**Anticipating arrival: tackling the national challenges associated with the redistribution of biodiversity driven by climate change**

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**Abstract**

1. The redistribution of species in response to climate change is expected to significantly challenge environmental management and conservation efforts around the globe. To date, we have had restricted understanding of the benefits and risks that species redistribution may pose to individual countries, and a limited appreciation of the variability in current opportunities for developing effective monitoring approaches that build on existing national frameworks.
2. To assess the present level of ecological, economic and societal risks and opportunities associated with new arrivals of species driven by changes in climatic conditions, we conducted a review of the available information on changes in animal species (both terrestrial and marine) distribution suspected to be linked to climate change in the United Kingdom over the past ten years (2008-2018).
3. We found evidence that at least 55 species have arrived in new locations in the country due to climate change in past decade, with 22 of them suspected to impact positively or negatively the recipient ecosystems, or nearby human communities. Ten of these 55 species were identified using keywords and hashtags on social media.
4. *Synthesis and application*s. Our work identifies pressing monitoring gaps relevant to the management of species on the move and discusses the potential for social media to help address current information needs. It also calls for more theoretical work to enable the quick identification of species likely to be problematic (or beneficial) and locations likely to experience significant ecological and societal impacts from biodiversity’s redistribution under a changing climate.

**Introduction**

There is a growing recognition that the redistribution of species driven by a changing climate is creating profound challenges for societies and regional economies around the globe (Pecl et al., 2017). As well as having serious consequences for economic development, livelihoods, food security, human health and culture, species’ redistribution is testing the limit of our understanding of ecological systems, highlighting key knowledge gaps in our ability to predict biodiversity’s response to global environmental change (Bonebrake et al., 2018). Global redistributions of species have happened before, with e.g. glacial cycles during the Pleistocene having had a significant impact on species distributions (Hewitt, 2000); the mechanisms underpinning the current reshuffle of wildlife are, however, new. To date, most recommendations to managers and governments in the peer-reviewed literature for appropriately tackling this global issue have focused on improved monitoring through access to real-time data streams and enhanced coordination; more targeted research agendas and increased funding to increase research on climate change driven species redistributions; quicker and more efficient integration of the available information into decision support frameworks; and better communication of the issues and progress made to policy makers and the general public (Pecl et al., 2017; Bonebrake et al., 2018).

Although laudable, these general recommendations are unlikely to trigger perceptible changes in practice without mechanisms and examples to help secure national-level buy-in. As established by years of trying to translate global biodiversity targets into tangible local actions, converting global recommendations into national responsibilities is indeed challenging, yet of paramount importance for addressing environmental issues (Collen et al., 2013). To date, we have a restricted understanding of the benefits and risks that species redistribution may pose to individual countries, and a limited appreciation of the variability in current opportunities for developing effective monitoring approaches that build on existing national frameworks (Pecl et al., 2017). Similarly, we have not matched key knowledge gaps with locations best suited for addressing them, making it for example difficult for research councils to identify priority topics in the research ﬁeld of climate change driven species redistributions that are relevant to their taxpayers. This lack of detailed information about what practical issues species redistribution raise in countries may prevent the identification of important theoretical and logistical challenges. Even without considering this heightened challenge of shifting species, most countries lack prioritization of areas or taxa for targeted biological monitoring in the first place (Amano, Lamming & Sutherland, 2016). To progress our thinking and improve our level of preparedness for the many changes that are coming with species redistribution (potentially leading to arrivals of new species in new environments; significant changes in abundance of certain species in some areas; local extinctions), it is thus essential to assess concretely capabilities and shortcomings, and identify practical solutions, at the scale at which decisions are made and implemented.

To this end, this contribution aims to use the United Kingdom (UK) as a case study to start gauging current national capabilities for tracking arrivals of new species in new environments and predicting their potential impacts. Here, we focus on new arrivals as these are easier to track than changes in abundance and local extinctions (Boakes, Rout & Collen, 2015). Specifically, we aim to (i) assess the present level of ecological, economic and societal risks posed by arrivals driven by changes in climatic conditions; (ii) evaluate current constraints to the effective monitoring of species redistribution; and (iii) suggest priority actions to increase the level of national preparedness for tackling the challenges associated with species on the move. We choose to focus on the UK as arrivals of species in new locations are expected to become more common with climate change. Wildlife in the UK is intensively monitored (Lenoir & Svenning, 2015): the UK is the fourth worldwide for the number of species occurrence records with over 66 million records (October 2018; <https://www.gbif.org/the-gbif-network>). Citizen science in the UK has proven increasingly popular with widespread support and publicity in recent years, which partly underpins the high availability of occurrence data (see e.g. Newson et al., 2016). The country also possesses an effective monitoring program for invasive species (Carboneras et al., 2018), meaning that several efficient systems for the detection of new species are already in place. Altogether, the UK is thus a useful study case for evaluating current national capabilities to monitor species on the move and for assessing potential risks associated with new invasions.

**Climate change and species on the move in UK**

To assess the present level of ecological, economic and societal risks and opportunities associated with new arrivals driven by changes in climatic conditions, we conducted a systematic review of the published literature detailing climate change driven changes in animal species distribution in the UK (around 40,000 animal species (terrestrial and marine) are suspected to occur in the country; <https://www.gbif.org/country/GB/summary>) over the past ten years (2008-2018). For that purpose, we focused on reports of (i) new animal species for the UK (whose arrival is a consequence of the species moving unassisted from a neighbouring country), and (ii) UK native animal species and established exotic animal species whose distributions are thought to be altered by climate change. We discarded all reports of human-assisted movement of animal species (native and exotic) leading to changes in their distribution; we also discarded sporadic sightings of animal species beyond their distribution range that were not associated with evidence that the species had indeed established at least one viable population in that area (Bates et al., 2014). Searched terms used on Web of Science were ‘climate change’, ‘warming’, ‘range shift’, ‘redistribute’, ‘expan\*’, ‘exten\*’ ‘UK/engl/brit/scot/Wales/welsh/Ireland/irish’. This led us to review 111 peer-reviewed papers. In addition to a systematic review, we (i) performed Twitter and Google searches; and (ii) reviewed all state of environment reports for the UK (birds, mammals, pollinators, butterflies). For both Twitter and Google searches, we used the following terms: “unusual species UK/England/Scotland/Wales/Ireland”, “first sighting UK/England/Scotland/Wales/Ireland”, and “new species UK/England/Scotland/Wales/Ireland climate change”. For species suspected to be on the move with climate change (e.g. species predicted to move in peer reviewed papers), common and Latin names were used to search Twitter and identify any recent sightings; search results were ordered by the most recent posts. All tweets used in our database included a date (since 2008) and location within the UK; most included a photo of the animal, with three providing other forms of verification.

Causal links between changes in species distribution and changes in climatic conditions can be difficult to establish; we here focused on identifying species for which evidence of a link between climate change and change in distribution could be traced. Specifically, we collected evidence (peer-reviewed article, grey literature, expert opinion) for each species included in our database to support the assertion that they were moving because of climate change. To assess the potential impact of these new arrivals, we (i) compiled available information on the reported consequences of these arrivals in the considered locations, and (ii) looked for reported impacts of the species we identified as being on the move in other locations in the UK where these species are more established. Our review suggests that at least 55 animal species (i.e., ~0.14% of all UK species) have invaded new environments within the UK in response to climate change over the 2008-2018 period. As a point of comparison, in other regions of the world where groups of taxa or communities in one location have been assessed, estimates suggest between 18 to 80 % of species have already undergone climate change driven changes in distribution (Chen et al., 2011; Poloczanska et al., 2016). We found only one report of an animal species (Anthrax anthrax) arriving naturally in the UK for the first time and establishing a viable population in the country for the period considered. Six of these 55 species are marine while 49 are terrestrial or freshwater species; 64% of these species are invertebrates; 9% are mammals. Some of these species were reported to establish a viable population in more than one new location, leading to 69 records being entered in our database for the 55 species identified: 50.7% of these records were from England, 40.6% from Scotland and 8.7% from Wales. One of these 55 species is found on the UK invasive list (*Styela clava,* the leathery sea squirt; the UK invasive list currently includes 101 animals <http://www.iucngisd.org/gisd/search.php>). Ten of the 55 species listed in our dataset were identified on social media. In many cases, interested members of the public will have posted uncommon or rare species for their area, asking for identification help or checking if their presence in the area is normal. So far, information available through social media has been largely ignored by biodiversity monitoring schemes, yet our results demonstrate that these platforms provide important complementary information for near real time tracking of species movement.

Of the 55 species known to have arrived in new locations in the UK, 24% (13 species) are known to have negative impacts on ecological communities and human societies. Reported negative societal impacts include damages to crops and production forests; biofouling; human disease spreading and increased risk of injuries; and pressure on residential maintenance and planning permissions. 20% (11 species) were reported to have potentially positive impacts (primarily through tourism). Examples of positive (e.g., through tourism) and negative ecological, societal and economic impacts associated with species expanding their distributions in the country are presented in Table 1.

**Data collection protocols and monitoring priorities**

*Current capacity to track species on the move with climate change*

The National Biodiversity Network is the entity centralising most information on species occurrence in the UK, being the key informant for the UK node of the Global Biodiversity Information Facility (GBIF). Taxon-specific conservation charities that collect information on species distribution, such as the Royal Society for the Protection of Birds, the Bat Trust and Butterfly Conservation, are important data providers for the National Biodiversity Network. Citizen science data account for a large proportion of all GBIF data (Groom, Weatherdon & Geijzendorffer., 2017), with some citizen science projects, such as iNaturalist and eBird, directly feeding into GBIF but not into the National Biodiversity Network. GBIF is thus the most comprehensive database on UK species distribution. To assess possible differences among taxa in their propensity to invade new environments, we estimated the proportion of records for a given taxon within our dataset; to partially account for detectability, we also estimated the proportion of records for a given taxon for the UK GBIF dataset (Figure 1). Interestingly, these proportions are mostly comparable, which suggests that the proportion of species likely to invade new environments with climate change is roughly constant among taxa.

The UK GBIF dataset has several drawbacks, including biased representation of taxa and uneven effort of sampling (Figure 1; Beck et al., 2014). For example, UK arachnids are badly represented in GBIF and effort of sampling is substantially higher in densely populated England compared to less populated Scotland. Other known issues include errors in geo-referencing (Yesson et al., 2007). When it comes to the monitoring of species on the move with climate change, GBIF data can be quite limiting, as occurrence data are not associated with metadata detailing cause for movement or flagging significant deviation from known distribution. Aiming to quantify the number of species on the move with climate change using GBIF data only can thus rapidly become challenging, as changes in the distribution of species need to be evaluated for each species and cross-referenced with external information to (i) establish that the change in distribution is indeed a deviation from the known distribution of the species; and (ii) assess the likelihood that movement is caused to some extent by climate change.

*Managing movement beyond invasive alien species*

As with most countries in the world, the UK does not currently have a comprehensive strategy for monitoring species redistribution underpinned by changing climatic conditions within its borders. Society is unprepared for the mass redistribution of species as current policies and agreements are not designed to manage novel species and/or communities, particularly if those species have no apparent societal ‘value’ (Scheffers & Pecl, 2019). In the UK, current emphasis is on detecting and managing the consequences of the movements of certain non-native species that have been accidentally or deliberately introduced by humans, and these are the invasive alien species (defined as species whose introduction is followed by a rapid spread and does or is likely to cause economic or environmental harm, or harm to human, animal, or plant health; Defra, 2018). Yet, as our analyses show, we detected 12 species, which are not among the top 101 invasive alien species, but which have arrived unassisted in new environments and are causing ecological, economic and/or societal damages (Table 2). This number is a gross underestimate of the likely impacts of species movements on ecosystems and society, given (i) the likely underrepresentation of invertebrates (particularly soil fauna and crustaceans) in our dataset, and (ii) the fact that we only focused on new arrivals, disregarding e.g. unusual blooms and mass abundances linked to climate change and known to negatively impact ecosystems and/or society. The challenges associated with species redistribution (in its broadest sense, i.e. including new arrivals, changes in local abundance and local extinctions) are fundamentally different from those associated with the management of invasive alien species: preventing human-induced introduction and eradicating established populations are the two most common steps for managing the threats posed by invasive alien species, yet these two steps are largely inadequate to manage species that are responding (and will continue to respond) to changes in climatic conditions (Bonebrake et al., 2017). Similarly, invasive alien species management only focuses on new arrivals, meaning that current monitoring frameworks are geared towards the detection of new species in new locations – some may argue at the expense of detecting changes in distribution and local extinctions, which is a far more complex endeavour (Boakes et al., 2015).

However, there are natural synergies between the invasive species management and the species on the move management agendas: for a start, invasive alien species that are established in a country and responding to climate change by changing their distribution in their new host country (such as, e.g., the box tree moth *Cydalima perspectalis*) are species we have described as being on the move. Second, approaches used to detect invasive species have already been modified to detect climate change driven extensions (see e.g. Robinson et al., 2015). Third, both agendas are interdisciplinary in their nature, being focused on the relationships between species redistribution, ecological impacts and wider implications for the economy and societies. Therefore, both issues are geared towards the consideration of approaches that bring together data and expertise from different sectors, such as health, agriculture/forestry and land development. Fourth, the substantial efforts devoted to the management of invasive alien species and the threats they pose has meant that coordination of data collection and sharing of information on species distribution have greatly improved, while public awareness and engagement of citizens on issues related to the movement of wildlife has increased. This will have undoubtedly contributed to the increase in occurrence data collected through citizen science initiatives, something that will ultimately benefit initiatives targeting the monitoring of new arrivals across the country.

As climatic conditions in most countries will significantly change in the next decades (IPCC 2018), however, it is now imperative that nations (i) better appreciate that invasive species are not the only group of species likely to impact our environment, economies and societies, and (ii) recognize that not all movement of wildlife lead to negative impacts, a narrative that is central to the adopted global strategy for managing invasive species (Early et al., 2016).

**Conclusions**

Climate change is a present, major driver of change: in the UK alone, our study has identified 55 species which have arrived in new environments in the past 10 years due partially or wholly to changes in climatic conditions, with 22 of them suspected to impact positively or negatively the recipient ecosystems and/or nearby human communities. Only animal species were considered during data collection, and there is likely to be further issues and similar range shifts to be reported for plants. Monitoring bias is a noticeable limitation for tracking species on the move, with butterflies and birds being amongst the most surveyed taxa in the UK. Records for these popular taxa are clearly highly valuable, but they may be unlikely to help track the full variety and strength of benefits and risks posed to societies by climate change through changes in species distribution. Shifts in distributions potentially causing ecological and societal issues are indeed more likely to be associated with uncharismatic, potentially secretive species that either play a key role in the functioning of ecosystems (such as true bugs and beetles) and/or whose life histories are closely intertwined with humans and human activity (e.g. ticks, urban spiders, mosquitoes). Crustaceans and molluscs, for example, appear in our dataset at a much lower proportion than on the invasive alien species list (Table 2) but are known to potentially be highly damaging in a new environment (Hänfling, Edwards & Gherardi., 2011). Our results also highlight the key role of social media for real-time monitoring of species in unusual locations (Chamberlain, 2018). To enhance the usefulness of this tool for ecological research, a well-publicised hashtag (e.g., #SOTM\_UK, an abbreviation for “Species On The Move in the UK”) or individual account (e.g., @SOTM\_UK) to which the public could direct their tweets would speed up the search process. A similar addition could be made to the GBIF or iNaturalist data input process, whereby species new to an area could be highlighted by the citizen scientist or the data validators. Admittedly, social media and citizen science are currently unlikely to help fill major knowledge gaps in countries lacking institutional capacity to effectively monitor their biodiversity. That said, biological records were entered in GBIF for >240 countries in 2017 alone (<https://www.gbif.org/country-report-data>), meaning that information collected by citizen scientists has the potential to become an important source of information for tracking species on the move globally. Altogether, this work allows us to identify pressing research gaps relevant to the management of species on the move. Theoretical work enabling the quick identification of species likely to be problematic (or beneficial) and locations likely to experience significant ecological and societal positive or negative impacts from biodiversity’s redistribution under a changing climate is clearly needed to identify, prioritize and then mitigate or prevent future risks. Certain geographic locations may be more likely to experience a higher level of societal and/or ecological pressure with the arrival of new species (e.g. those near the coast or with higher human population densities; Gaertner et al., 2017). Such work could be informed by current approaches considered for the management of invasive alien species, where possible methods for the prediction and mapping of arrivals have already been well established (del-Val, 2015; Robinson et al., 2015; Vicente, 2016). Within this theoretical context, one might hypothesise that specific traits are associated with larger redistributions (e.g. highly mobile species) or more damaging impacts (e.g. species that are vectors for disease) (Sunday et al., 2015; Estrada et al., 2016).

Ultimately, the lack of an integrated platform dedicated to tracking, and communicating about, species on the move (including both new arrivals and local extinctions) is a hindrance to pre-empting or mitigating the ecological, economic and societal impacts of shifting distributions. Currently, multiple layers of information from different databases have to be cross-checked and assembled to obtain a national picture of the number of species on the move and the likely impacts of their movements. However, possible solutions already exist. For example, Redmap Australia (www.redmap.org.au) is a citizen science-based data collection program that is designed to monitor marine species on the move around Australia’s coastline (Pecl et al., 2014). A similar project for the monitoring of UK species could replace the need to manually search social media and news outlets, while promoting awareness of the challenges associated with climate change driven redistributions.

**Authors’ contributions** NP conceived the ideas and designed methodology; JS collected the data; NP led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

**Data accessibility** Data available from the Dryad Digital Repository doi:10.5061/dryad.5h3r278 (Pettorelli et al., 2019).

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Table 1: Examples of species having arrived in new environments in the United Kingdom between 2008 and 2018 with climate change; reported impacts associated with these species are also listed.

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| --- | --- | --- |
| **Impacts** | **Location of colonisation** | **Species** |
| Crop pests | Manchester  London | Oak borer beetle (*Agrilus biguttatus*)  Box tree moth (*Cydalima perpectalis*) |
| Biofouling | NW Scotland | Leathery sea squirt (*Styela clava*) |
| Disease spread | Essex | Ornate cow tick (*Dermacentor reticulatus*) |
| Risk of injury | Leicester  NW Scotland | Tube-web spider (*Segestria florentina*)  Leathery sea squirt (*Styela clava*) |
| Increased fish stocks | Dorset  Lundy Island  Islay | Bluefin tuna (*Thunnus thynnus*)  Jack fish (*Seriola rivoliana*)  Red mullet (*Mullus surmuletus*) |
| Increased local tourism | Scotland  Nottinghamshire  Kent | Little egret (*Egretta garzetta*)  European bee eater (*Merops apiaster*)  Purple heron (*Ardea purpurea*) |
| Expansion of threatened wildlife alters planning permissions and farming and fisheries practices | Shetland  Kent  Dorset | Nathusius pipistrelle bat (*Pipistrellus nathusii*)  Purple heron (*Ardea purpurea*)  Bluefin tuna (*Thunnus thynnus*) |

Table 2: Comparison of the percentage (%) of species from a given taxon classified as invasive alien species versus the percentage of species from a given taxa reported as having arrived in new environments with climate change (here referred as Species On The Move, SOTM). For the purpose of this table, SOTM are species which have been found to establish a viable population in at least one new location between 2008 and 2018. We used the IUCN Global Invasive Species Database to identify invasive animal species in the UK (<http://www.iucngisd.org/gisd/>). The number of species for each category is provided (in brackets).

|  |  |  |  |
| --- | --- | --- | --- |
| **Taxon** | **Percentage of invasive alien species belonging to this taxon**  **(out of the 101 invasive alien species known to occur in the UK)** | **Percentage of SOTM belonging to this taxon (out of the 55 species in our dataset)** | **Percentage of SOTM with negative impacts belonging to this taxon (out of the 13 species in our dataset)** |
| Insects | 17.8 (18) | 50.9 (28) | 23.1 (3) |
| Annelids (worms) | 5 (5) | 0 | 0 |
| Arachnids | 1 (1) | 7.3 (4) | 23.1 (3) |
| Crustaceans | 8.9 (9) | 1.8 (1) | 7.7 (1) |
| Cnideria | 0 | 1.8 (1) | 0 |
| Tunicates | 2 (2) | 1.8 (1) | 7.7 (1) |
| Molluscs | 10.9 (11) | 1.8 (1) | 0 |
| Marine fishes | 1 (1) | 5.5 (3) | 7.7 (1) |
| Freshwater fishes | 16.8 (17) | 0 | 0 |
| Birds | 12.9 (13) | 20 (11) | 7.7 (1) |
| Reptiles | 1 (1) | 0 | 0 |
| Amphibians | 2 (2) | 0 | 0 |
| Mammals | 13.9 (14) | 9.1 (5) | 23.1 (3) |
| Ectoprocta (aquatic invertabrates) | 4 (4) | 0 | 0 |

Figure 1: Percentage of entries (out of the 69 collected) for each taxa in our database (referred as SOTM records) versus the percentage of occurrence recorded for each taxa in the GBIF UK database. The figure also includes icons illustrating which types of impacts the taxa in our dataset are associated with (with buildings referring to impacts on infrastructures; crops to impacts on food production; ambulance to impacts on health and safety; leaf to ecosystem health impacts; and people referring to cultural impacts or impacts on tourism). For readability purposes, the nature of the impacts reported (positive or negative) is not detailed; however, most of the examples we assembled primarily mentioned negative impacts.

