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RESEARCH ARTICLE

Assessing the success of a horizon scanning approach in predicting invasive non-native species arrival

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Abstract

1. Despite increasing awareness of invasive non-native species (INNS) and enhanced biosecurity controls in many countries, INNS are still arriving and establishing in new destinations, remaining a globally acknowledged threat to native biodiversity. Preventing the introduction of INNS, as opposed to controlling them once they have arrived, is recognised as the most effective approach to their management. Horizon scanning represents one of the key tools to identify high-risk INNS that have yet to arrive within a region and has been applied in many contexts around the world, but to date there have been no studies that systematically assess the effectiveness of this approach.
2. Here, we revisit the horizon scan for Great Britain conducted in 2013 that assessed the likelihood of high-risk INNS arriving within the next 10 years, establishing and having an impact on biodiversity and ecosystems. We evaluated the success of this exercise in predicting arrival of these species within the subsequent 10 years.
3. Ninety-two species were shortlisted in the 2013 horizon scan. In total, 31 of the 92 species identified in the 2013 horizon scan had arrived by 2023. We found that 12 of the top 20 species had arrived within 10 years. In predicting arrival,

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there was a significant effect of species having arrived previously to Great Britain, and the number of countries in Western Europe and Baltic countries in which an INNS was found prior to 2013.

4. *Policy implications*: We conclude that horizon scanning provides a rapid, affordable and successful mechanism to predict the arrival of high-risk INNS. We highlight the importance of citizen science, including biological recording, and of local expertise for detecting and documenting arrival of INNS. We discuss knowledge gaps that could help inform and improve future horizon scanning. In addition, we recommend regularly repeating horizon scanning exercises to support biosecurity and awareness raising for INNS.

KEYWORDS

biodiversity, biological invasions, expert elicitation, impact, management, mitigation prevention

1 | INTRODUCTION

Species have been introduced and spread by human activity for thousands of years, but at an increasing rate since the onset of globalisation (IPBES, 2023). The rate of species introduction to new locations has increased dramatically since the 1800s and shows no signs of slowing (IPBES, 2023; Seebens et al., 2017). Globally, the proportion of non-native species that become invasive (INNS) in their introduced range varies between taxonomic groups and is around 6% for plants and 22% for invertebrates (IPBES, 2023). This number increases to over 50% for vertebrates introduced into Europe and North America (Jeschke, 2008; Jeschke & Strayer, 2005). Future scenarios suggest that the number of established INNS globally will increase by 36% between 2005 and 2050 (Seebens et al., 2017). Biological invasions are one of the top five direct drivers of global biodiversity decline (Díaz et al., 2019) and a recent meta-analysis has shown that INNS were more detrimental to native ecosystems than global warming or nitrogen deposition (Lopez et al., 2022). INNS are implicated in 60% of all known extinctions [Extinct, or Extinct in the Wild (IUCN, 2001)], and in 16% of cases, were the sole factor responsible (IPBES, 2023; Smith, 2020). However, in practice, a relatively small number of INNS drive biodiversity loss (Smith, 2020). For example, Doherty et al. (2016) showed that 30 predatory INNS were linked to declines and extinctions of 738 vertebrate species.

The Kunming-Montreal Global Biodiversity Framework (2022) presents a list of targets to support biodiversity, including reducing the rate of introduction and establishment of invasive alien (non-native) species by at least 50% by 2030 (Target 6) (Convention on Biological Diversity). In Great Britain (England, Scotland and Wales) alone there are 3248 known non-native species (JNCC, 2021), of which 2016 are established (self-sustaining populations) (Roy, Preston, et al., 2014). One hundred and ninety-four of these 2016 species (~10%) are considered invasive with negative impacts on biodiversity and wider ecosystem viability (108 terrestrial, 47 freshwater and 39 marine species) (Harrower et al., 2021). This includes the eastern grey squirrel (*Sciurus carolinensis*) which has led to declines of the native red squirrel (*S. vulgaris*) (Bruemmer et al., 2010), the aquatic macrophyte New Zealand pygmyweed (*Crassula helmsii*) which comes from Australia and New Zealand and was first recorded as naturalised in Great Britain in 1956 and has negative impacts on native plants and ecosystems (Smith & Buckley, 2020), and a marine snail, *Urosalpinx cinerea*, which is a predator of European native oysters (*Ostrea edulis*) (Oakley, 2006). The potential impacts of INNS extend beyond biodiversity, to include the economy, human health and well-being (Bacher et al., 2018; Diagne et al., 2021). For example, Cuthbert et al. (2021) suggest costs of INNS to the British economy of between £5.4 and £13.7 billion since 1976 but, due to a lack of information for many species, this value is likely to be an underestimate. More recently, Eschen et al. (2023) suggested costs of INNS to the British economy of around £3.9 billion per year, although this cost is largely due to the effects of Ash dieback caused by the fungus *Hymenoscyphus fraxineus* (Baral & Bemmann, 2014).

In Great Britain, government agencies recently published the INNS strategy (2023–2030), with one of the overarching aims to reduce the risk of introduction and establishment of INNS and their impact (Defra et al., 2023). Preventing the arrival and/or establishment of new INNS is considerably cheaper and more effective in minimising impacts, compared to management actions after the event (Cuthbert et al., 2022; Kim et al., 2006). As such, early detection is important in informing rapid response systems and mitigation measures to reduce the probability of species arriving and subsequently establishing (Reaser et al., 2020). Horizon scanning for INNS is a systematic approach for identifying potential threats in terms of arrival and establishment and offers opportunities to reduce these risks, for example, through supporting biosecurity watch lists (Roy, Peyton, et al., 2014). The specific factors explaining which species are more likely to arrive and establish will differ in varying contexts, such as for a continental country compared with islands, but in all cases, it is important to broadly assess relevant environmental conditions, pathways and socioeconomic factors.

An adapted expert-elicitation process developed by Roy, Peyton, et al. (2014) was originally used in 2013 to predict which INNS could arrive and pose a threat to biodiversity and ecosystems in Great Britain within the following decade. A prioritised list of 92 high-risk species was generated by reviewing 591 INNS that were not established in Great Britain at that time [in the original paper by Roy, Peyton, et al., (2014) 93 species are mentioned, but only 92 were listed]. This approach to prioritisation of species has subsequently been used in, for example, the Antarctic Peninsula (Hughes et al., 2020), Europe (Roy, Bacher, et al., 2019), Ghana (Kenis et al., 2022), Ireland (Lucy et al., 2020), Italy (Monaco et al., 2020), Belgium (Adriaens et al., 2022), Kenya (Mulema et al., 2022), Greece (Arianoutsou et al., 2023), the Mediterranean Sea (Tsiamis et al., 2020), Spain (Cano-Barbacil et al., 2023) and the UK Overseas Territories (Dawson et al., 2022; Peyton et al., 2019, 2020; Roy, Peyton, et al., 2019).

Despite the increased use of horizon scanning to predict the arrival of INNS, the efficacy of the method has not hitherto been comprehensively assessed. The horizon scanning exercise of Roy, Peyton, et al. (2014) was used as an approach to underpin strategies to reduce the probability of INNS arriving and establishing in Great Britain such as contingency planning, rapid responses and surveillance by refining citizen science alert systems, for example Plant Alert and Asian Hornet Watch (Defra et al., 2023). However, the effectiveness of these strategies and the allocation of resources to target mitigation to those high-risk species is dependent on the accuracy of these expert opinion-based approaches. This requires an evaluation of the method, its predictive power and, ultimately, its benefits to INNS policies and management activities. A repeat horizon scanning exercise for INNS in Great Britain during December 2019 provided an opportunity to review the list of INNS that had arrived since the first horizon scan in 2013 and to evaluate the success of the approach for predicting new arrivals.

The horizon scanning list of Roy, Peyton, et al. (2014) was compiled based on knowledge of species impacts and availability of data at the time of the assessment. The relative position of a species on the list reflected the considered likelihood of the species arriving, establishing and having a negative impact on biodiversity and ecosystems, as agreed by the experts involved in the process. Here, we review the outcomes of species included on this list after a 10-year period since the horizon scanning list was proposed and specifically how many and which of the 92 species arrived.

We then looked for factors that were correlated with the arrival of high-risk INNS. Identifying these causal factors provides a basis for focusing future expert-elicitation horizon scanning exercises and possible management actions. We predicted that the likelihood of an INNS arrival would be correlated with:

(i) Functional group: Predatory species are more likely to arrive, not only because some are intentionally introduced, for example as pets (Doherty et al., 2016) but as they can also utilise diverse food resources (in contrast to monophagous herbivores) and show high levels of within-year mobility, for example, compared to plants;
(ii) Historic trends for environment: Existing data for Great Britain suggest invasive non-native terrestrial species may be more likely to arrive than either marine or freshwater species (Roy et al., 2012). This could be for several possible reasons, including greater availability of data, more introduction pathways or more trade in terrestrial species;
(iii) Number of pathways: Species that are associated with a higher number of introduction pathways will be more likely to arrive (Lockwood et al., 2009);
(iv) Prior arrival: Species with historical evidence of prior arrival, but not successful establishment, would be more likely to arrive again; and
(v) Proximity to Great Britain: So-called "door-knocker" species with records from countries in close proximity to Great Britain (i.e. based on national occurrence records) are more likely to arrive (NOBANIS, 2015).

2 | METHODS

2.1 | Arrival and establishment of horizon scanning species

In 2013, Roy, Peyton, et al. (2014) brought together experts in INNS to determine a shortlist of species that could arrive, establish, and potentially have a negative impact on biodiversity and ecosystems in Great Britain within 10 years. For the current paper, the shortlist of 92 species that were predicted in 2013 to arrive within 10 years, establish and have a negative impact was assessed again to determine the current arrival and establishment status (Blackburn et al., 2011).

For consistency of approach, where possible, the same expert thematic group leads reviewed the lists of species that had arrived in Great Britain, as in 2013 (Roy, Peyton, et al., 2014). These reviews were undertaken based on the best available evidence and using the databases and other literature available, to determine whether the listed species had arrived and/or established. These databases included (as in 2013) the GB Non-Native Species Information Portal (GBNNSIP) and the Botanical Society of Britain and Ireland (BSBI) Distribution Database (DDb) in addition to the British and Irish Plant Atlas 2020 (Stroh et al., 2023) up to the end of 2022. Peer-reviewed and grey literature were also reviewed, using keyword searches that consisted, for example, of 'species scientific name' and 'common name' and 'arrived' and 'Great Britain'.

As with the original horizon scan, arrival for animals (other than captive waterfowl) was considered as the introduction into Great Britain and its entry into the wild (wider countryside, outside of direct human husbandry) that was mediated by human intervention or by a natural pathway if non-native at its origin. For plants, in the original 2013 horizon scan (Roy, Peyton, et al., 2014), species grown in gardens or in planting schemes in urban habitats were not included within the assessment. Given the challenges of determining the establishment status of plant species from single-visit data, the authors considered it pragmatic and more accurate to consider arrival into the wild and establishment synonymously for plants. Therefore, both animals and plants were considered established if they were maintaining self-supporting populations in the wild. The assigned status from the authors was also reviewed by additional expert opinion (e.g. biological recorders including BSBI Vice County Recorders). Table 1 lists the 31 INNS species that have arrived since 2013, with the record date.

2.2 | Additional species information and traits

In addition to assessing whether species had arrived and established, we also reviewed and included information for each species on the following factors expected to affect arrival and establishment success:

(i) Functional group: To determine the effect of resource utilisation strategies on arrival, species were defined based on whether they were primary producers (e.g. plants) or animals that were aquatic filter feeding, herbivorous, omnivorous, parasitic or predators;
(ii) Environment: Species were allocated to their principal biome, that is marine, freshwater or terrestrial;
(iii) Number of introduction pathways: The Convention on Biological Diversity (CBD) Level II introduction pathways (CBD, 2014; Harrower et al., 2018) were assigned for each INNS from a review of the literature, with a confidence score based on a three-point system. A 'High' confidence score was given when a species was documented to have been introduced via a given pathway either in Great Britain or somewhere else in the world; 'Medium' was used where evidence was found in the literature for a related species being introduced via this pathway; 'Low' was used where there was limited evidence for this pathway. The full list of pathways can be found in the see Appendix S1;
(iv) Whether a species has arrived before in Great Britain: Prior arrival identified the existence of a viable arrival pathway and a source population (at least historically) in close enough proximity to arrive, even if that population did not persist. Based on expert opinion, literature and database searches, we categorised each species as either having or having not arrived in Great Britain in the past; and
(v) The number of Western European and Baltic countries that a species was recorded in prior to 2013. This defined the number of possible source countries in close enough proximity for likely arrival of INNS. The Global Biodiversity Information Facility (GBIF) was searched to locate presence through records of the 92 species from the following countries/crown dependencies: Belgium, Channel Islands, Denmark, Estonia, Finland, France, Germany, Ireland, Latvia, Lithuania, Netherlands, Norway, Poland, Portugal, Spain and Sweden. These are countries from which species could naturally disperse, as well as being geographically close to Great Britain providing increased opportunities for arrival via trade, the wind, water currents or their own species-specific dispersal mechanisms, for example plant seeds/vegetative fragments, or flight for invertebrates and birds.

The GBNNSIP was reviewed in January 2024 to compare the target species in the 2013 list that have arrived against a background rate of arrival.

2.3 | Statistical analysis

We tested whether the arrival of an INNS was predicted by functional group, environment, number of CBD Level II introduction pathways, previous biological invasion history in Great Britain, and the number of countries in Western Europe and Baltic countries with a native or non-native presence of a species. The analyses in this paper are tests of correlation rather than causation. Generalised linear models (GLM) were used to test the response of species arrival to a full model containing all the above terms as fixed effects. Due to the limited number of data points ($n=92$), interaction terms were not considered. Model simplification was by deletion of least significant terms from a saturated model using chi-squared tests of significance and a binomial GLM with a logit link function was used. All analyses were performed using R Statistical Software (v4.3.2; R Core Team, 2023). Plotted treatment means were model-derived estimated marginal means produced using the emmeans package (Lenth, 2024).

3 | RESULTS

Thirty-one of the 92 (34%) species on the list of INNS derived through horizon scanning in 2013 had arrived and/or established in Great Britain by December 2022 (Table 1). Sixty percent of the top 20 INNS had arrived within 10 years, and this reduced to 53% for the top 30 species. Arrival scores (Roy, Peyton, et al., 2014) were used in 2013 to predict how likely it would be for a species to arrive in Great Britain and were scored between 1 and 5 (unlikely to very likely). Of the 46 species given an arrival score of 5 in 2013, 50% ($n=22$) had arrived by 2022. Furthermore, 35% of the species considered to be relatively likely to arrive (species with a score of 3 or more) and 35% of the relatively high-impact species (species with a score of 3 or more) had arrived within 10 years. Appendix S1 provides further information for all 92 species identified in the 2013 horizon scan.

These 31 species comprised five plants (23% of the total plants on the list), two freshwater invertebrates (11% of the total freshwater invertebrates on the list), seven terrestrial invertebrates (78% of the total terrestrial invertebrates on the list), ten vertebrates (45% of the total vertebrates on the list) and seven marine species (primary producers, invertebrates and vertebrates), which made up 35% of the total marine species on the list (Table 2). Of these 31 species, three were eradicated, these being the Asian longhorn beetle,

TABLE 1 Thirty-one INNS from Roy, Peyton, et al. (2014) that have been reported in Great Britain since 2013.

Rank in 2013	Year reported in Great Britain/ confirmed as established	Thematic group	Species	Common name	Functional group
1	2014	Freshwater invertebrate	*Dreissena rostriformis bugensis**	Quagga mussel	Filter feeder
2–10	2013	Terrestrial invertebrate	*Anoplophora glabripennis*	Asian longhorn beetle	Herbivore
2–10	2014	Marine	*Hemigrapsus sanguineus*	Asian shore crab	Omnivore
2–10	2014	Marine	*Hemigrapsus takanoi**	Brush-clawed shore crab	Omnivore
2–10	2014	Marine	*Homarus americanus*	American lobster	Omnivore
2–10	2015	Plant	*Myriophyllum heterophyllum*	American water-milfoil	Primary producer
2–10	2015	Vertebrate	*Procyon lotor*	Raccoon	Omnivore
2–10	2019	Vertebrate	*Threskiornis aethiopicus*	African sacred ibis	Omnivore
2–10	2016	Terrestrial invertebrate	*Vespa velutina nigrithorax*	Yellow-legged (Asian) hornet	Predator
11–20	2016*	Terrestrial invertebrate	*Linepithema humile**	Argentine ant	Omnivore
11–20	2014	Marine	*Mnemiopsis leidyi*	American comb jelly	Predator
11–20	2015	Marine	*Rapana venosa*	Veined rapa whelk	Predator
21–30	2015	Terrestrial invertebrate	*Dryocosmus kuriphilus**	Oriental chestnut gall wasp	Herbivore
21–30	2014	Vertebrate	*Nyctereutes procyonoides*	Raccoon dog	Omnivore
21–30	2015	Vertebrate	*Tamias sibiricus*	Siberian chipmunk	Omnivore
21–30	2013	Marine	*Gracilaria vermiculophylla**	Rough agar weed	Primary producer
31–92	2021	Plant	*Acacia dealbata**	Mimosa, silver wattle	Primary producer
31–92	2014	Vertebrate	*Acridotheres tristis*	Common myna	Omnivore
31–92	2016	Terrestrial invertebrate	*Aedes albopictus*	Tiger mosquito	Hematophagous
31–92	2021	Plant	*Akebia quinata**	Chocolate vine	Primary producer
31–92	2020	Terrestrial invertebrate	*Anoplophora chinensis*	Citrus longhorn beetle	Herbivore
31–92	2021	Freshwater invertebrate	*Chelicorophium robustum*	An amphipod	Omnivore
31–92	2017	Vertebrate	*Chelydra serpentina*	Snapping turtle	Omnivore
31–92	2019	Vertebrate	*Chrysemys picta*	Eastern painted turtle	Omnivore
31–92	2021	Plant	*Fraxinus pennsylvanica**	Green ash	Primary producer
31–92	2018	Terrestrial invertebrate	*Halyomorpha halys*	Brown marmorated stink bug	Herbivore
31–92	2015	Vertebrate	*Mephitis mephitis*	Striped skunk	Omnivore
31–92	2015	Vertebrate	*Nasua nasua*	Coatimundi	Omnivore
31–92	2021	Marine	*Pterois* sp.	Red lionfish	Predator
31–92	2021	Plant	*Saururus cernuus**	Swamp lily	Primary producer
31–92	2013	Vertebrate	*Tadorna ferruginea*	Ruddy shelduck	Omnivore

Note: The original rank given in 2013 is given, along with the thematic group used to assign species in the workshop, species name and English common name (Catalogue of Life, accessed March 2024), and the assigned functional group. Species that are considered to have established since the 2013 horizon scan are marked with an asterisk.

TABLE 2 Number of species, within different taxonomic groups, classified in three categories: Arrived and/or established or have been eradicated in Great Britain between 2013 and 2022.

Taxonomic group	Number of taxa (2013 GBHS list)	Arrived	Established	Eradicated	Not considered to have arrived and established in Great Britain since 2013
Plants (terrestrial and freshwater)	23	5 (and established in the wider countryside)	4	1	18
Freshwater invertebrates	18	2	1	-	16
Terrestrial invertebrates	9	7	2	2	2
Vertebrates	22	10	-	-	12
Marine	20	7	2	-	13
Total	**92**	**31**	**9**	**3**	**61**

Note: In relation to the overall numbers for freshwater taxa, terrestrial invertebrates, terrestrial vertebrates and marine species, the number of taxa = number of arrived species + number of species that have not arrived since 2013, with the number of species that have arrived consisting of the number that have arrived and established or arrived and have been eradicated. Bold values indicate total number of taxa from the 2013 GBHS list, the total number of taxa considered to have arrived and the total number of taxa not considered to have arrived and established.

American water-milfoil and yellow-legged (Asian) hornet, and a further nine are considered established (Table 2; Appendix S1). Twelve of the 31 arrived species had not previously been recorded in Great Britain, prior to the 2013 horizon scan (Appendix S1).

The most common native ranges of the 31 species that arrived in Great Britain were temperate and tropical Asia, North America, and for the marine, the temperate North Pacific (Figure 1).

Figure 2 illustrates potential pathways of introduction for the 31 INNS. The CBD Level I pathway categories 'Transport-stowaway' ($n=49$), 'Escape' ($n=39$) and 'Transport-contaminant' ($n=28$) have the highest occurrence amongst the 31 species that arrived. Multiple CBD Level II pathways sit within the CBD Level I pathways and given that species can travel through multiple pathways, the number of CBD Level I pathways is greater than the number of INNS. Of the species that arrived in Great Britain between 2013 and 2022, all but the brown marmorated stink bug had records from Great Britain and Western European and/or Baltic countries/waters prior to 2013.

3.1 | Variables important in predicting species arrival

Following model simplification, there was a significant effect of 'arrival before 2013' ($\chi^2_1 = 6.03$, $p < 0.01$). For species with a previous history of arrival in Great Britain, the model predicted a 51.6% (95% CI: 32.9%–69.9%) probability of arrival compared to species that were never found in Great Britain which had only a 22.6% (95% CI: 13.2%–35.8%) chance of arrival. In addition, the number of countries in Western Europe and Baltic countries a species was found in prior to 2013 was also a significant predictor of arrival ($\chi^2_1 = 4.3$, $p=0.05$) (Figure 3).

3.2 | Background species arrival in Great Britain

The GBNNSIP was reviewed in January 2024 to determine how many non-native species had arrived in Great Britain between 2013 and 2022. One hundred and twelve species were considered to have arrived and/or established in Great Britain in addition to the 31 species on the horizon scan list documented as having arrived.

4 | DISCUSSION

The first INNS horizon scan for Great Britain was evaluated through reviewing the arrival and establishment status of the species predicted to arrive. There was evidence that over a third (31 species, 34%) of the 92 species with a documented risk to negatively impact biodiversity and ecosystems that were predicted to arrive were subsequently reported. In 13 cases, these were considered established ($n=9$) or established but were subsequently eradicated ($n=4$) as part of an active management policy to prevent their spread (Table 2; Appendix S1). Predictive success varied between taxonomic groups,

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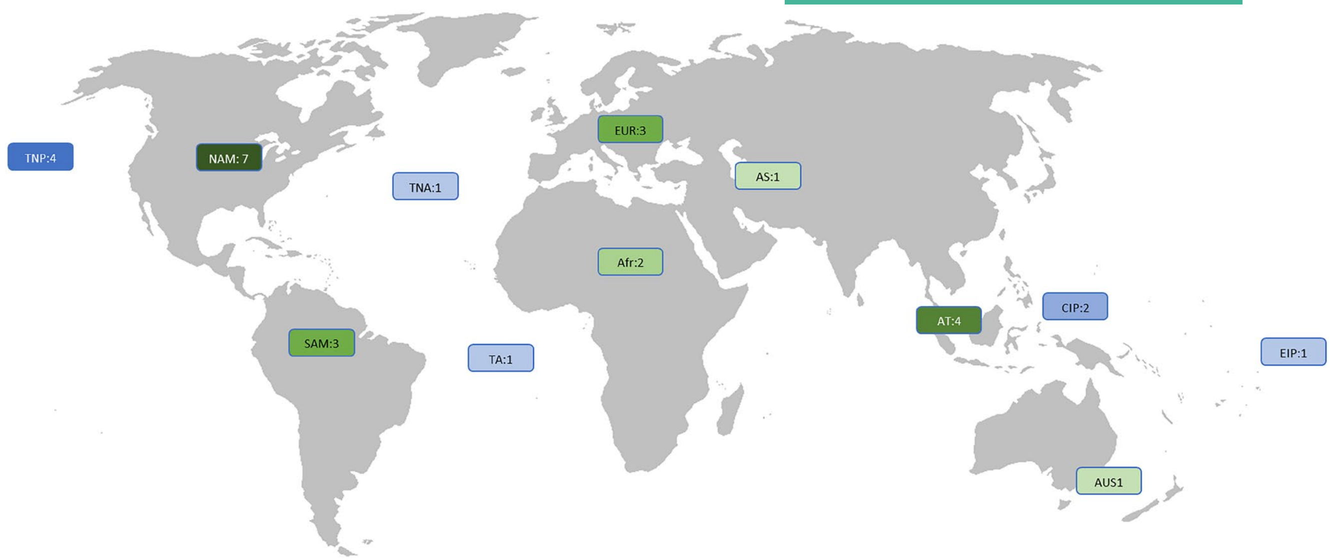

FIGURE 1 Native range of the 31 species that arrived in Great Britain since 2013. The strength of shading in the boxes indicates the number of species to have arrived from this native range. Some species are native to more than one region. The native range codes are based on the World Geographical Scheme for Recording Plant Distributions (WGSRPD) (Brummitt, 2001), as follows: Afr, Africa; As, Asia temperate, AT, Asia tropical; Aus, Australia; CIP, central Indo-Pacific; EIP, eastern Indo-Pacific; Eur, Europe; Nam, North America; Sam, South America; TA, tropical Atlantic; TNA, temperate north Atlantic; TNP, temperate north Pacific. The two freshwater invertebrate species that had arrived in Great Britain since 2013 are from the Ponto-Caspian region (defined as Europe and Asia temperate in the WGSRPD).

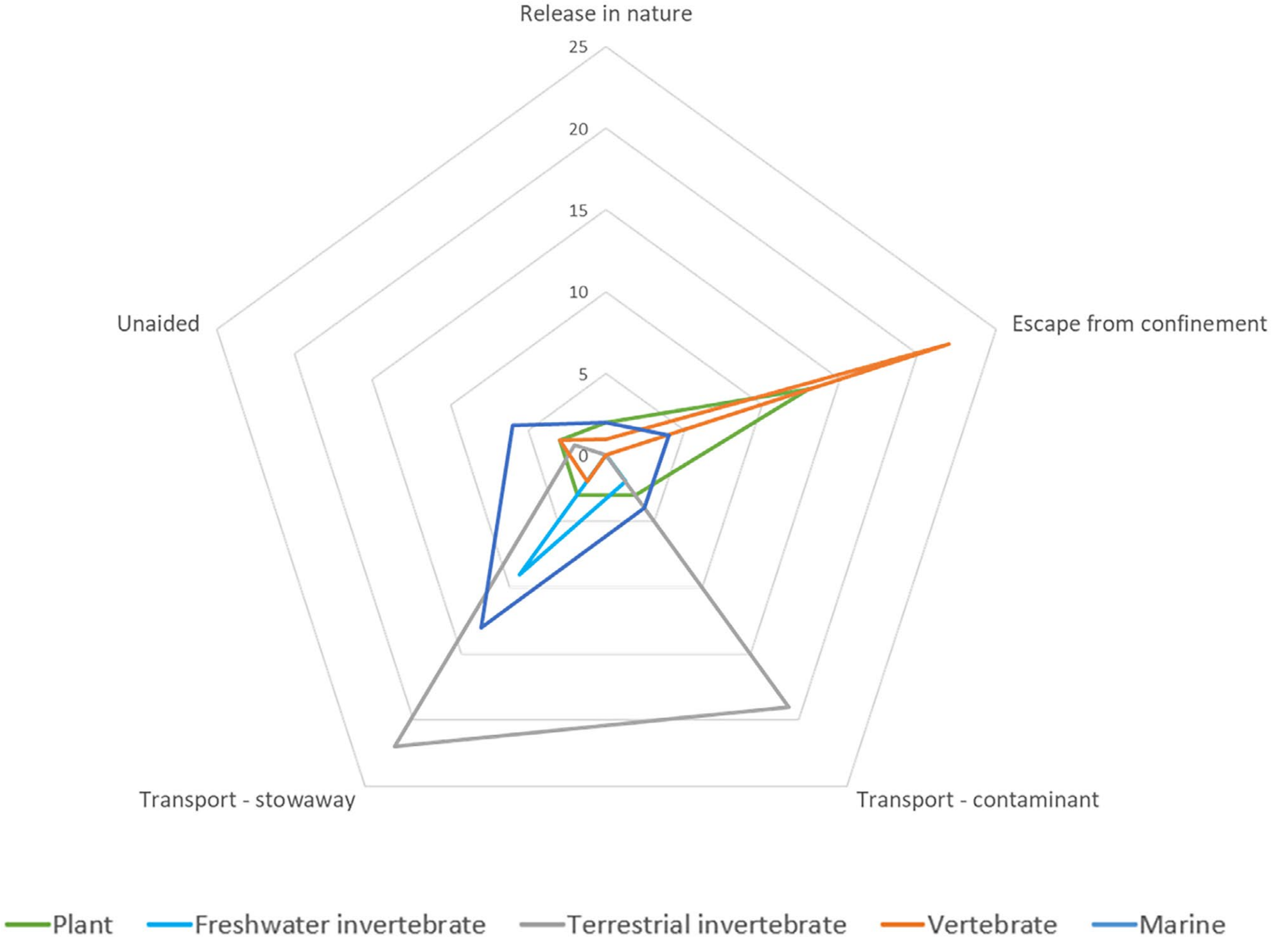

FIGURE 2 The predicted CBD Level I pathway categories of the 31 species from Roy, Peyton, et al. (2014), represented by thematic group, that have arrived in Britain since 2013 (CBD, 2014; Harrower et al., 2018).

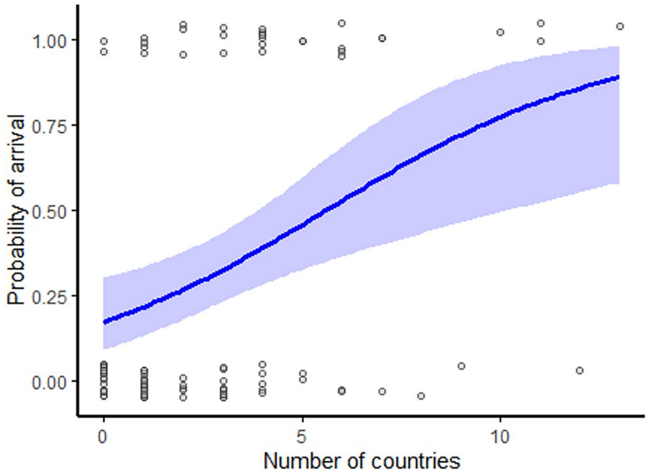

FIGURE 3 Predicted arrival probability (±95% confidence intervals) for INNS according to the number of Western European and Baltic countries with a recorded presence of an INNS prior to 2013. All plotted values are derived directly from the fitted model and back transformed from logit values to raw probabilities.

for example, 78% ($n=7$) of terrestrial invertebrates arrived compared with 11% ($n=2$) of freshwater invertebrates, which could be due to the high dispersal capacity of some terrestrial invertebrates, but this could be linked to the influence of sampling and recording effort and ease, in terrestrial environments compared with freshwater. The accuracy of the predictions was highest for species included in the top 10. Invasion success does decline as more species are included the following: 90% for 1–10; 60% for 1–20; 53% for 1–30; 34% for 1–92. There is also a decline if the groupings are considered separately: 90% for 1–10; 30% for 11–20; 40% for 21–30; 25% for 31–92.

The confirmed arrival of over a third of the 92 species on the Roy, Peyton, et al. (2014) horizon scan list indicates that horizon scanning is a policy-relevant tool for predicting which species are most likely to arrive. These 31 INNS are additional to the 112 non-native species that arrived between 2013 and 2022, meaning that 22% (31 out of 143) of all recorded species that arrived were predicted by the previous horizon scan. It is worth noting that the 2013 horizon scan listed only high-risk INNS, so it would not have included many of the non-native species that subsequently arrived but had not been predicted, because they were not considered to have negative impacts on biodiversity. Moreover, clearly, the arrival of some of the species identified through horizon scanning was followed by a management action, including their rapid removal and their inclusion in targeted surveillance programmes (e.g. yellow-legged hornet). Although we did not quantify this, this suggests horizon scan species are detected quicker and responded to more effectively, suggesting active uptake of the horizon scan lists by INNS policy and management.

It is interesting to speculate on why 112 species had arrived since 2013 but had not been predicted by the scan to do so. There are several possible reasons for this. There has been a huge increase in the availability of data on INNS and impacts and pathways. A rapid and preliminary review of the 112 species showed that 24 may have negative impacts, with a further 22 being uncertain to have negative impacts on biodiversity and ecosystems. As such, these species could have been suggested for assessment during the 2013 horizon scan. However, this retrospective assessment is based on the information available now, not from 2013. It is very difficult to retrospectively judge what information was available for the assessors at the time, but these species could have been missed for any of the following possible reasons pertaining at the time:

1. There was no information available on their impacts and as such they would not have been listed;
2. There was no information on their pathways;
3. They were not known to be being traded; and
4. There was no specific expert on this particular taxonomic group in the exercise.

It is predicted that the efficacy of horizon scans will improve with time as more information becomes available on INNS around the world, such as through the GRIIS lists, and as INNS impacts are more readily understood and documented. However, given that globally 25% of INNS have no prior history of invasion (Seebens et al., 2018), and acknowledging the complexities of biological invasions (e.g. niche shifts; Bates & Bertelsmeier, 2021; Núñez-Tobajas et al., 2024), it is considered unlikely that the horizon scan process can ever be 100% effective in predicting species arrival.

A significant positive correlation was observed between the number of countries in Western Europe and Baltic countries with records for a species and the probability of that species arriving in Great Britain. This result supports the importance of the role of propagule pressure in biological invasions (Hayes & Barry, 2008; Simberloff, 2009). However, this result may be a consequence of the circular initial listing and scoring process, whereby INNS that are found near to Great Britain are more likely to be known of and therefore more likely to be listed. There was also a significant positive correlation between a species having arrived before and being likely to arrive again. Two-thirds of the species that arrived had been recorded (but not established) previously in Great Britain ($n=19$). Again, this gives support to the importance of propagule pressure in biological invasions, but it should be noted that prior arrival could mean that recorders become more aware of these species and surveillance is heightened compared with species that have not arrived before. As such, there might then be a reporting bias. There is the possibility that these species remained in the environment and were just not detected, rather than failed to establish and then arrived again. This would be quite possible where species are more inconspicuous or live in areas that are hard to survey, such as the marine environment, but in the case of species that are more conspicuous, such as raccoon, this is considered unlikely.

Interpretation of the analyses was constrained by small sample sizes in some categories (e.g. three INNS classified as parasites) and the lack of a balanced survey design. The low predictive power of the other variables (functional group, environment and number of CBD Level II introduction pathways) needs to be taken in context of the data set on which the analysis was based, that is, it focuses on 92 species predicted as being likely to arrive in Great Britain from 2013 and potentially having an impact on biodiversity. This analysis of the data set was not undertaken as part of an experiment or trial and as such species characteristics that predict arrival are not necessarily allocated in a balanced manner. As such, while these variables were not predicted as having a significant effect, their importance in determining the invasion risk of species in a wider context should not be ignored. For example, that primary producers only comprise six (four terrestrial, one freshwater and one marine) of the 31 species that arrived could be an indication that there may be a lag effect, with species not yet spreading in the wider environment. With respect to pathways, if a specific pathway was more important for a species in terms of the frequency of introduction along that pathway or the volume of individuals involved, the number of pathways might not make any difference to its probability of arrival. In addition, while pathway action plans, initiating management actions at the most relevant pathways of introduction, are the best option for prevention, pathway assignment comes with considerable amounts of uncertainty. For example, in this work, only 3% of the pathways were assigned with 'High' confidence by the authors, the majority being assigned with 'Medium' confidence (Appendix S1). Future evaluations of predictive success of horizon scans could include refinement of the model variables based on a gap analysis of the attributes of the species where arrival was not predicted.

The INNS native range was not included in the analysis as it was considered to be more closely linked in determining the likelihood of a species establishment in Great Britain rather than arrival. Arrival probability is linked to global trade networks (Chapman et al., 2017; Hulme, 2009), but this can be obscured by secondary spread, that is the introduction of a non-native species from other established populations in the introduced range (Bertelsmeier & Keller, 2018).

4.1 | Records of new arrivals from other horizon scans

INNS horizon scanning lists have been generated for other countries and territories around the world. Arrivals of prioritised INNS have also been documented for some of these lists, although often only reported in grey literature. For example, at least four species included in the 2017 and 2019 Cyprus horizon scanning lists (Peyton et al., 2019, 2020) have arrived since: the common myna (*Acridotheres tristis*) (BirdLife Cyprus, 2023), the yellow fever mosquito (*Aedes aegypti*) (Martinou, pers. comm), the tiger mosquito (Martinou et al., 2022) and the little fire ant (*Wasmannia auropunctata*) (Demetriou et al., 2022). Records of the Chinese mitten crab (*Eriocheir sinensis*) (National Biodiversity Centre, 2021a) and the quagga mussel (National Biodiversity Centre, 2021b) have been reported from Ireland since the 2017 horizon scan (Lucy et al., 2020) was undertaken. Two species arrived from the Italian horizon scan list, the ascidian *Styela clava* in 2021 in the Lagoon of Venice (Mastrototaro et al., 2022) and the quagga mussel in 2022 in Lake Garda (Salmaso et al., 2022). These new arrivals indicate that horizon scanning is a useful method to prioritise INNS that could potentially arrive in a given area.

4.2 | Potential bias in the data

The authors acknowledge that there may be a bias introduced into the analysis due to the enhanced availability of biological records since the 2013 horizon scan, due to increases in mobilised historic data through platforms such as GBIF, the data collected as part of the creation of new Atlases (e.g. Stroh et al., 2023), the availability of recording tools, the popularity of citizen science and due to targeted communication campaigns on INNS (Defra et al., 2023). This may have led to an increase in biological recording activity for some taxonomic groups. However, both assessments of species status were done using the best available data at the time with the same expert leads participating and determining whether a species had arrived before or was considered to have established. This assessment of establishment status was done both prior to the 2013 horizon scan (and thus species not established were included on the original 2013 list) and post the 2013 horizon scan through analysis of the GBNNSIP and collation of peer-reviewed and grey literature. The authors consider that although bias could be brought in through increased availability of data, by working with the same expert thematic leads that undertook the original scan, any further bias would be minimised.

The detection of the species that have arrived may be biased by their ease of identification, likelihood of encountering the species, the accessibility of the sites and habitats where they typically occur and the apparency of their negative impacts. For both the 92 listed species and 112 species from the GBNNSIP, the number of arrivals is likely to be an underestimate of the true number due to, for example, delays in detection (Aikio et al., 2010). Cryptic species or species that are found in remote or inaccessible areas may be less likely to be encountered and recorded (Isaac & Pocock, 2015). Detection probability of marine species, for example, is potentially lower due to the difficulty of surveying some marine environments and relatively fewer potential recorders than in terrestrial environments (Wood et al., 2024). Linked to this, biosecurity for marine and freshwater species can be more complicated to implement than for terrestrial species, such as their movement through 'unaided' and 'corridor' pathways (e.g. Galil et al., 2017; Gollasch et al., 2006) and as such, could be expected to yield more arrivals in the future. Biosecurity measures for some taxonomic groups can also pose challenges. For example, biosecurity measures are often considered too difficult to implement for terrestrial molluscs, which use a broad range of dispersal pathways as they are not restricted to specific host plants (in comparison to many other terrestrial invertebrates) (Cavadino, 2022). The list of 31 species that have arrived includes an unidentified lionfish (*Pterois* sp.) where a sighting was made, but no specimen was recovered. Although *Pterois volitans* was on the 2013 list, the inclusion of *P. miles* in the 2013 list might also have been important, as this species is present and spreading in the

Mediterranean (e.g. Kletou et al., 2016). Finally, a lack of knowledge and expertise within certain groups may also impact the results for both predicting species arrival and determining if they have arrived. Roy et al. (2017) outlined knowledge and information needs to enhance understanding of microorganisms, including pathogens, within biological invasions. Furthermore, the critical knowledge and data gaps acknowledged through the Thematic Assessment Report on Invasive Alien Species and their Control (IPBES, 2023) highlight the challenges of broadening the scope of horizon scanning to include microorganisms.

4.3 | Data availability and global applicability

In Great Britain, there is a wide range of sources of information on the occurrence of INNS, including the biological recording schemes and societies (www.brc.ac.uk), which provide reliable records of the arrival and in some cases establishment state of many INNS (Pescott et al., 2015; Pocock et al., 2015; Wood et al., 2024). Challenges remain, however, in attempting to comprehensively collate records, in a timely manner, from all the potential sources in which they may first appear, including social media, reports in 'grey literature', or via projects that, for multiple reasons, do not share their data widely. These challenges could be exacerbated in areas or countries where the flow of biodiversity information is limited and where the availability of information on species presence or establishment status is lacking. As stated in the recent Thematic Assessment Report on Invasive Alien Species and their Control (IPBES, 2023), it is widely acknowledged that there are data gaps on species distributions in many countries around the world. Some of the most species-rich regions of the world are poorly represented within global platforms, such as the Global Biodiversity Information Facility (www.gbif.org) and iNaturalist (www.inaturalist.org). There is a clear need to build capacity and provide adequate resourcing to help fill these gaps as in all regions of the world, at early stages of the biological invasion process, information available to assess the risk of a non-native species may be limited. There is also a need to act urgently to address the growing threat of biological invasions and there are benefits to bringing together experts to share information and review the risks and status of INNS using the best available evidence, even when there is a paucity of data (Vanderhoeven et al., 2017). As such, the recommendations we make in this study as to the factors that influence the arrival and establishment of INNS could be applied around the world.

Records of the INNS collated in this paper were collected from a variety of sources. Databases, such as the BSBI DDb, the GBNNSIP and open access repositories such as GBIF, are not exhaustive for hosting data on species present in Great Britain. Likewise, although the data in the GBNNSIP, DDb, and to a lesser extent GBIF and the National Biodiversity Network Atlas (UK—England, Northern Ireland, Scotland and Wales) are verified, the establishment status of species is not always easy to determine. In Great Britain, there are currently discussions around the criteria for confirming establishment status as part of the work in reporting towards Target 6 of the Kunming-Montreal Global Biodiversity Framework. Determining establishment status for many species is not always straightforward. For example, the American lobster is not considered established in Great Britain, despite a juvenile being found in British waters in August 2019 as this record does not necessarily mean there is a sustained population (see Barrett et al., 2020; Tinlin-Mackenzie et al., 2022). Understanding the establishment INNS status is of crucial importance for land managers, with respect to mitigating the negative impacts of the species.

4.4 | Timescales in reporting INNS

Estimating biological invasion time lags has implications for predicting the impacts of INNS (Coutts et al., 2018). Some INNS rapidly cause negative impacts on native species, for example, through disease transmission (Graystock et al., 2016; Roy et al., 2017) and predation (Doherty et al., 2016). For many species, however, there is a time lag in one or more stages of the biological invasion process, specifically between introduction into a region and presence in the wild as well as between establishment and spread within the region (Crooks, 2011). Oxford ragwort (*Senecio squalidus*), for example, escaped confinement in the Oxford Botanic Gardens in the 1700s but only started to spread during the mid-1900s, possibly due to increases in transport infrastructure and in areas of disturbed land following bombing in the two world wars (Crooks, 2011). Climate change will also play a role in increasing spread and/or establishment of non-native species (e.g. Essl et al., 2019) and may reduce these lag times in future. Time lags also mean it takes longer (up to centuries) for negative impacts to unfold (Crooks, 2005; Essl et al., 2015; Lyons et al., 2019) which can impede prediction and ultimately management (Booy et al., 2017, 2020; Coutts et al., 2018). Delays in detection and publication of occurrences of INNS (e.g. Menchetti et al., 2023; but see Genovesi et al., 2024; Menchetti et al., 2024) are also important as they could mean that negative impacts could be occurring without being mitigated. Delays in detection may also reduce the ability to evaluate the occurrence of other time lags in the process that could be operating (Crooks, 2005). An example of a delay between detection and identification is the greater white-toothed shrew (*Crocidura russula*) which arrived in Great Britain before 2015, but the first evidence of it (from a photograph of an individual killed by a cat) was not positively identified until 2022.

4.5 | Trade networks and INNS

Networks of trade are important predictors on the movement of species around the globe (Chapman et al., 2017). Potential changes in the trade of goods and movement of people from and to Great Britain and the wider United Kingdom, following the departure of the United Kingdom from the European Union, may have important consequences in the future for both predicting the arrival of

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species into Great Britain and their interception, early detection and rapid response (Epanchin-Niell et al., 2021). Available data on the frequency of import and number/volume (propagule pressure) of traded species could be used as an additional predictor of the likelihood of arrival in future horizon scans wherever they are undertaken in the world. The results presented here show that temperate Asia, North America and the temperate North Pacific are important native ranges of INNS that have arrived in Great Britain recently, but the authors acknowledge this could be different in other countries depending on trade relation and fashions and trends, for example, in horticulture or the pet trade. For Great Britian, increased trade with non-European countries in the future (Jackson & Shepotylo, 2018) may mean the arrival of more INNS from these regions. As such, increased biosecurity (Hulme, 2011), surveillance (Holden et al., 2016) and communication (Smith et al., 2020) strategies as part of these new or expanded trade arrangements will be critical to prevent these potential impacts being realised.

4.6 | Policy relevance and management

The GB Non-Native Species Secretariat used the original list of INNS derived through horizon scanning in 2013 (Roy, Peyton, et al., 2014) to develop early warning rapid response protocols enacted for the yellow-legged hornet (*Vespa velutina)* by setting up an alert system to enable the capture/receipt of new records (Biological Records Centre, 2023). The Alert System that has been implemented as part of the GBNNSIP receives many potential sightings of the yellow-legged hornet and teams are dispatched to eradicate the nests for confirmed sightings. This Alert System has meant that the yellow-legged hornet has not established in Great Britain so far, despite 118 records of the yellow-legged hornet and 109 nests eradicated between 2016 and 2023 (Defra, 2024).

Nine of the 92 2013 horizon scan species are listed as Species of Special Concern in Great Britain (Secretary of State et al., 2021) and six of these have arrived. Species of Special Concern are 'restricted from being brought into the territory of Great Britain, kept, bred, transported, placed on the market, used or exchanged, allowed to reproduce, grown or cultivated, or released into the environment'. A further seven of the 2013 horizon scan species are being considered for potential listing as Species of Special Concern in Britain, six of which have been risk assessed. Of these, chocolate vine (*Akebia quinata*) is considered to have arrived and there has been an unconfirmed sighting of egg cases of Japanese oyster drill (*Ocinebrellus inornatus*).

4.7 | Evaluation methods

In this study, we regarded the number of INNS predicted to arrive and subsequently arriving as the measure of success. There are, however, other ways that horizon scans could be evaluated. For example, one metric could be the 'success' of awareness raising of INNS listed in horizon scans that results from the systematic review of the impacts of species and their likely arrival. Another measure of success could be increased surveillance for target species and rapid action when a target species arrives resulting in prevention of its establishment (e.g. the work on yellow-legged hornet). The initiation and creation of pathway action plans, alongside detailed pathway analyses based on species listed in horizon scans, can inform biosecurity and pathway management and the creation of these plans could be included as a further measure of success. Another metric could be the savings gained through prevention of establishment in terms of environmental and economic costs. These potential costs could be assessed or deduced from the InvaCost database, which aims to give a global estimate of the economic cost of biological invasions (Diagne et al., 2021).

5 | CONCLUSIONS

Preventing the establishment of INNS is more effective and cheaper than management post-establishment, and results presented here show that horizon scanning provides a cost-effective and successful method of predicting species arrival. This technique therefore provides policymakers the chance to act on INNS prevention and mitigation before the species arrive and establish, or spread. To meet the targets on reducing the impacts of INNS as outlined in the Kunming-Montreal Global Biodiversity Framework (Convention on Biological Diversity, 2022), communities of experts from across disciplines will need to continue to work together to address the increasing threats from INNS to nature and human well-being. Horizon scanning offers an opportunity to achieve this by bringing experts from across disciplines together to review and discuss INNS introductions, impacts, distribution and spread and to develop and build interdisciplinary networks. While the costs of undertaking horizon scanning using expert elicitation and consensus approaches have been low, equivalent to travel and subsistence for the events, they rely on time contributed voluntarily by species experts. For example, Roy, Peyton, et al. (2019) estimated volunteer in-kind contribution costs of almost £1 million for the horizon scanning study for 13 UK Overseas Territories (Dawson et al., 2022). Even so, horizon scanning is considered by the authors to provide a rapid, affordable and effective mechanism to predict the arrival of INNS. In order to fulfil the recommendation from the CBD that data sources and indicators should be compiled and regularly updated, the authors suggest repeating horizon scans at 5-year intervals.

AUTHOR CONTRIBUTIONS

Jodey M. Peyton, Helen E. Roy, Oliver L. Pescott and Alan J. A. Stewart conceived the ideas and designed the methodology; Jodey M. Peyton, Stephanie Rorke, David C. Aldridge, Oliver L. Pescott, Katharina Dehnen-Schmutz, David G. Noble, Jack Sewell, Alan J. A. Stewart, Tim Adriaens, Björn C. Beckmann, J. Robert Britton, Juliet Brodie, Peter M. J. Brown, Imogen C. N. Cavadino, Paul F. Clark, Alison M. Dunn, Jim Foster, Colin Harrower, Martin C. Harvey, Michelle C. Jackson, Tomos Jones, Christine A. Maggs, Gabrielle

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data available from Figshare: https://doi.org/10.6084/m9.figshare.25935166 (Peyton et al., 2024).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Appendix S1. Details of GBHS species in Great Britain: This dataset comprises data on the arrival status of 92 Invasive Non-Native Species (INNS) assessed in 2013 through a horizon scanning workshop to predict and prioritise the species most likely to arrive, establish and impact biodiversity and ecosystems within Great Britain between 2013 and 2022.

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