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The contribution of volunteer recorders to our understanding of biological invasions

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The process of invasion and the desire to predict the invasiveness (and associated impacts) of new arrivals has been a focus of attention for ecologists over centuries. The volunteer recording community has made unique and inspiring contributions to our understanding of invasion biology within Britain. Indeed information on non-native species (NNS) compiled within the GB Non-Native Species Information Portal (GB-NNSIP) would not have been possible without the involvement of volunteer experts from across Britain. Here we review examples of ways in which biological records have informed invasion biology. We specifically examine NNS information available within the GB-NNSIP to describe patterns in the arrival and establishment of NNS providing an overview of habitat associations of NNS in terrestrial, marine and freshwater environments. Monitoring and surveillance of the subset of NNS that are considered to be adversely affecting biodiversity, society or the economy, termed invasive non-native species (INNS), is critical for early warning and rapid response. Volunteers are major contributors to monitoring and surveillance of INNS and not only provide records from across Britain but also underpin the system of verification necessary to confirm the identification of sightings. Here we describe the so-called 'alert system' which links volunteer experts with the wider recording community to provide early warning of INNS occurrence. We highlight the need to increase understanding of community and ecosystem-level effects of invasions and particularly understanding of ecological resilience. Detailed field observations, through biological recording, will provide the spatial, temporal and taxonomic breadth required for such research. The role of the volunteer recording community in contributing to the understanding of invasion biology has been invaluable and it is clear that their expertise and commitment will continue to be so.

ADDITIONAL KEYWORDS: biological recording – citizen science – early warning – habitat – impact – invasion biology – surveillance.

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INTRODUCTION

Non-native species (NNS) are being introduced into countries at unprecedented and unpredictable rates and those that become invasive threaten biodiversity by decreasing the uniqueness of ecosystems at genetic, functional and taxonomic levels (McKinney & Lockwood, 1999; Smart *et al*., 2006; Vila *et al*., 2011). The Millennium Ecosystem Assessment (Anonymous, 2005) ranked invasive non-native species (INNS), alongside climate change, habitat destruction, pollution and overexploitation, as one of the main drivers of biodiversity loss globally. The recent dramatic increase in the rate of movement of species from their native geographic regions to new regions, in which they are considered non-native, aligns with increases in globalisation and associated rises in transportation by humans (Hulme, 2009).

The process of invasion and the desire to predict the invasiveness (and associated impacts) of new arrivals has been a focus of attention for ecologists over centuries (Elton, 1958). Indeed Charles Darwin evoked the 'Naturalisation Hypothesis or Conundrum' (Darwin, 1859) predicting the importance of phylogenetic relatedness in determining invasiveness such that NNS with close relatives in the invaded range will be less invasive than those which are only distantly related to species within the recipient habitats (Daehler, 2001; Jiang, Tan & Pu, 2010; Thuiller *et al*., 2010). Such traits-based approaches continue to fascinate ecologists and provide opportunities for exploring invasions.

Recent research recognises the inherent complexity of ecological systems and the influence of the evolutionary history of the interactions between species within a population in determining invasion success of new arrivals (Thuiller *et al*., 2010). Furthermore, the wider community context is also likely to play an important role in the invasion process (Shea & Chesson, 2002). The recently proposed unified framework for biological invasions reconciles and integrates characteristics across a range of established invasion frameworks and eloquently outlines the invasion process and specifically the stages and barriers to invasion from transport and introduction to establishment and spread (Blackburn *et al*., 2011). The volunteer recording community have made unique and inspiring contributions to our understanding of invasion biology within Britain.

GB NON-NATIVE SPECIES INFORMATION PORTAL: UNDERPINNING UNDERSTANDING

The GB Non-Native Species Information Portal (GB-NNSIP) is an on-line information system (http://www.nonnativespecies.org), involving a network of people including the volunteer recording schemes and societies alongside the Biological Records Centre (BRC) and other organisations engaged in sharing information on NNS (Roy *et al*., 2014c). The GB-NNSIP covers species within England, Scotland and Wales (hereafter referred to as 'Britain') and comprises a register of NNS, together with supporting information including country of origin, arrival pathway, establishment status, occurrence within habitats, date of first record, human impact and environmental impact. The GB-NNSIP is being updated at least annually and is dynamically linked to the National Biodiversity Network (NBN) Gateway (https://data.nbn.org.uk) which provides maps of the distribution of the NNS within Britain. The role of volunteers, primarily through the recording schemes and societies, in providing both information on species and occurrence data, has been invaluable. Indeed compiling the information within the GB-NNSIP would not have been possible without the contributions of volunteer experts from across Britain.

Lists of NNS are seen as an essential tool in the management of biological invasions (McGeoch *et al*., 2012). The use of such lists is diverse and far-reaching. There have been many influential research studies based on NNS lists which have increased understanding particularly in relation to pathways of arrival (Hulme, 2009) and impacts on biodiversity (Vila *et al*., 2011), both acknowledged as critical elements within biodiversity strategy. Indeed implementation of policy and legislation is often based on NNS lists (Lodge *et al*., 2006) prioritising those species considered to be adversely affecting biodiversity, society or the economy which are termed invasive non-native species (INNS). Early warning, prevention and control measures for INNS rely on information such as identity, associated biology and distribution (McGeoch *et al*., 2012). Here we have examined NNS information available within the GB-NNSIP to describe patterns in the arrival, establishment and spread of non-native species within Britain.

ARRIVAL

The arrival of a species within a new region is dependent on successful transport and introduction but survival and reproduction is essential for the species to become established (Blackburn *et al*., 2011). The mechanism of arrival can be difficult to determine (Eversham & Arnold, 1992). Recent advances have been made in harmonising the terminology used to describe pathways and information within the GB-NNSIP has been instrumental to these developments (CBD, 2014). Over the coming years it will be

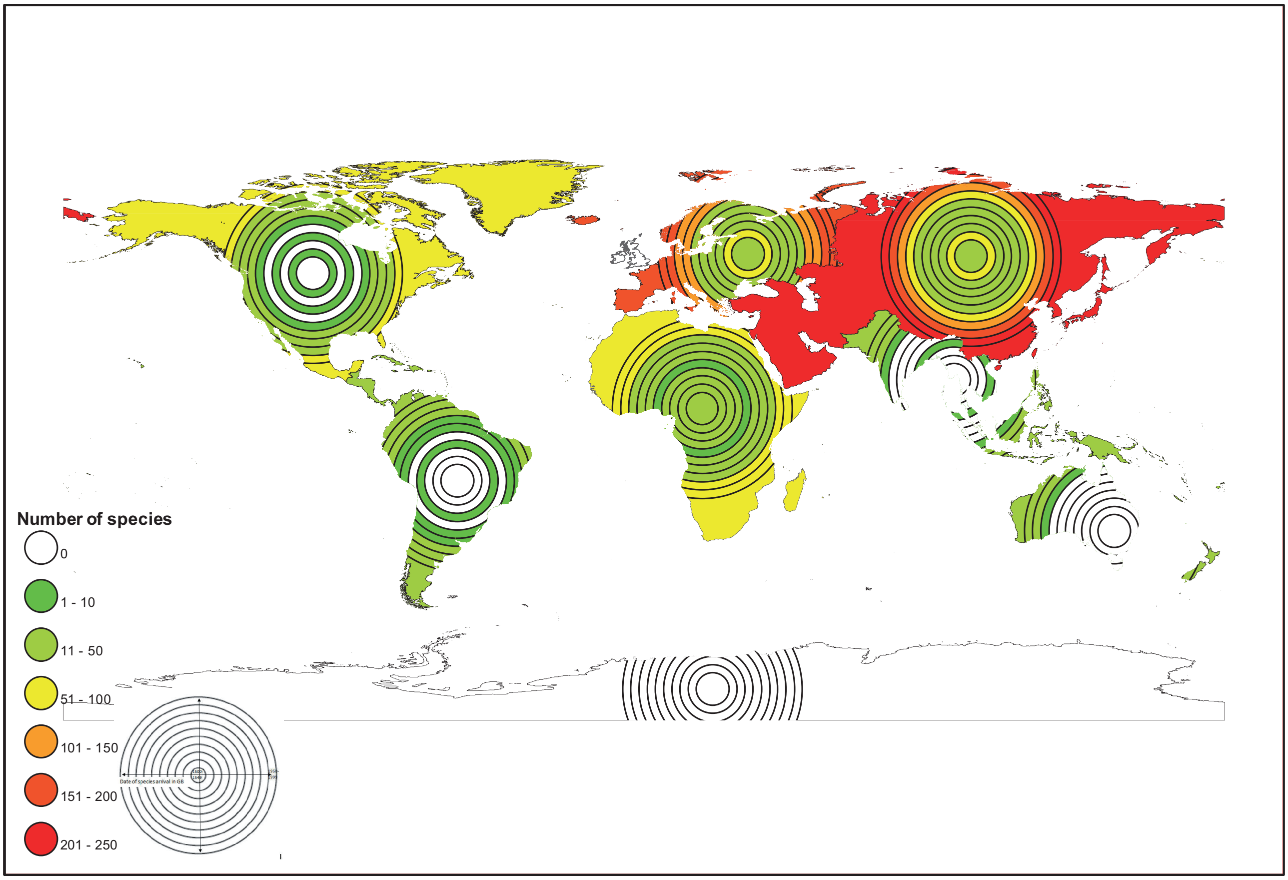

Figure 1. Origins of established non-native species (NNS) and the date of first record in Britain. The place of origin is shown at continent level, some species have a native range that covers multiple continents. The number of NNS indicates the total number of NNS within a native range including that continent and first record for Britain in that date range. The innermost circle denotes the date range 1500–1549 and each further concentric circle refers to a 50-year time period with the outermost circle representing the most recent date range 1950–1999. The colour of the continent relates to the most recent time period displayed.

essential to prioritise research on pathways of arrival to inform strategies for preventing future INNS incursions. It is also necessary to understand the origins of NNS. Historically a large proportion of the NNS arriving in Britain were native within Europe indicative of the close transport and trade links throughout history (Preston, Pearman & Hall, 2004). However, there has been a shift in the countries of origin of the NNS arriving within Britain which align with an increase in trade and travel from regions beyond Europe (Fig. 1). Recently there has been a particular increase in the number of species arriving from temperate Asia; globalisation has facilitated and intensified the intentional and unintentional introduction of NNS (Meyerson & Mooney, 2007).

ESTABLISHMENT

There has been a dramatic increase in the number of species arriving and becoming established (founding reproducing populations) within Britain over the last 400 years and there is no indication of this trend slowing (Fig. 2). Indeed since 1950 there have been 10.5 additional NNS arriving and establishing per year in contrast to 0.9 additional NNS per year from 1600–1799. The number of established NNS deemed to have a negative ecological or socio-economic impact (INNS) is also increasing with 1.1 of the new species per year causing an impact since 2000 (Roy, 2014; Roy *et al*., 2014c). There are more than 3000 species listed within the GB-NNSIP but only 1919 are considered to be established within Britain. Plant species dominate within the GB-NNSIP; the 1919 established NNS comprise 1494 established non-native plants, 420 established non-native animals and five other species. The escalation in the rate of new arrivals is not unique to Britain and has been reported for Ireland (O'Flynn, Kelly & Lysaght, 2014) and across Europe (Pyšek *et al*., 2010) and, indeed, globally (Meyerson & Mooney, 2007) and is widely attributed to an increase

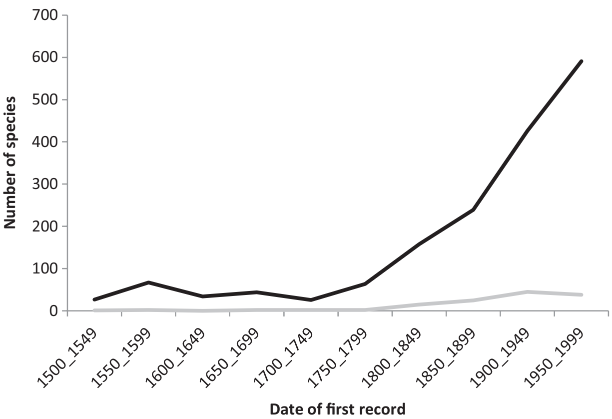

Figure 2. Number of established non-native species (black line) and the number that are designated as having a negative ecological impact, so-called invasive non-native species (grey line), against date of first record.

in trade and transport in recent decades (Hulme, 2009).

SPREAD

The invasibility of communities, habitats and ecosystems has been the focus of invasion biology research for decades (Lonsdale, 1999; Richardson & Pyšek, 2006). However, it is recognised that invasion of a region by a NNS involves complex ecological processes driven by traits of both the invader and the invaded community (Shea & Chesson, 2002). Indeed biological invasions represent an exciting opportunity to contribute to the understanding of community ecology (Shea & Chesson, 2002). Biological records have underpinned the study of establishment and spread of NNS within Britain (Eversham & Arnold, 1992; Manchester & Bullock, 2000; Botham *et al.*, 2009). Non-native species occur across the British landscape (Fig. 3) but a greater number of NNS are present within England compared with either Scotland or Wales. The high number of NNS within the south-east of England is almost certainly related to climatic factors coupled with prevalence of urban habitats and high population density; there are particularly high numbers of NNS within urban localities.

The association of NNS with urban habitats is widely recognised (Pyšek, 1998; Alston & Richardson, 2006; Botham *et al.*, 2009). Indeed urban localities represent highly disturbed habitats which are also typified by high fertility and so highly suitable for ruderal species (Botham *et al.*, 2009). Furthermore, the number of NNS introduced into urban settlements, particularly in gardens and parks, is high and so constitutes considerable propagule pressure (Holle & Simberloff, 2005; Botham *et al.*, 2009). Research using botanical data collected by the Botanical Society of Britain and Ireland confirms the strong association of non-native plants with urban habitats but suggests that there has been a reduction in the urban association of archaeophytes in recent decades (Botham *et al.*, 2009). The GB-NNSIP includes information on the habitats occupied by non-native species within Britain, much of which comes from the detailed observations of the volunteer recording community. A qualitative and descriptive review of the habitat associations represented within the GB-NNSIP provides intriguing insights which stimulate the development of hypotheses for empirical testing (Figs 4–6). The botanical information is particularly comprehensive within the GB-NNSIP and exploring the habitat associations of non-native plants in terrestrial environments against date of first record highlights changes in patterns (Fig. 4I, II). The strong association with urban environments (EUNIS category J) is apparent and the proportion of recent arrivals within urban environments is higher than for historic invasions. Interestingly there are no clear patterns between the habitat associations of the INNS and date of first record although association with grasslands (EUNIS category E) is strong for both NNS and INNS of plants. Previous research has highlighted the importance of fertile grasslands as recipient habitats for non-native plants, particularly disturbed and fertile components of these habitats (Maskell *et al.*, 2006).

Habitat associations between NNS, beyond the plants, and in non-terrestrial environments have so far received limited attention. However, a few patterns emerge from examining the habitat associations of non-native animals against date of first record which are worthy of description (Figs 4III, IV, 5, 6). Interestingly, urban habitats do not appear to be the major recipient of non-native animals and it is possible that this reflects both the capacity of animals to disperse and spread rapidly, and the range of pathways through which they arrive. There appears to be an increase in the proportion of non-native animals, particularly those considered to be invasive, associated with marine habitats (EUNIS category A). This could reflect increased intensity of recording within these habitats in recent years but it would be valuable to investigate further. Inland waters (EUNIS category C) seem to be increasingly under pressure from new invasive arrivals. The number of freshwater invertebrates arriving from the Ponto-Caspian region is a growing concern and it has been stated that Britain might be on the brink of ‘Ponto-Caspian invasional meltdown’ (Gallardo & Aldridge, 2014). The recent arrival of the quagga mussel, *Dreissena rostriformis bugensis*, is the latest of a number of new

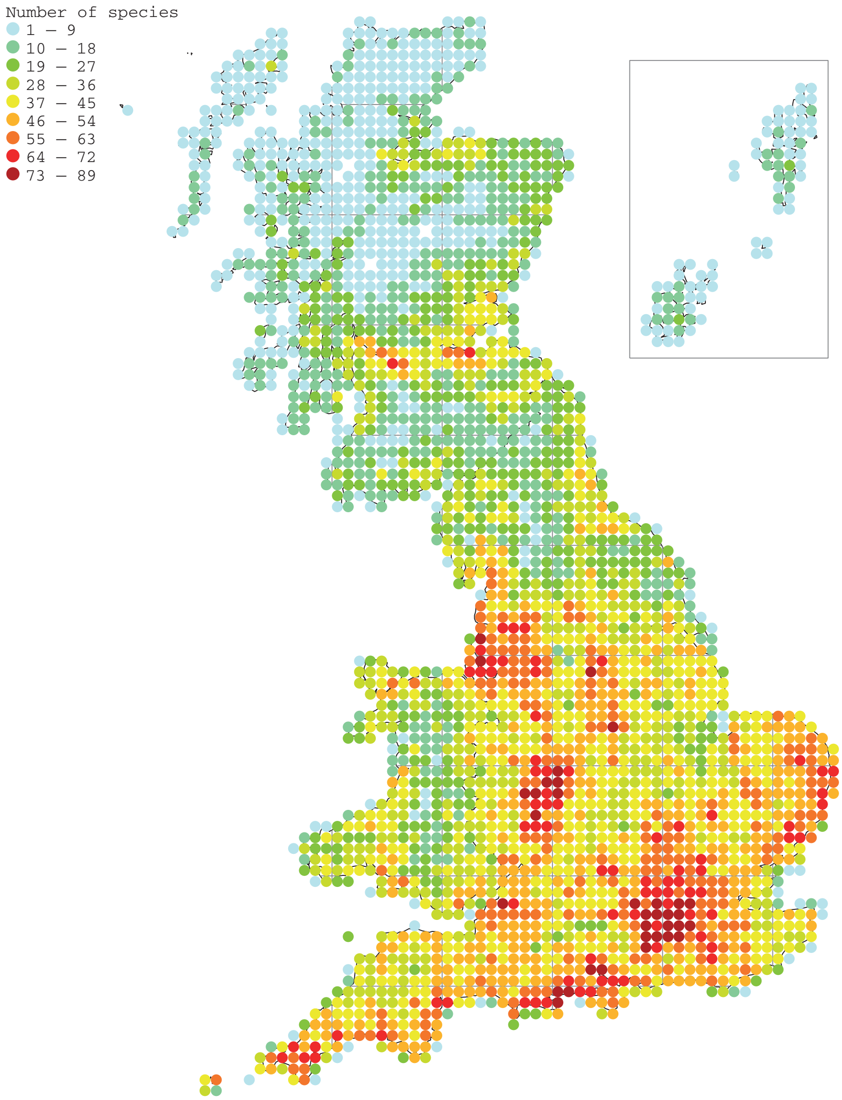

Figure 3. Richness of invasive non-native species (number of species per 10 km square). Data extracted from the NBN Gateway (https://data.nbn.org.uk/) for 171 species listed as invasive non-native species (Table S1 but excluding marine species other than those recorded in coastal hectads) on 24 October 2014.

arrivals to freshwater habitats. Recreational use of water bodies for fishing and boating are considered to be major pathways of introduction for NNS and highlight the importance of biosecurity and raising awareness through campaigns such as 'Check, Clean, Dry' (Anderson *et al.*, 2014).

Clearly there is considerable scope for research on habitat associations of NNS. It would be particularly interesting to explore the interactions between habitat fragmentation and invasion (Hoffmeister *et al.*, 2005). While it is apparent that urban and disturbed habitats are particular foci for invasion, it is critical to consider habitats as a heterogeneous matrix on a landscape scale. For some species habitat fragmentation might limit spread while for others the disturbance created through fragmentation might facilitate spread. It would be interesting to explore this through modelling approaches using biological records alongside life-history traits and land cover data. Investigating the vulnerability of protected areas to invasion by considering their connectivity to hot spots of invasion could provide useful insights for conservation management (Thomas *et al*. THIS SI).

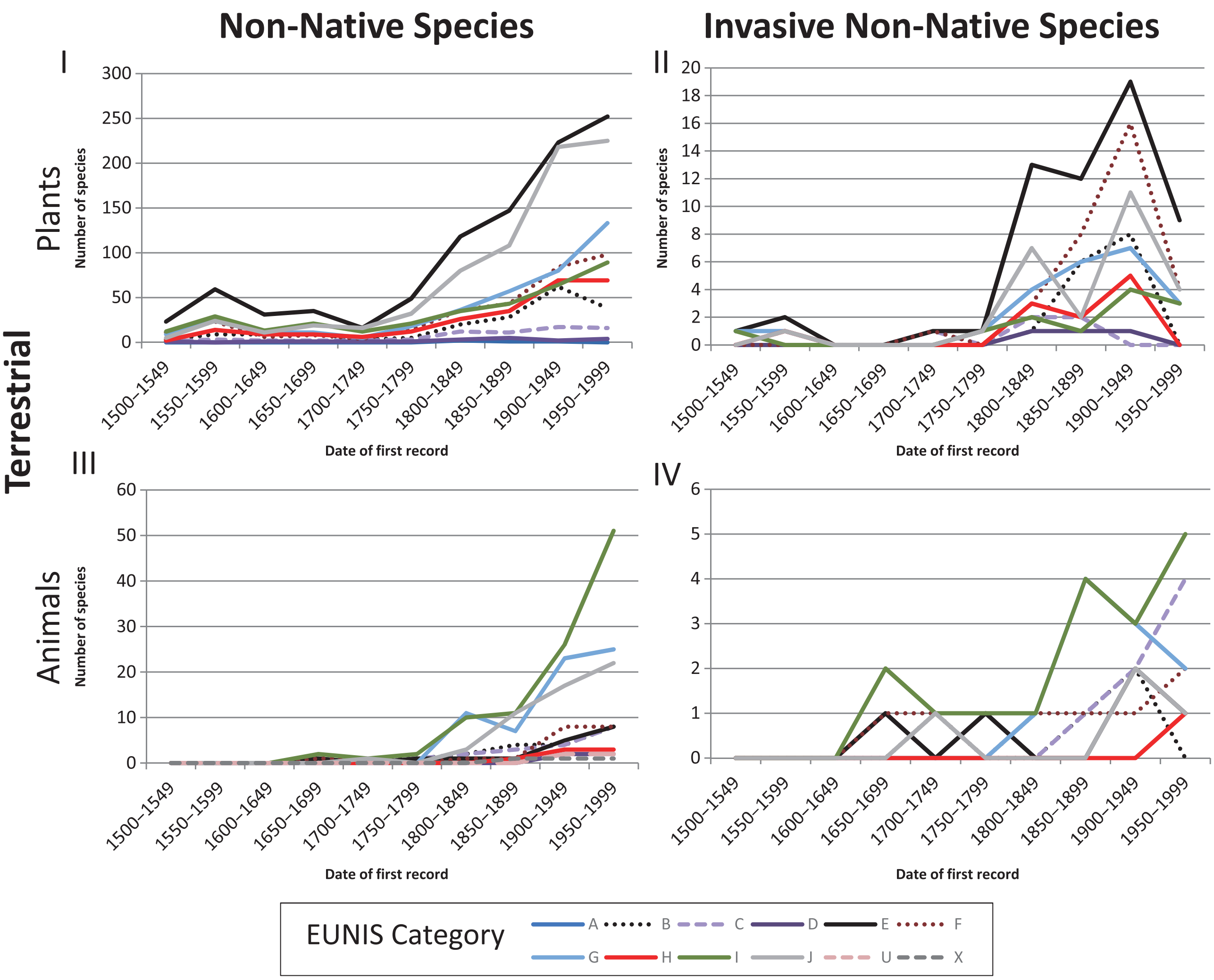

Figure 4. Number of non-native and invasive non-native plants (I and II respectively) and non-native and invasive non-native animals (III and IV respectively) associated with terrestrial habitats against date of first record. Habitat information is included with the GB-NNSIP as EUNIS categories (A = marine habitats; B = coastal habitats; C = inland surface waters; D = mires, bogs and fens; E = grasslands and lands dominated by forbs, mosses or lichens; F = Heathland, scrub and tundra; G = woodland, forest and other wooded land; H = inland unvegetated or sparsely vegetated habitats; I = regularly or recently cultivated agricultural, horticultural and domestic habitats; J = Constructed, industrial and other artificial habitats; U = unknown; X = habitat complexes).

HORIZON SCANNING AND EARLY WARNING

Horizon scanning to prioritise the threat posed by potentially new INNS which are not yet established within a region is seen as an essential component of INNS management (Copp, Templeton & Gozlan, 2007; Shine *et al*., 2010). There have been a number of horizon-scanning exercises, based on information from the literature coupled with risk assessment frameworks or modelling approaches, for INNS in Britain involving discrete taxonomic groups, such as plants (Thomas, 2010) or animals (Parrott *et al*., 2009), or distinct environments such as freshwater (Gallardo & Aldridge, 2013). More recently a horizon-scanning approach was developed that combined the structured approaches of literature review and risk assessment (Branquart *et al*., 2009) with dynamic consensus methods (Sutherland *et al*., 2011) to deliver a ranked list of species that are likely to arrive, become established and have an impact on native biodiversity within the next 10 years (Roy *et al*., 2014b). Breadth of information across taxonomic groups and environments is essential for horizon scanning and the volunteer recording community in the UK provide an excellent example of 'wisdom from the crowd' (Galton, 1907; Sutherland & Woodroof,

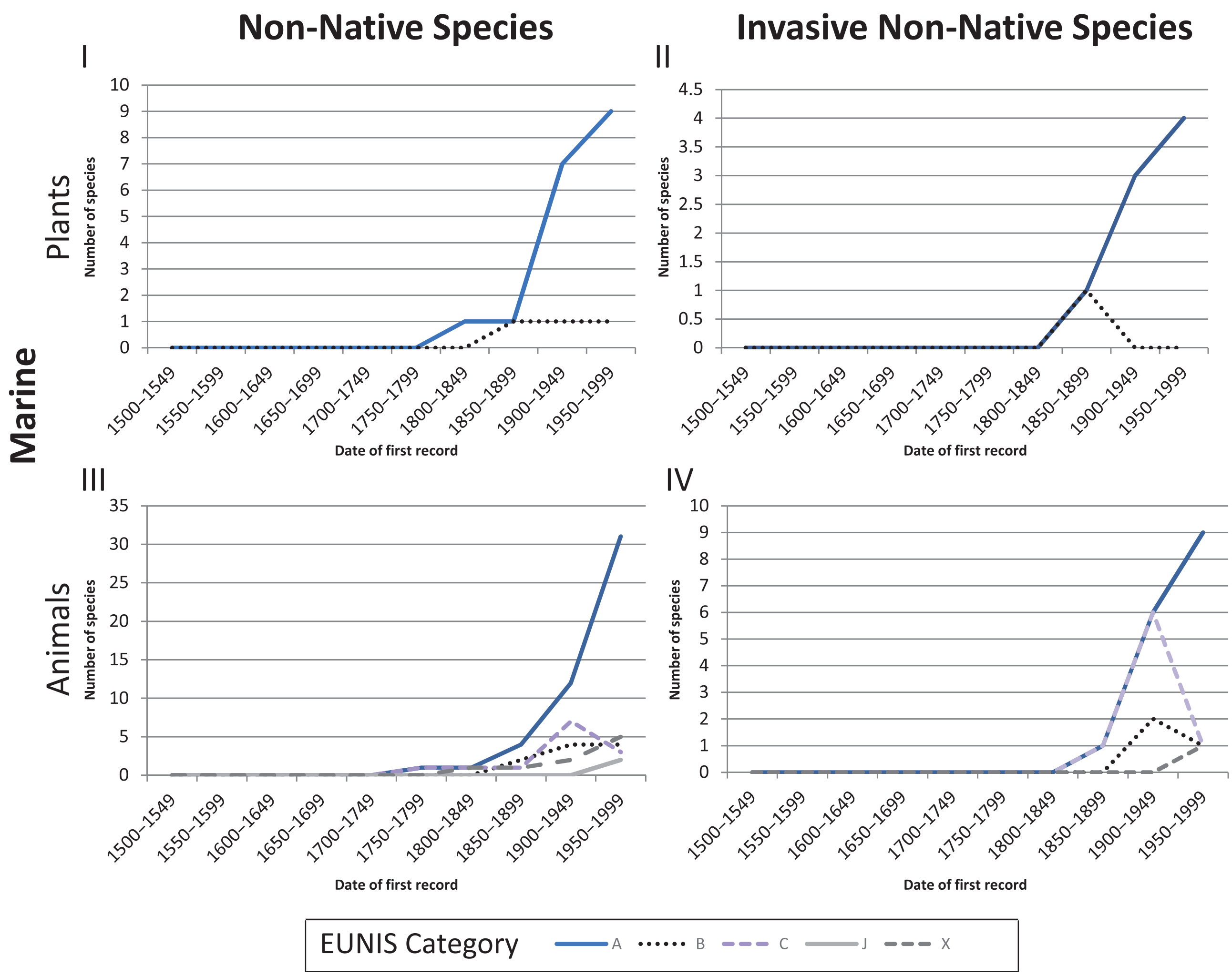

Figure 5. Number of non-native and invasive non-native plants (I and II respectively) and non-native and invasive non-native animals (III and IV respectively) associated with marine habitats against date of first record. Habitat information is included with the GB-NNSIP as EUNIS categories (A = marine habitats; B = coastal habitats; C = inland surface waters; J = Constructed, industrial and other artificial habitats; X = habitat complexes).

2009; Lorenz *et al.*, 2011) whereby the complementary expertise within this community ensures the required collective knowledge (Roy *et al.*, 2014b). The list of NNS on the resulting horizon-scanning list included a 'top ten' and four of these species (*D. rostriformis bugensis* (Mollusca: Bivalvia), *Hemigrapsus sanguineus* (Crustacea: Brachyura), *Hemigrapsus takanoi* (Crustacea: Brachyura), *Procyon lotor* (Mammalia: Carnivora) were reported within 6 months following publication. The quagga mussel, *Dreissena rostriformis bugensis*, was unanimously agreed to constitute the highest risk of all the species considered (Roy *et al.*, 2014b) and in October 2014 was reported as established in a reservoir in Surrey, UK (http://www.nonnativespecies.org/alerts/index.cfm). The quagga mussel is an ecosystem engineer and has a history of becoming the dominant benthic organism within invaded systems (Sousa, Gutierrez & Aldridge, 2009) with a wide range of direct and indirect impacts (MacIsaac, 1996; Schloesser *et al.*, 2006; Ward & Ricciardi, 2007; Sousa *et al.*, 2009; Cross, Wong & Che, 2010).

MONITORING AND SURVEILLANCE

The volunteer recording community are major contributors to monitoring and surveillance of NNS. It is essential that the species prioritised through risk assessment and horizon scanning are publicised to raise awareness and encourage reporting. Volunteers not only provide records from across Britain but also underpin the system of verification necessary to confirm the identification of sightings. The so-called 'alert system' (Fig. 7) promoted through the

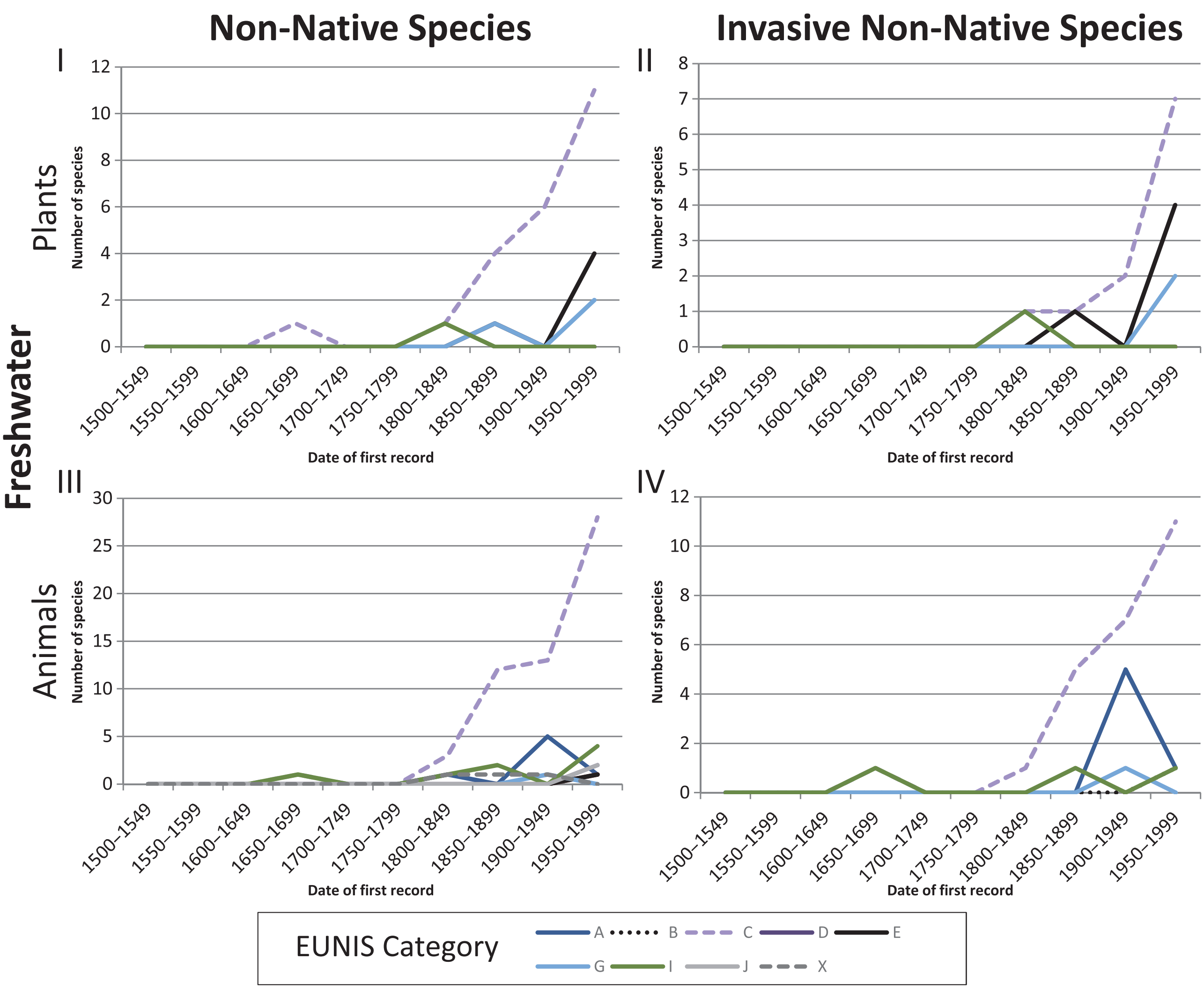

Figure 6. Number of non-native and invasive non-native plants (I and II respectively) and non-native and invasive non-native animals (III and IV respectively) associated with freshwater habitats against date of first record. Habitat information is included with the GB-NNSIP as EUNIS categories (A = marine habitats; B = coastal habitats; C = inland surface waters; D = mires, bogs and fens; E = grasslands and lands dominated by forbs, mosses or lichens; G = woodland, forest and other wooded land; I = regularly or recently cultivated agricultural, horticultural and domestic habitats; J = Constructed, industrial and other artificial habitats; X = habitat complexes).

Non-Native Species Secretariat website (http://www.nonnativespecies.org) links to iRecord (http://www.brc.ac.uk/irecord/), a website for managing wildlife records, and enables rapid reporting and verification of species considered as a priority for action. On-line capability enables people to register for notification of selected species of interest and ensures rapid data flow to support effective decision-making.

The alert system includes species identified as high-risk through horizon scanning (Roy *et al.*, 2014b). The Asian hornet, *Vespa velutina*, is one such species. This species was first recorded in France in 2005 and spread rapidly across the country and into Spain in 2010 (Perrard *et al.*, 2009; Villemant *et al.*, 2011). It is a predator of pollinating insects and so poses a threat to native biodiversity (Perrard *et al.*, 2009; Villemant *et al.*, 2011). There has been considerable publicity through the media on this species and also targeted promotion to the beekeeping community. Consequently many people have sent sightings of concern through iRecord (374 suspect Asian hornet records) and a designated e-mail account for alert species (1162 suspect Asian hornet records; Fig. 8). To date there have been no confirmed sightings of the Asian hornet in Britain; most of the records have been identified as European hornets, *Vespa crabro*. However, the high number of records received through the e-mail alert (Fig. 8) system is

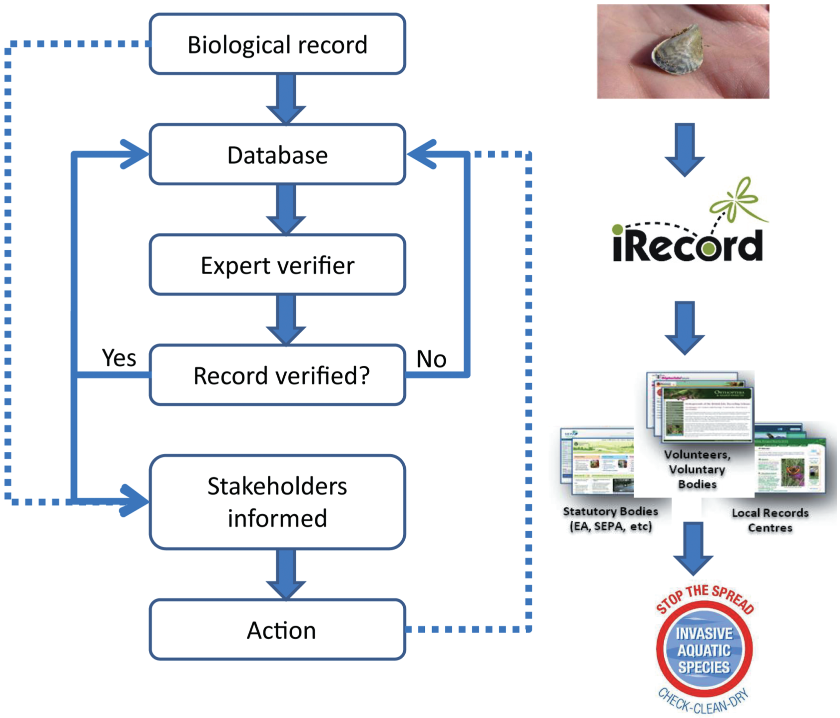

Figure 7. Outline of the 'alert system' in which a biological record is received either by e-mail or within iRecord. The record is checked by an expert and either confirmed (verified) or not. The database is updated and stakeholders are informed if the record is verified so that they can take appropriate action. In some cases stakeholders are notified prior to verification if rapid response is necessary.

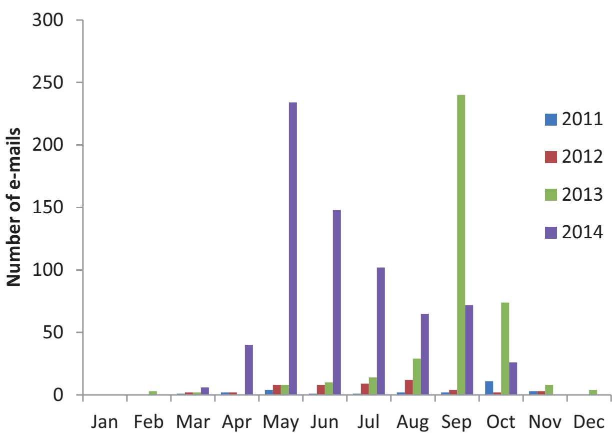

Figure 8. Number of reports of suspected *Vespa velutina* received through the designated e-mail account for the 'alert system'. Date range 2011 to 2014. Note that there have been no confirmed sightings of *V. velutina* within Britain.

encouraging and highlights the role of volunteers, expert and non-expert, in surveillance and monitoring of NNS. The peaks in numbers of records received (September 2013 and May 2014) coincide with reports in the national press and demonstrate the importance of effective communication to raise awareness.

UNDERSTANDING IMPACTS

INNS are widely stated to be one of the major drivers of biodiversity loss (Millenium Ecosystem Assessment, 2005), however there is a lack of empirical evidence for the impacts of many NNS which are considered to be invasive. There is a clear need to increase understanding of the effects of NNS on other wildlife to inform risk assessment and prioritisation of management strategies (Roy *et al.*, 2014d). However, invasions also provide opportunities to gain unique insights to advance understanding of processes within community ecology. It is essential that impacts are quantified using experimental approaches alongside field observations. Biological recording could play a critical role in the latter, however currently the interactions between species are rarely captured within biological records. There is considerable potential to encourage recorders to include such additional information and many naturalists document interactions as comments alongside the standard information (what, when, who and where) that constitutes a record.

Biological records collated through the UK Ladybird Survey (formerly the Coccinellidae Recording Scheme) have been instrumental in providing evidence that the harlequin ladybird, *Harmonia axyridis*, is contributing to the declines in distribution of native ladybirds (Brown *et al*., 2011; Roy *et al*., 2012). Linking this research with life-history traits, climate and land cover data highlights the role of *H. axyridis* coupled with urbanisation in causing local extinctions of native ladybirds (Comont *et al*., 2012, 2014; Purse *et al*., 2014). It will be intriguing to explore the extent to which such changes in ladybird community structure affect the ecological resilience of the network of aphidophagous insects (Roy & Lawson Handley, 2012). A high degree of biodiversity is widely considered to enhance the resilience of ecosystems to invasion (Elmqvist *et al*., 2003) but few studies within invasion biology have included ecosystem-scale approaches to underpin this intuitive theory. Biological records have the potential to contribute to the understanding of ecological resilience and specifically to the assessment of the state of ecosystems following perturbation. The development of methods for constructing ecological networks from biological records is an exciting prospect and worthy of prioritisation going forward.

CONCLUSIONS

The contributions made by volunteers to our understanding of invasion biology have been invaluable. The GB-NNSIP (alongside the European inventory, DAISIE) is possibly one of the most comprehensive regional databases of information on non-native species worldwide. The wealth of information on British wildlife, both native and non-native, is inspiring, and the large-scale and long-term datasets comprising biological records compiled and collated by the volunteer recording community provide a unique resource for addressing questions of major ecological importance (Roy *et al*., 2014a). The information available through publications on life-history traits, such as PLANTATT (Hill, Preston & Roy, 2004), provide additional rich resources to inform analyses. The development of databases of life-history traits for other taxonomic and functional groups should be prioritised. Integrating detailed traits-based information with biological records across taxonomic groups and including relevant interactions will enhance understanding of biological invasions immeasurably.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the on-line version of this article at the publisher's web-site:

Table S1. List of Invasive Non-Native Species considered to adversely affect biodiversity in Britain.