican Republic, Guadeloupe, Israel, Japan, Kenya, Mexico, Puerto Rico, USA, Venezuela	High
Nanday parakeet (<i>Nandayus nenday</i>)	Argentina, Bolivia, Brazil, Paraguay	Spain	Barcelona (5 pairs) (Anton et al. 2017)	Israel, Puerto Rico, Spain (Canary Islands), USA	Low/ unknown
Alexandrine parakeet (<i>Psittacula eupatria</i>)	Southern Asia	Belgium, Germany, Italy, Turkey (<i>Greece, Netherlands, Spain, UK</i>) (Ancillotto et al. 2016).	A minimum of 1000 individuals in Europe (Ancillotto et al. 2016; Gedeon et al. 2014)	Bahrain, Israel, Japan, Jordan, Oman, UAE, Yemen	Low/ unknown [†]
Ring-necked parakeet (<i>Psittacula krameri</i>)	Southern Asia and sub-Saharan Africa	Austria, Belgium, France, Germany, Greece, Italy, Netherlands, Portugal, Slovenia, Spain, Turkey, UK (<i>Ireland, Switzerland, Ukraine</i>)	95 populations have established since the 1960s. At least 85,000 birds (Părau et al. 2016).	Australia, Bahrain, Barbados, Cape Verde, Cayman Islands, China, Cuba, Egypt, Hong Kong, Iran, Iraq, Israel, Japan, Jordan, Kenya, Kuwait, Lebanon, Maldives, Malta, Mauritius, Oman, Philippines, Puerto Rico, Qatar, Reunion, Saudi Arabia, Singapore, South Africa, Thailand, UAE, USA, Venezuela, Yemen	High

* includes *belizensis* and *oratrix* subspecies (following the taxonomy used by EASIN).

[†] European Commission horizon-scanning identified it as a one of the 95 (very) high risk species across the EU within the next 10 years (Carboneras et al. 2018).

Materials and methods

Impact categories

We assessed the environmental and socioeconomic impacts of the eleven alien parrot species (Table 2) within Europe (see Suppl. material 1: Appendix B2 for countries included). We applied the impact categories proposed by the Generic Impact Scoring System (GISS; Kumschick and Nentwig 2010), with the following modifications. We omitted the ‘hybridisation’ category as there are no parrots native to Europe and the “predation” category, as all parrot species in this study are primarily herbivores (aggressive interactions whereby alien parrots kill or severely wound native species were categorised as ‘competition’, as these interactions are almost always related to food or nest-site conflicts). We therefore considered 10 impact categories (Table 1).

Building the impact evidence base

We utilised an innovative “wiki-review” process to facilitate comprehensive inclusion of sources and subsequent impact evidence into the evidence-mapping database. The process combined literature searches and preparation of impact review documents and databases by 15 selected experts from the EU collaborative network on alien parrots “ParrotNet” (COST Action ES1304), followed by an online editing and consultation phase conducted by a larger expert panel (open to ParrotNet participants and additional experts).

Each selected expert was first assigned an impact category and conducted a literature review to gather associated evidence on parrot impacts. Although a formal systematic review approach was not used due to the breadth of the study and its inclusive nature, experts conducted systematic keyword searches of the literature (i.e. using search terms pertinent to the respective impact category in combination with the scientific name of each species or either the term “parrot”, “parakeet”, “amazon”, “budgerigar” or “lovebird”). There was no restriction on publication year. Experts classified all evidence found on parrot impacts by *geographical area*, *source type*, *study design* and *impact direction* (see Table 1 and Suppl. material 1: Appendix B1 for definitions). Impact data was also distinguished as either being evidence of “actual impact” (i.e. from free-living individuals/populations within Europe) or “potential impact” (i.e. from outside Europe and/or in captivity). Where possible, primary sources were included, otherwise relevant data from reviews and other secondary sources were used and categorised as “indirect report” under *study design*. Experts were provided with a set of database fields in Excel wherein all evidence reports were entered. This database was designed such that each row comprised of a single record of evidence (i.e. evidence entry). If any given evidence source reported more than one impact, these were entered into the evidence database as separate entries. For example, if a source reported agricultural

damage caused by both RNP and MP, this would constitute two separate evidence entries (one per parrot species).

Upon completion, all impact reviews and associated evidence-mapping databases were placed online and the larger expert panel invited to review, edit and add information. Specifically, they read through one or more impact reviews and added any evidence not yet included, with a focus on evidence from grey literature, unpublished data and evidence in their native language and/or from their country of residence. This subsequent wider-consultation was open between March and December 2016, undertaken by 47 experts in (parrot) invasion biology and covered 17 languages (Bulgarian, Catalan, Dutch, English, Estonian, Finnish, French, German, Hebrew, Italian, Polish, Portuguese, Romanian, Russian, Slovenian, Spanish and Turkish). Several additional relevant sources, published between the end of the consultation period up to May 2017, were added by the lead authors.

Finally, to complement the “wiki-review”, we consulted stakeholders from locations across Europe where parrots have established in order to identify any additional evidence of socioeconomic impact. Stakeholders included representatives of farmer/landowner associations, government officials responsible for agricultural damage or public complaints officers, airport bird collision officials and bird or conservation NGOs. Altogether, 69 stakeholders were contacted between October and December 2015, from nine countries (Belgium, France, Germany, Italy, Netherlands, Portugal, Spain, Turkey and UK) and 41 responded (59% response rate), representing all aforementioned countries except Turkey. All stakeholders who responded to our survey provided anecdotal information on minor damage to crops (notably, by RNP) - information which was already well-captured in our “wiki-review”. Since these insights were not collected by stakeholders in a rigorous way and were mainly based on personal or anecdotal knowledge, these responses were not included in the database, but serve as a form of validation to the findings of the literature search and are summarised separately in Suppl. material 1: Table C1.

Impact severity scoring

Impact severity was assessed via the GISS impact assessment protocol (Kumschick and Nentwig 2010), which covers both environmental and socioeconomic impacts and has been extensively applied to birds (see Suppl. material 1: Table A2). During the evidence mapping and “wiki-review” stages, experts were not asked to assess the impact severity, as we believe that this process should be standardised to avoid biases resulting from, for example, utilising different thresholds. A single assessor systematically examined all evidence entries and attributed an impact score to each (independently reviewed for consistency by two other experts). The same score was obtained for the majority of evidence entries between the assessor and two independent reviewers. However, when there were disagreements, we discussed these objectively until a consensus was made. GISS scores invader impacts using a six-level scale ranging from 0 (‘no impact detect-

able') to 5 ('highest impact possible'). We added a "Not Assessable" ("NA") category, which was assigned to evidence entries where it was not possible to determine impact severity (due to the evidence being ambiguous, incomplete or failing to explicitly associate an impact as coming from a specific parrot species). Definitions of each impact category, scoring level and thresholds were set, following a workshop discussion with over 20 experts and are provided in Suppl. material 1: Appendix B3 (e.g. damage to crops that exceeds 5% was set as high damage in fields or fruit consumption). Finally, while there have been some attempts to score the strength of beneficial impacts created by alien species (Kumschick et al. 2012), there is currently no widely-adopted protocol. Consequently, although we included all beneficial impact evidence, we did not score their level of impact.

Data representation and analysis

In order to obtain a general overview of the evidence base, we first used descriptive statistics to synthesise and summarise how reported impacts were distributed across species, impact category, geographical area, source type, study design and direction of impact. Secondly, we mapped the spatial distribution of the evidence for deleterious impacts (Europe and worldwide) across impact categories, providing a visual representation of where different reported impacts originated. Finally, we investigated how criteria on evidence inclusion influenced the outcome of IAS impact assessments, for all alien parrots in Europe (combined and per species). Following Turbé et al. (2017), impact scores were summarised per impact category by taking both the average (using the full set of recorded impacts) and maximum (based on the most severe recorded impact only) scores. Entries that could not be assigned a numerical impact score, including all those reporting beneficial impacts, were excluded here. Specifically, we explored how impact severity scores (average and maximum) varied by species, impact category, geographical area, source type and study design.

Results

Evidence-mapping database

A total of 386 independent evidence entries were obtained from 233 sources, spanning from 1895 to 2017 (with a noticeable increase from the late 1990s onwards). Although peer-reviewed publications were the most common evidence source, 42% of entries came from grey literature or unpublished data. Entries spanned sources written in 10 different languages (predominantly English: 71%), from all continents (save Antarctica) and 32 countries (Europe: 39%; other invaded range: 20%; native range: 32%; captive: 9%; Suppl. material 1: Fig. C1a–b). Most entries reported potential (62%), not actual, impacts for Europe. All 11 alien parrot species within Europe were included

in the database, although the vast majority of entries (83%) referred to either the RNP (64%) or MP (19%). Regarding impact category, most entries referred to agriculture (42%), followed by competition (19%), herbivory (19%), disease (8%), human health (5%), infrastructure (4%) and human well-being (3%). In terms of study design, most entries were anecdotal (50%), followed by non-experimental (33%), indirect reports (11%) and experimental (6%). The vast majority of entries reported deleterious impact (82%), whilst 10% provided evidence of no impact and 8% beneficial impacts. The complete impact evidence-mapping database, including assigned impact scores, is provided in Suppl. material 1: Appendix D and can be consulted interactively online via an R Shiny application (<https://goo.gl/ZwWZPo>).

Deleterious and no impact evidence

Within Europe (Fig. 1a), most evidence of deleterious impact referred to populations in Spain (30%), the UK (18%) and Belgium (13%). Competition with native species and agricultural damage were the main impact categories (31% and 29%, respectively). Evidence of actual deleterious impact was found for six parrot species, but 93% of these entries related to RNP or MP (Suppl. material 1: Table C2). It is also important to note that 12% of impact entries from Europe were from captive populations, including all evidence from Poland (where currently no parrot populations are established). These entries were mostly related to disease transmission in captive populations and consequently only provide tentative evidence of potential impact of feral populations on human health. For non-native areas outside Europe (Fig. 1b), most evidence of deleterious impact came from Israel (39%; all referring to RNP and largely reporting agricultural damage) and the USA (36%; largely reporting socioeconomic impact by MP). Within the ‘native range’ impact category (Fig. 1b), most deleterious impact entries were reported from India (59%) or Pakistan (17%) and referred to agricultural damage by RNP. Overall, 39 entries (10%) found no evidence of impact (Suppl. material 1: Table C2).

Beneficial impact evidence

Overall, 29 entries reported evidence of beneficial impact (45%: competition, 41%: herbivory, and 14%: human well-being). Beneficial entries for indirect facilitation of conditions, either by providing resources or by competing with native species’ local competitors, were all anecdotal, with 18% of all competition evidence from Europe being beneficial (referring to nesting cavities made by RNP and *Psittacula eupatria*, use of MP nests as breeding sites and protection via RNP anti-predatory (‘mobbing’) behaviour). Evidence of beneficial impacts relating to herbivory reported that parrots can disperse seeds of native species or feed on and damage alien plants. Most of this evidence (82%) came from the native ranges of the six respective species and, except for one experimental study, were either anecdotal or non-

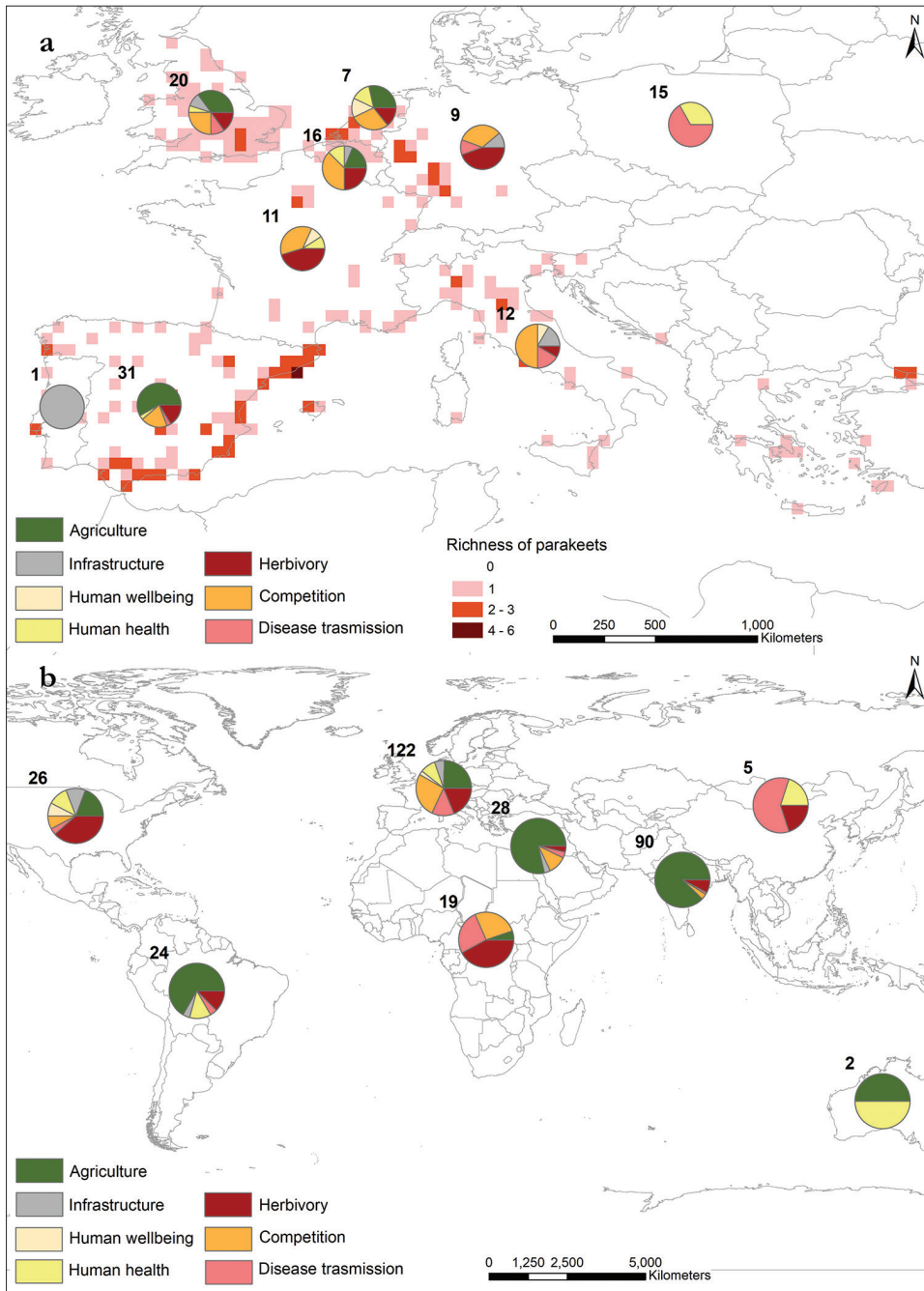


Figure 1. Spatial distribution of deleterious impact evidence for the 11 alien parrot species in Europe, by **a** countries within Europe ($n = 122$) and **b** regions across the world ($n = 316$; Africa, Australia, Europe, Far East, Indian-subcontinent, Latin America, Middle East, North America). Evidence is further split by GISS impact category. Numbers refer to corresponding number of evidence entries, which include those from captivity. Parrot species occurrence data used to derive parrot species richness maps were taken from the Global Biodiversity Information Facility (GBIF, www.gbif.org).

experimental. Finally, evidence on benefits to human well-being came largely from anecdotal sources, with 75% from Europe (all RNP), one entry from the USA (MP) and none from native ranges.

Impact severity scores and the effects of evidence selection criteria

Almost half (48%) of all evidence entries could not be assigned an impact score. Within the entire database (386 entries), 19 entries scored a “4” for impact severity; these reported potential impact (i.e. outside of Europe) and all but two related to agricultural impact. Only three entries obtained the maximum score of “5”: two reports (one anecdotal and one indirect) of competition between RNP and the endangered Echo parakeet (*Psittacula eques*) in Mauritius and an indirect report of the RNP being involved in bird-aircraft strikes in the UK. When using all collected evidence recorded in any geographical area, maximum impact across impact categories was highest for both competition and infrastructure (5), whereas mean impact was greatest for agriculture (2.35) and infrastructure (1.93) (see Suppl. material 1: Table C3, which also contains a breakdown per species).

Impact scores were separated by actual versus potential impact (i.e. recorded within or outside of Europe, respectively), source type and study design (Figs 2–3; per species: Suppl. material 1: Tables C4–5). Most actual impact scores were $\leq$ “1” (72%), compared with 41% for potential impacts. For all species combined, both mean and maximum impact scores were higher for potential than for actual impacts, except for human health and human well-being (equal values) and maximum infrastructure impact (actual > potential, Fig. 2a–b). Both mean and maximum impact scores also varied with source type, but not in a consistent manner across impact categories (Fig. 2c–d). Finally, concerning study design, mean impact score generally increased from indirect report/anecdotal through to experimental (Fig. 3a); however, this was not the case for maximum impact scores (Fig. 3b).

Focusing on the RNP, most scores related to non-experimental evidence of agricultural impact from the native range (Fig. 4a), followed by non-experimental evidence about competition in Europe (Fig. 4b). Mean and maximum scores for actual impacts were highest for infrastructure, whereas the highest mean and maximum scores for potential impacts were for agriculture and competition, respectively (Suppl. material 1: Table C4). For the MP, most scores related to non-experimental evidence on agricultural impact in Europe and to anecdotal evidence on infrastructure damage in Europe (Fig. 4c–d). Both within and outside of Europe, mean and maximum impact scores were highest for evidence of agricultural impact (Suppl. material 1: Table C4).

Agricultural impact by parrots was reported for 16 crops within Europe (mainly maize, plums and tomatoes) and outside Europe for 33 crops (mainly maize and sunflower), although impact severity scores could only be assigned to 11 and 21 crop types, respectively. Although sample sizes were low, the highest actual (European) impact was reported for plums, pumpkin, sunflower, maize and tomato. Potential (non-European)

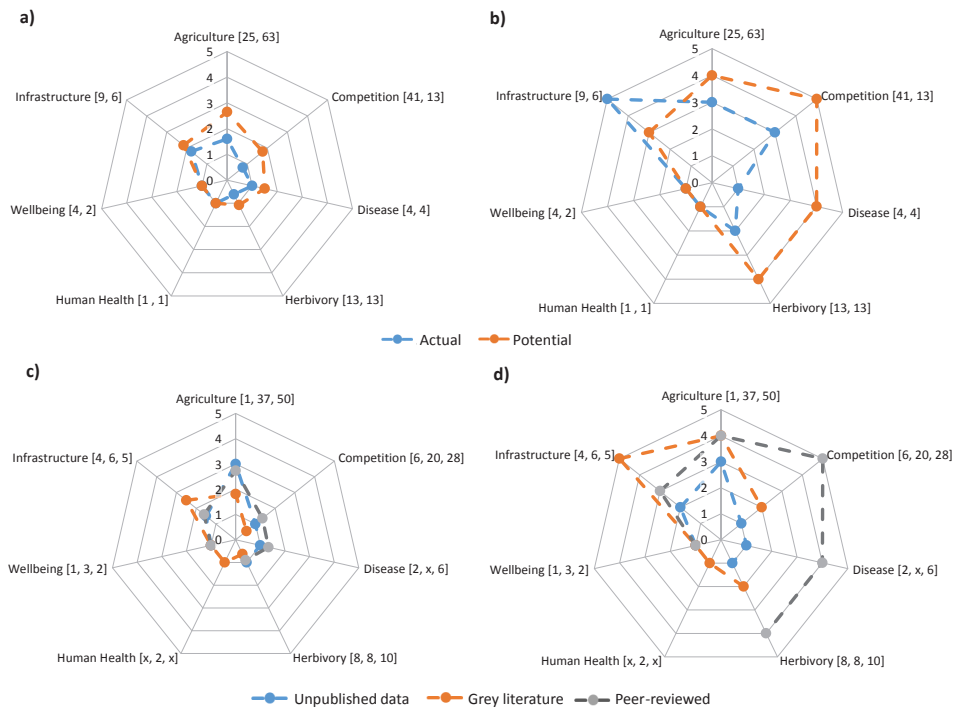


Figure 2. Impact scores for all 11 alien parrot species combined per impact category, broken down by actual versus potential impact (**a** mean **b** maximum) and source type (**c** mean **d** maximum). Sample sizes are shown in square brackets and relate to levels as ordered in the legend (x signifies no data with an impact score).

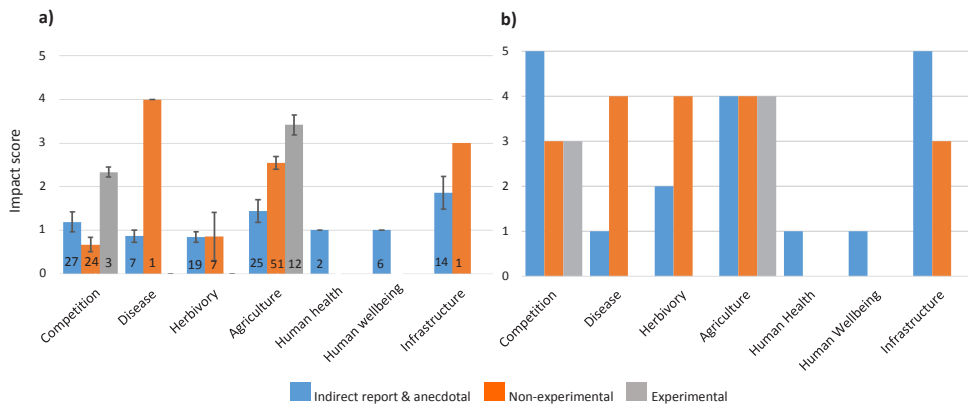


Figure 3. Impact scores for all 11 alien parrot species combined per impact category, broken down by study design (**a** mean $\pm$ SE **b** maximum). Samples sizes for both plots are shown within the bars of the first plot.

crop impact was greatest for rice, mango, pomegranate, sunflower and maize. Within Europe, most evidence of MP agricultural damage comes from Spain, whereas the damage attributable to the RNP originates mainly from Belgium and the UK.

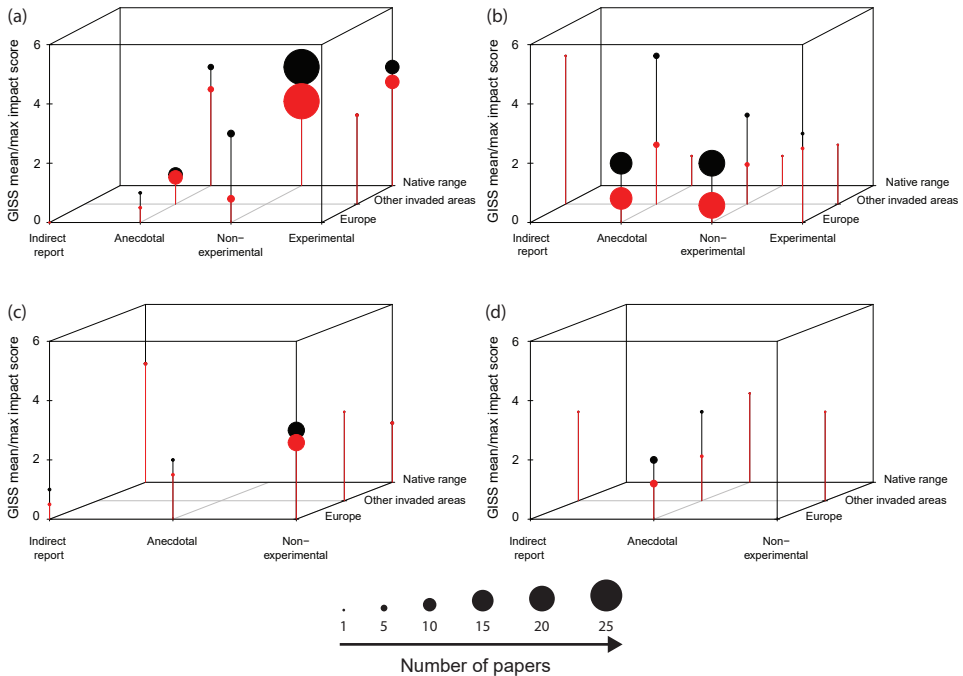


Figure 4. Mean (red) and maximum (black) impact scores broken down by study design and geographical area for **a** RNP agricultural impact **b** RNP competition impact **c** MP agricultural impact and **d** MP infrastructure impact. Highest possible impact score = 5.

Discussion

Evaluation of impact evidence-mapping scheme and “wiki-review”

A range of impact assessment protocols exist to assist necessary prioritisation of IAS management. However, protocols vary in the types of evidence included. Here, we argue that all impact records encountered during any IAS impact assessment should first be summarised into a transparent, openly-accessible, inclusive and standardised evidence base, allowing one to track how variation in accepted evidence influences the severity of final, overall impact scores. We believe doing this will strengthen the existing standards of IAS impact assessments and contribute towards scientifically, socially and politically acceptable IAS management decisions.

Both the evidence-mapping scheme and “wiki-review” used in this study facilitate the creation of such an evidence base. The former enables a more structured and transparent evaluation of impacts for any alien species within any geographical location. It can also allow the interchange or publication of datasets, potentially preventing unnecessary replication of literature review efforts, facilitate rapid updating and enable comparison of outcomes of assessments with respect to different protocols. The “wiki-review” process facilitates the collection of non-peer-reviewed information plus evidence from additional

(non-English) languages. Collectively, these two sequential approaches can help address some of the main challenges surrounding the reliability of IAS risk analysis, as highlighted by Vanderhoeven et al. (2017). Firstly, they facilitate improved quality control of impact assessments, by reducing the likelihood of “data laundering”, whereby the results of impact assessments are used to draw conclusions and make decisions without being aware of the potentially limited quality of the underlying evidence (Strubbe et al. 2011). Secondly, they can help formalise a peer-review process between assessors and reviewers, as advocated by Vanderhoeven et al. (2017). We do not believe that either our proposed evidence-mapping scheme or “wiki-review” represent a major additional burden for expert evaluators. However, it would be worthwhile exploring the extent to which non-experts could conduct them and so allow experts to focus on the subsequent IAS impact assessments.

The use of the impact evidence-mapping scheme here does not resolve some long-standing important issues, which are part of impact assessments. For instance, the use of anecdotal data, information from the native range, evidence on beneficial impacts, summarising methods for impact severity and setting up clear thresholds to what is considered high or low impact (Strubbe et al. 2011, Turbé et al. 2017, Bartz and Kowarik 2019). However, it does allow them to be explicitly identified and therefore accounted for in the subsequent risk management stage. Firstly, the quality of data across evidence entries is likely to vary considerably. Here, we classified the evidence by study design, as a proxy for evidence quality and reliability (on the basis of susceptibility to bias). Our database of alien parrot impacts in Europe showed important variation in impact scores with respect to study design. Although anecdotal data is, by definition, a poorer quality evidence type, it is not necessarily irrelevant and should be included in impact assessments. The reason for this is that there is a trade-off between impact detectability and management efficiency (Simberloff et al. 2013). When alien species start to establish, their impacts may be hard to detect due to small population sizes and low awareness. It also takes some time to establish a sound evidence base of impact for such novel alien species. However, from a management perspective, this early stage is critical, since populations are still small and any mitigation attempts will likely be most cost-effective. Anecdotal information can be valuable in directing both research and a fast response in the early stages of invasion. By explicitly classifying such variation in the evidence base, the evidence-mapping scheme draws attention to this matter and thereby increases transparency in the choices made during risk management.

A second outstanding issue is how to deal with evidence from the native range and other invaded areas. We argue that impacts from these geographical areas should be mapped but kept separate from evidence obtained from the focal study region, as extrapolation may not be straightforward (Kulhanek et al. 2011). It has previously been suggested that impacts in the introduced range are likely to be more severe than in the native range (Kumschick et al. 2011); however, we did not find this to be always true. Damage by RNP and MP to agriculture and infrastructure are limited within Europe, despite both species being locally abundant, with impact scores being greater in their native or other invaded ranges. Focusing on agriculture, it is important to highlight that, as a result of global climate change, farming practices within Europe will increasingly have to adapt to warmer

climates. For example, maize, sunflower, orchards and vineyards are sectors set to expand as the climate warms (Olesen et al. 2011) and for which evidence of parrot damage within Europe (albeit localised) and other invaded ranges already exists. Therefore, climate-driven expansion of certain crops across Europe, bringing them into contact with parrots, could place increasing pressure on farmers and the economy. Again, our scheme allows decision-makers to visualise the available evidence from the focal study region, other non-native ranges and native ranges and subsequently decide which and how to utilise it.

Lastly, evidence-mapping results in a set of recorded impacts, but these need to then be scored and summarised into a single, overall impact score to allow ranking IAS according to the magnitude of the threats they pose. The summarising method has strong implications on the magnitude of impacts assigned to alien species and our results clearly demonstrate that. Both scoring methods (maximum and mean) have strengths and weaknesses and we suggest that summarising impact based on both approaches is of inherent and complementary value for guiding management decisions (see also Turbé et al. 2017). Integrating beneficial impacts into the scoring system is even more challenging, as the direction of an impact depends on some sort of valuation relative to a desired situation and is therefore relative (if not subjective) (Bartz and Kowarik 2019). For example, we scored protection of heterospecifics from predators by mobbing parrots as beneficial, but it would be a deleterious impact from the point of view of the predators. Beneficial impacts attributed to IAS are an often ignored factor (Schlaepfer et al. 2011) and currently not a formal part of IAS impact assessment. Including direction of impacts as a category in the evidence-base will therefore also highlight that impacts (in either direction) are never fully objective and always “user-dependent”: some impacts may be valued differently by distinct sections of the scientific community and the general public. Including beneficial impacts into the evidence base, even when it is not (yet) an integral component of the impact score, enables relevant people to consider this evidence at the subsequent risk-management and risk-communication stages. Furthermore, our evidence-mapping scheme needs to be used in tandem with recent recommendations aimed at reducing disagreement between expert assessors (e.g. Turbé et al. 2017, Vanderhoeven et al. 2017; González-Moreno et al. 2019), to obtain more comprehensive impact assessments. Altogether, we argue that mapping all of the available evidence allows all the above-mentioned issues to be transparently considered during the decision-making phase of risk management.

Impacts of alien parrots in Europe, as a function of “admissible evidence”

The approach followed in this study has resulted in the most comprehensive and transparent assessment of alien parrot impacts within Europe to date. Allowing different levels of the evidence base (Table 1) to enter into the assessment can seriously affect not only evidence quantity, but also impact severity scores and identification of main impact mechanisms (e.g. as seen in both the MP and RNP). When considering only actual impact (and also excluding indirect and anecdotal reports), we find that RNP

mostly cause minimal and only rarely moderate impacts in Europe (i.e. GISS scores 1-3). These relate mainly to competition with native cavity nesting species. For instance, the threatened greater noctule bat (*Nyctalus lasiopterus*) in Seville (Spain) can be forced out of roosting cavities by RNP, which has only recently been found to contribute to declining bat populations (Hernández-Brito et al. 2018). Such long-term studies investigating the effect of competition on the local abundance of species are scarce in the invasion literature (Strayer et al. 2006). It is also important to highlight that roughly half of the entries for competition within Europe found explicit evidence of no impact. RNP are shown to damage crops and trees in Europe, but evidence is scarce and localised. When allowing impact evidence from other invaded ranges into the evidence base, RNP is considered both a more serious agricultural threat and competitor with threatened species (due to its competition with the threatened echo parakeet in Mauritius). If native-range impact information is considered, numerous studies have found the RNP to be a moderate to major agricultural pest, predominantly in India. Finally, indirect and anecdotal evidence indicate that RNP can cause minor herbivory, disease, human health and well-being impacts, but severe (GISS score 5) infrastructure impact, although it must be emphasised that the latter is based on one (indirect) report finding RNP to be involved in <1% of bird-aircraft strikes at Heathrow Airport (UK) (Fletcher and Askew 2007) and should therefore not be taken out of context.

Evidence of MP impact in Europe (excluding indirect and anecdotal reports) comes from only two studies reporting agricultural damage in Spain (Barcelona) (Senar and Domènech 2001; Senar et al. 2016), where they are shown to be a moderate threat to at least ten crop types. Only when indirect and anecdotal reports are included do we find some evidence of infrastructure damage via the communal stick nests they build and a few additional low impact cases relating to agriculture and herbivory. No evidence of deleterious competitive interactions with the MP could be found in Europe. In fact, 71% of the species' actual competition entries were beneficial (e.g. facilitating nesting conditions for other species). Allowing impact evidence from other invaded ranges into the evidence base causes the MP's damage to infrastructure score to increase, along with limited evidence of both minimal competition and human well-being impacts. Native range evidence suggests MP could be capable of causing major agricultural damage to both maize and sunflower.

For the remaining nine parrot species, either no or very little information on impacts within Europe were retrieved (mainly indirect reports or anecdotal). These species all have localised and (very) small European populations and negligible actual impact. Even when allowing impact evidence from other invaded ranges or the native range, assessments for these species remain unchanged, except for *Amazona aestiva* which is an agricultural pest in parts of its native range (e.g. Villalobos and Bagno 2013).

Knowledge gaps and biases in the evidence base

One of the benefits of the evidence-mapping scheme used here is that it facilitates identification of knowledge gaps and can potentially influence the direction of future

IAS research. Roughly half of all entries in our database did not allow assignment of an impact severity score, due to ambiguous evidence; e.g. a given source failing to explicitly associate an impact as coming from a specific parrot species. Although parrots are a relatively well-studied bird group which is at least partly attributable to their being noisy and conspicuous (Evans et al. 2016), there is a general paucity of published research on established parrot species impacts within Europe. For example, the majority of experimental studies in our evidence base relate to agricultural impacts by RNP in their native India, whereas we found only two experimental studies reporting impacts within Europe – both relating to competition by RNP (Strubbe and Matthysen 2009; Peck et al. 2014). We also lack studies that explicitly assess and/or quantify the general public's opinion on alien parrots, their impacts and their management, which is recognised to be complex and multifaceted (Crowley et al. 2019; Luna et al. 2019), but highly important to understand in order to promote effective management. Finally, within Europe, most impact categories are underpinned by only one or a few studies (even for RNP). Despite growth in the study of invasion biology (Richardson and Pysek 2008), empirical evidence of the impact of IAS can be difficult to obtain and, as a result, IAS impacts are generally poorly documented. Nonetheless, in Europe, at least in the case of RNP and MP, our study indicates minimal to locally moderate impacts based on the available evidence to date.

One broad reason to explain why little impact data exist for most alien bird species generally, is that some populations may be perceived to cause negligible or no harm (i.e. below the threshold) and, consequently, are not studied (Evans et al. 2016). Lack of data in this situation reflects a perceived (but perhaps unreal) lack of impact. Pysek et al. (2008) highlighted a tendency for studies to focus on species considered to have the most severe impacts (e.g. RNP and MP in our study) and neglect others (e.g. the remaining nine parrot species). This also raises an outstanding issue regarding what is the threshold beyond which an alien species becomes invasive or a negative impact becomes a significant negative impact (see Bartz and Kowarik 2019). This links with the issue that there will always be a time lag between initial introduction of an alien species and a detectable impact (Edelaar and Tella 2012). On the other hand, studies that fail to find a deleterious effect (e.g. Cardoso and Reino 2018) are likely not published and under-reported (Schlaepfer et al. 2011). Assembling a comprehensive database, which includes anecdotal evidence of deleterious impacts and evidence of no impact as suggested here, can potentially help direct research towards important possible impacts.

IAS management and policy implications

The outputs from impact assessments alone should not be used to prioritise alien species for management, as impact assessment is only one subcomponent of risk assessment, which in turn is only one subcomponent of risk analysis (Suppl. material 1: Fig. A1). However, our extensive impact evidence base and associated impact assessments suggest possible management and policy considerations for alien parrots in Europe.

We find limited evidence of widespread (severe) parrot impacts across Europe. Instead, impacts within Europe are predominantly localised and differ across countries/regions. Hence, it is unlikely to be necessary, at present, to put any of the 11 parrot species on the Union List. Most parrots in Europe are currently known from relatively few and disjunct populations and necessary management actions, if any, can be carried out at local or regional levels. RNP and MP are more widespread and populations may span national borders (e.g. across the lowlands of northern France, Belgium, the Netherlands and Germany or across parts of the Mediterranean seaboard; Pârâu et al. 2016; Postigo et al. 2019). Effective management of these species will likely benefit from designating them as “invasive species of local and regional concern”, as per Articles 11 and 12 of the EU regulation on IAS.

The rise of “invasive species denialism” (Ricciardi and Ryan 2018, Russell and Blackburn 2017) challenges invasion biologists to better present the available evidence, because disagreements often arise when uncertainty on impacts are confounded by differences in personal values. More broadly, there are concerns that a culture of “evidence complacency” may be prevalent in many areas of conservation amongst academics, practitioners and decision-makers (O’Connell and White 2017; Sutherland and Wordley 2017). Hence, especially in our contemporary “post-truth” world (Higgins 2016), we re-emphasise the importance of all IAS management and policy decisions to be made, based upon having access to impact assessments produced using a transparent, comprehensive and publicly available evidence base and for there to be a clear evidence audit trail.

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Supplementary material I

Supplementary background, methods and results

Authors: Rachel L. White, Diederik Strubbe, Martin Dallimer, Zoe G. Davies, Amy J.S. Davis, Pim Edelaar, Jim Groombridge, Hazel A. Jackson, Mattia Menchetti, Emiliano Mori, Boris P. Nikolov, Liviu G. Pârâu, Živa F. Pečnikar, Tristan J. Pett, Luís Reino, Simon Tollington, Anne Turbé, Assaf Schwartz

Data type: background, description, measurement

Explanation note: Appendix A: Supplementary background, Appendix B: Supplementary methods, Appendix C: Supplementary results.

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Supplementary material 2

Impact evidence database

Authors: Rachel L. White, Diederik Strubbe, Martin Dallimer, Zoe G. Davies, Amy J.S. Davis, Pim Edelaar, Jim Groombridge, Hazel A. Jackson, Mattia Menchetti, Emiliano Mori, Boris P. Nikolov, Liviu G. Pârâu, Živa F. Pečnikar, Tristan J. Pett, Luís Reino, Simon Tollington, Anne Turbé, Assaf Shwartz

Data type: description, measurement

Explanation note: Appendix D: Impact evidence database.

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