Biodiversity Climate change impacts report card Technical paper

9. Non-native Species

Philip E. Hulme

The Bio-Protection Research Centre,

PO Box 84, Lincoln University,

Christchurch, New Zealand.

Telephone: +64 3 321 8317

Fax: +64 3 325 3864

email: (philip.hulme@lincoln.ac.nz)

Summary

1. It is *virtually certain* that the number of non-native species introduced into Great Britain will continue to increase throughout the 21st century and this is *very likely* to be at a rate higher or similar to the highest rates observed in the past **[high agreement, robust evidence]**.

2. The major drivers underpinning this increase in non-native species introductions are socioeconomic involving increased trade, transport, travel and tourism as well as population growth. Climate change is *virtually certain* to contribute to increased probabilities of non-native species establishment, especially of non-native species regularly intercepted at the border or that arrive from proximate areas on the continent **[high agreement, robust evidence]**. However, the magnitude of any direct climate effect on the number of new non-native species will be small relative to the role of accidental and deliberate introductions driven by contemporary and historic socioeconomic drivers **[high agreement, medium evidence]**.

3. The populations of some casual non-native species *are likely* to be limited by climate and are thus are expected to exhibit greater rates of establishment under climate change assuming sources of introduction (propagule pressure) remain at least at current levels. However, independently of climate, changes in land use and in agricultural practices are *virtually certain* to result in casual species of non-native plants disappearing from Great Britain **[medium agreement, medium evidence]**.

4. Most established non-native species are *virtually certain* to increase their distribution range in Great Britain over the next century **[high agreement, robust evidence]**. However, such range increases *very likely* be the result of natural expansion of populations that have yet to reach equilibrium with their environment, rather than a direct consequence of climate change **[medium agreement, limited evidence]**. It is *unlikely* that the relative contribution to range expansion due to climate, natural demographic processes, anthropogenic drivers and their interaction will be easily disentangled **[medium agreement, limited evidence]**.

5. Projections of future distributions of non-native species using bioclimate models should be interpreted with caution since different methods can provide quite different projections, they rarely include non-climatic constraints on the distribution of species and are strongly dependent on the scale and resolution of the data from which they are developed. Thus bioclimate projections are *about as likely as not* to only depict a measure of the potential rather than realised distribution of non-native species following climate change **[medium agreement, medium evidence]**.

6. In terms of invasive non-native species that have known economic or biodiversity impacts, the taxa that are *very likely* to be the most responsive to the changes in temperature and precipitation forecast for the United Kingdom are plant pathogens, especially thermophilic rust fungi, and mobile insect herbivores that are pests of agricultural crops **[high agreement, medium evidence]**. This includes existing established non-native species as well as

the likelihood of new introductions. Insect pests of forestry are *about as likely or not* to become greater problems under climate change but the outcome is highly dependent on the degree of phenological synchrony between the host tree and the herbivore leading to some pests becoming less effective **[medium agreement, medium evidence]**. For plants, vertebrates and less mobile invertebrates, climate change is *about as likely as not* to have a greater effect on local abundance than geographic range in Great Britain, particularly towards the northern limits of their existing ranges where impacts might be expected to increase **[low agreement, low evidence]**.

What is a non-native species?

A **non-native** organism (synonyms include alien, exotic, introduced, and non-indigenous) is a species, subspecies, or lower taxon deliberately or accidentally introduced by human action beyond the limits of its current or former natural range and dispersal potential ((Defra 2003); (Hulme 2007)). This definition mirrors the view that, at least in Great Britain, a native species is one that has arrived before Neolithic times, or has arrived since without human agency from a region where it is itself native (Webb 1985). The distinction emphasises the action of humans, rather than a particular ecological or taxonomic characteristic, as the determinant of non-native species status resulting from the movement of a species outside the range it occupies naturally or could not occupy without direct or indirect introduction, cultivation or husbandry. Although this definition of non-native is embodied in regulatory provisions ((Defra 2003)), it is not universally accepted due to the perceived arbitrariness of political rather than biogeographic boundaries (Kendle & Rose 2000; Warren 2007; Selge *et al.* 2011). This is not the case in United Kingdom, where data on non-native species are reported separately for Great Britain and Ireland although this creates a mismatch between the political responsibilities for nature conservation and the biogeographic approach to reporting on non-native species. Unfortunately, data specific to Northern Ireland cannot readily be disaggregated from the Ireland information and thus this Technical Report primarily addresses trends for Great Britain but these are expected to be broadly consistent with forecasts for Northern Ireland. A final distinction in the terminology used in the United Kingdom, is that hybrids that have arisen in the region are classed as native to that region regardless of the place of origin of parental species (whether one, both or neither parents are non-native) whereas the wider international view is that *de novo* hybridisation involving at least one non-native parent would result in the hybrid having non-native status (Pysek *et al.* 2004).

The role climate change plays in range expansions or contractions has also challenged the distinction between native and non-native species (Webber & Scott 2012). However, the inclusion of the term “introduction” in the definition makes it clear that this means the movement of a species by human agency rather than range expansion as a consequence of climate change (Hulme 2007). A native species that expanded its geographic distribution as a result of climate change would maintain its native status in the new range, even if it crossed political and biogeographic boundaries as long as range expansion occurred without the aid of human transport e.g. migrating Lepidoptera (Sparks *et al.* 2007). While natural dispersal is an increasingly likely route for the introduction of invertebrate pests e.g. nun moth (*Lymantria monachai*) and plant pathogens e.g. stem rusts (*Puccinia* spp.) native to Europe, such organisms would not be defined as non-native in Great Britain, even though their establishment as a result of climate change would not be welcomed. If human transport is essential for range expansion into environments that have become suitable as a result of climate change, then the species would be classed as non-native. In contrast, a non-native species that expands its distribution as a result of climate change would be classed as non-native in the new environment independently of whether or not human transport was involved. Such movement can often be over large distances and occur at high rates (Hulme 2012a). Thus, while human activities may facilitate the expansion of species into new ecosystems through habitat changes, global warming, atmospheric nitrogen fertilization, acid rain, etc., such species should not be considered non-native unless there is clear evidence of significant leaps in distribution attributable to human-aided transport (Pyšek *et al.* 2004). These definitions are designed to ensure native species undergoing natural range expansions into neighbouring regions do not become the targets for control which might be the case if they were viewed as non-native (Council of Europe 2009). However, this definition is the source of confusion where species origins are unclear which is often the case for many marine organisms (Gómez 2008) and plant pathogens (Jones & Baker 2007). There are also circumstances where humans are perceived as having only accelerated the arrival of species that would normally have arrived in Britain in due course e.g. sycamore (*Acer pseudoplatanus*). Conflicts may also arise where adaptation strategies, such as managed relocation, could result in species of conservation concern being classed as non-native following translocation beyond their current or former natural range and dispersal potential (Thomas 2011; Vila & Hulme 2011).

While the distinction between native and non-native status is recognised as essential to understand the biogeographic history, spatio-temporal dynamics and habitat associations of animal and plant species, it potentially poses problems when applied arbitrarily to species management (Preston 2009; Warren 2009). However, three classes of non-native species are usually distinguished which differ in the degree to which they may impact on natural or managed ecosystems:

1. A **casual non-native** (synomyms include adventive) is a species that may flourish and even reproduce occasionally outside cultivation or husbandry in an area, but that eventually dies out because it cannot form self-replacing populations and relies on repeated introductions for its persistence. Most non-native species introduced to Great Britain do not survive to establish persistent populations and die out after one or a few generations because they are not suited to the local conditions. While this may be attributable to poor climate conditions other factors include competition or predation from native species, lack of suitable host plants or animals, absence of necessary mutualists or simply that too few individuals are introduced to overcome the demographic stochasticity inherent in small founder populations.
2. An **established non-native** species (synonyms include naturalised) is a non-native species which is found in natural or semi-natural ecosystems with free-living, self-maintaining and self-perpetuating populations unsupported by and independent of humans. Only a small proportion (~10%) of non-native species introduced into Great Britain region usually become established (Williamson 1996).
3. An **invasive non-native** represents a subset (~10%) of established non-native species that is perceived as an agent of change, and threaten human health, economy and/or native biological diversity (Hulme 2007). Although, among policymakers, the term invasive non-native species is synonymous with a negative impact (Defra 2003) it is often equated in the scientific literature with extensive spatial spread (Pysek *et al.* 2004). In Great Britain, economic impact and spatial extent are not correlated (Hulme 2012b) highlighting a major disparity between policymakers and scientists in the way invasive species are classified. Since both native and non-native species can be invasive (in so far as they become widespread in natural habitats and cause impacts) it is essential that the term “invasive” is not used as a synonym for non-native.

These distinctions are important to keep in mind but it should be noted that these definitions are fluid in that in the course of a species being introduced its status may change, at first being noted as casual then established until finally viewed as invasive. These transitions may simply reflect stochastic demographic processes that initially limit establishment or prevent spread but examining these separately is important when interpreting potential changes in non-native species numbers and distribution as a result of climate change.

How big is the problem of non-native species in Great Britain?

Before examining how climate change might alter the character of non-native species, it is essential to understand their taxonomic composition, origins, and distributions. The first systematic assessment of non-native species in Great Britain provides an excellent opportunity to summarise the current state of knowledge regarding non-native species and the following section draws heavily on this assessment (Roy *et al.* 2012). A similar comprehensive assessment for Ireland has as yet to be undertaken (Stokes *et al.* 2004). There are at least 3758 non-native species in Great Britain, although one third of species have ambiguous records and status cannot be assigned with complete confidence. A total of 1795 non-native species are established in the wild, the vast majority are higher plants (73%), followed by insects (15%), other invertebrates (8%), vertebrates (3%) and lower plants (1%). Established non-native species are primarily components of terrestrial ecosystems, particularly grasslands (44%), urban and industrial habitats (17%), woodlands and scrub (11%) and coastal habitats (11%). Inland surface waters account for 8% of non-native species, while in the marine environment, species are found in similar numbers in the littoral zones (2%) and open seas (2%). Although established non-native species originate from all the inhabited continents, the dominant source differs in relation to the biome in which the species are found in Great Britain. Thus in terrestrial environments, more than half the species have European origins (56%), whereas in freshwaters the main source is North America (51%) while in the marine both North America (25%) and temperate Asia (29%) have contributed significant numbers of species. Most established non-natives in terrestrial and freshwater biomes are the results of escapes from gardens, aquaria, agriculture or aquaculture, whereas the majority of non-natives in the marine biome appear to have entered unintentionally either in ballast water or as foulants on the hulls of vessels.

Approximately 15% of established non-native species are believed to have a negative ecological or human impact and might be classed as invasive (*sensu* Defra 2003). Of the 282 species known to have negative impacts, insects (40%) and higher plants (37%) are the most frequently recorded followed by other invertebrates (13%), vertebrates (8%) and lower plants (2%). However, as a proportion of species in each taxonomic group, vertebrates are most likely to cause negative impacts (48%) followed by insects (42%), whereas only 7% of higher plants are recorded as problematic. The proportion of established non-native species causing impacts is much higher in freshwater (40%) than either the terrestrial (13%) or marine (27%) biome. The difference in the distribution of established and invasive non-native species across biomes highlights the need to target policy and management towards invasive rather than simply established non-native species. This is true also when assigning risk to particular origins of non-native species. Whereas most established non-native species in terrestrial biome originate from Europe, only a small proportion (8%) cause impacts whereas species from other origins such as temperate Asia (30%) and Africa (27%) and are more likely to pose problems. In contrast, in the marine biome those origins that contribute most established non-native species are also the sources of the highest proportion of impacting species (temperate Asia 32%, North America 31%). In the freshwater biome, most species originate from North America where a third of species have a reasonable likelihood of impacts (34%) but more than half of the species from Africa, temperate Asia, Australasia, Europe and South America also have impacts. There is also a tendency for the importance of pathways in introducing established non-native species to differ from those introducing invasive non-natives. For example, a greater proportion of terrestrial higher plants introduced through forestry have impacts (27%) compared to ornamentals (8%) and this reflects the tendency for foresters in the UK to have preferentially introduced species with invasive characteristics (McGregor *et al.* 2012).

But how significant are the impacts of the 282 invasive non-native species? A recent estimate of the total cost of established non-native species in Great Britain amounts to almost £1.7 billion per annum (Williams *et al.* 2010). While an impressive sum in absolute terms it still represents less than 0.1% GDP. However, the total sum only reflects the direct market costs, such as the money spent on control measures or the reduction in productivity due to the presence of an established non-native species and thus costs are weighted heavily towards agriculture and forestry (70%) and infrastructure (17%). The distribution of costs is strongly skewed with over one third of the total attributable to only five non-native species: rabbit (*Oryctolagus cuniculus*), Japanese knotweed (*Fallopia japonica*), field speedwell (*Veronica persica*), wild oat (*Avena fatua*) and brown rat (*Rattus norvegicus*). The direct costs for biodiversity conservation amount to only £41 million per annum and largely reflect expenditure on research and in the management of rhododendron (*Rhododendron ponticum*), mink (*Neovison vison*), Himalayan balsam (*Impatiens glandulifera*), grey squirrel (*Sciurus carolinensis*), ruddy duck (*Oxyura jamaicensis*) and signal crayfish (*Pacifastacus leniusculus*).

The indirect cost to biodiversity arising from established non-native species is much harder to estimate. In 2008; established non-native species were believed to pose a threat to 14% of priority species and 47% of priority habitats listed in biodiversity action plans and revealed an increasing trend in impact since 2005 (JNCC 2010). Non-native species may impact on the populations of specific native species through hybridisation, by facilitating the spread of pathogens, via trophic impacts (grazing, predation) and/or competition for resources (Hulme 2007). Hybridisation between non-native and native species is a potentially serious threat to biodiversity especially where hybrids are fertile and interbreed to the extent they threaten the genetic integrity of native species. In Great Britain fertile hybrids are known to occur between wild (*Felis silvestris catus*) and domestic (*F. s. lybica*) cats, native (*Beta vulgaris vulgaris*) and cultivated (*B. v. maritima*) beet, as well as native (*Bombus terrestris audax*) and commercial (*B. t. dalmatinus*) bumblebees. Several non-natives have also facilitated the introduction of their pathogens and these have had a marked impact on native populations and subsequently facilitated the establishment and spread of the non-native host. Dramatic examples in Great Britain include the transmission of parapox virus between non-native grey and native red squirrels (*Sciurus vulgaris*) and plague fungus in North-American signal crayfish (*Pacifastacus *leniusculus*) that has spread to the only species of crayfish native to the British Isles (*Austropotamobius pallipes*). As a result of predation, the American mink is held partially responsible for the decline in native water vole populations (*Arvicola terrestris*) in Great Britain while the predatory New Zealand flatworm (*Arthurdendyus triangulate*) is suspected of causing declines and local extinctions of earthworms in western Scotland. Mandarin ducks (*Aix galericulata*) are assumed to compete with the native goldeneye (*Bucephala clangul*), while Himalayan balsam outcompetes other plant species and reduces riparian plant diversity by about a third (Hulme & Bremner 2006). However, in many cases direct impact of non-native species are difficult to quantify and recently a detailed assessment of the evidence of significant harm to biodiversity identified just 49 species (Winn *et al.* 2011). These include three algae and 16 invertebrates in the marine biome, four plants, four invertebrates and four vertebrates in the freshwater biome; and eight higher plants, six mammals, two birds and two invertebrates in the terrestrial biome (Defra 2012). However, this list is by no means definitive or generally accepted. For example, the plant conservation charity PlantLife (www.plantlife.org.uk) lists 43 aquatic and terrestrial plants as being of concern.

How might climate change impact the character of non-native species?

A widespread expectation of climate change is that alterations in global temperature and precipitation regimes will favour an increase in the number, distribution and impact of non-native species (Hardwick *et al.* 1996; Thuiller *et al.* 2006; Vila *et al.* 2006; Callaway *et al.* 2012). Climate change may potentially influence the character of non-native species in Great Britain through at least eight different processes:

1. New non-native species may be introduced either accidentally or deliberately as a result of changes in trade, tourism, immigration and/or the needs of agriculture, horticulture or forestry.
2. New non-native species may be introduced through natural dispersal from their range in continental Europe where they are themselves non-native as a result of their current ranges increasing or greater dispersal opportunities as a result of changes in wind and ocean currents attributable to a changing climate.
3. Existing non-native species that are frequently introduced accidentally into Great Britain but have in the past failed to establish may, under improved environmental conditions, be able to establish in the wild as a result of climate change.
4. Existing non-native species that are already cultivated (e.g. garden plants) or raised deliberately (e.g. glasshouse biocontrol agents; aquarium biota) but that have failed to establish due to climate constraints may, as a result of climate change, experience higher probabilities of survival, population growth and persistence in the wild should they escape from confinement.
5. Established non-native species whose distribution in Great Britain is currently limited by climate may increase their range if future environmental conditions are more favourable, to the extent these species may be deemed invasive.
6. The impacts of invasive non-native species may alter under climate change, especially if existing native communities become more vulnerable to invasion

or the per capita effects of invasive species exacerbate environmental stress e.g. water availability.

7. Extreme climate events have the potential to influence all the above processes and facilitate new introductions from overseas, assist the spread of established non-native species through more intense wind and water dispersal (e.g. storms and floods), open new areas for colonisation and worsen the impacts of invasive non-native species. A detailed survey of vegetation change in Great Britain after an extreme climate event in 1987 reveal no evidence of increased richness, abundance or impact of non-native species (Smart et al. 2014).
8. The management of invasive species may become more challenging if their fecundity, resilience to management (e.g. regrowth potential) or resistance to pesticides increases under climate change.

While each of these eight processes are certainly feasible the evidence base for climate change impacting them remains sparse with rarely more than a handful of supporting examples even when drawn from studies across the globe ((Hellmann *et al.* 2008; Walther *et al.* 2009). While temperature is widely recognised to directly affect the development, survival, range and abundance of species, much less is known about the effects of precipitation. The main effect of projected temperature changes in Great Britain will be to influence the likelihood of species overwintering successfully and extending the summer season by increasing the available thermal budget for growth and reproduction. However, the evidence base for temperature affecting non-native species in Great Britain is small and caution should be applied when extrapolating examples from other parts of the world since both current and future climatic conditions in Great Britain may differ considerably from other global regions where climate change impacts may be more extreme (e.g. polar regions, mediterranean-type ecosystems). The following sections attempt to pull together the best possible evidence for these processes potentially occurring in Great Britain and in particular the role climate change may play in the likelihood of a) new non-native species introductions; b) the establishment of existing non-native species; c) the spread of established non-native species; and d) the impact of invasive non-native species.

Climate change and the risk of new non-native species introductions.

Humans have deliberately or accidentally introduced species into Great Britain for several thousand years (Preston *et al.* 2002), yet we have little information as to how rates of introduction have changed over time since the number of species introduced and subsequently failing is unknown. In the absence of data on these failures, evidence of the rate at which non-native species have established in Great Britain may provide a proxy for the overall temporal change in non-native species introductions. Consistent with patterns observed in many parts of the world, the rate at which non-native species have become established in Great Britain has progressively increased since 1700 (Fig. 1). Although mean annual temperature in central England shows an increasing trend over this period (Fig.1) and is correlated with the numbers of established non-native species (r= 0.83, df 4 P = 0.041), climate suitability is only one component that will determine the character of new introductions to Great Britain. Furthermore, rates of introduction of taxa that may be expected to be more sensitive to warming such as plant pathogens (Jones & Baker 2007) and invertebrates (Smith *et al.* 2007) show no recent increase that might be attributable to climate change. Over this same time period, Britain has witnessed dramatic economic development, increasing both the volume and diversity of international trade, as well as marked population growth and urbanization resulting in major changes in land-use ((Findlay & O'Rourke 2007; Hulme 2009b). Historical data are too coarse to disentangle the relative roles of climate and economy on the number of established non-native species. However, there are at least three lines of evidence that suggest that climate change might play a relatively minor role in shaping trends in future non-native species introductions.

1. Examination of the origins of introductions highlights that the earliest introductions were from other parts of Europe (Roy *et al.* 2012). Only after 1800 were significant numbers of species from other regions recorded, initially from North America and more recently temperate Asia. These patterns of introduction are consistent with the growth of international trade and long-distance transport (Hulme 2009b), rather than shifts in the climatic suitability of Great Britain. Furthermore, although warmer temperatures may facilitate the establishment of frost sensitive species in Great Britain, there is no evidence that non-native plant species recently established in Great Britain are any more or less frost sensitive that species establishing over the last 200 years (Hulme 2009a)
2. Comparison of the number of non-native bryophytes, fungi, vascular plants, terrestrial insects, aquatic invertebrates, fish, amphibians, reptiles, birds, and mammals across 28 European countries reveals that variation is largely determined by differences in national wealth and human population density, rather than climate, geography, or land cover (Pysek *et al.* 2010). The economic and demographic variables reflect the intensity of human activities and integrate the effect of factors that directly determine the outcome of species introductions such as propagule pressure, pathways of introduction, eutrophication, and the intensity of anthropogenic disturbance.
3. There are many regions of the world which have similar climate to Great Britain, highlighting a potentially huge global pool of possible non-native

species capable of establishment, yet only a small fraction have actually become established in the region. If climate change alters the regions to which Great Britain is climatically well-matched it may increase, or at least alter, the global pool of potential non-natives capable of establishment. Yet, the size of the global pool of potential non-native species does not seem to accurately reflect the actual composition of established non-native species in Great Britain (Smith *et al.* 2007; Roy *et al.* 2012). Thus while a good climate match may be necessary to facilitate the establishment of non-native species (McGregor *et al.* 2012) it does not appear sufficient on its own to determine the likelihood of introduction.

The foregoing runs counter to the many studies that use bioclimate models to project the likelihood that a non-native species might become established in Great Britain (Baker *et al.* 1996; Cannon 1998; Baker *et al.* 2003). However, climate suitability is only one element that will influence the likelihood that a species will establish and bioclimatic models rarely include the process of introduction, dispersal as well as interactions between species, such as competition, predation and parasitism although these may play a more significant role in establishment (Baker *et al.* 2000). Thus while it is likely new non-native species may become established in Great Britain as a result of an ameliorated environment arising from climate change, predicting their identity requires more than bioclimate projections. However, discerning whether new introductions are a direct result of climate change ameliorating the environment, an indirect effect due to adaptation strategies to climate change resulting in new patterns in human immigration, trade and agriculture, or independent of climate change, will remain a challenge. For example, the decade between 2000 and 2010 was the warmest on record in Great Britain and 125 non-native species have been recorded as new arrivals, 40 of which have established (Roy *et al.* 2012). This rate is no higher than the average decadal rate seen in the previous three centuries (Fig. 1), yet conceivably some of these new arrivals might have established due to warmer temperatures.

So where should efforts best be focused to identify the likely establishment of new non-native species in Great Britain? Studies should target non-native species that have a high probability of being introduced into Great Britain but whose establishment in the wild is limited by the current environmental conditions and these constraints are likely to be relaxed under a future climate. Four areas seem useful targets:

1. Non-native species regularly intercepted by quarantine officers as contaminants of goods or stowaways on commodities or transport vectors. The shield bug (*Nezara viridula*) has been regularly recorded associated with imports of vegetable produce but could establish under warmer temperatures (Shardlow & Taylor 2004). The Argentine ant (*Linepithema humile*) is occasionally recorded as a casual non-native species arriving in Great Britain as a stowaway on commodities and while there is no record of a colony surviving the British winter, this is not expected to be the case under a warmer climate (Defra 2009).
2. Non-native species already established in continental Europe that could spread naturally or accidentally to Great Britain. The North American western corn rootworm (*Diabrotica virgifera*) has gradually spread across Europe since the 1990s and is at the edge of its climatic limits in Great Britain, but climate change is likely to lead to SE England becoming suitable for this species

(Baker *et al.* 2003). The Asian tiger mosquito (*Aedes albopictus*), has never been reported in Great Britain, but on the continent colonies (since exterminated) have been recorded as far north as Normandy, and warmer, wetter weather would favour its establishment in Great Britain (Defra 2009). The Indian house crow (*Corvus splendens*) has established a breeding population in the Netherlands, probably representing the climatic limits for breeding but climate change that relaxes this potential constraint may facilitate population expansion in The Netherlands and enhance the risk of the species entering and establishing in Great Britain (Natural England 2009). The round goby (*Neogobius melanostomus)* a Ponto-Caspian fish, has already spread to the estuaries of the Netherlands and Belgium where it is likely to be dispersed as stowaways on the hulls of ships and establishment in the estuarine and freshwaters of Great Britain would be likely should these become warmer under climate change (Kornis *et al.* 2012).

3. Non-native species deliberately introduced for economic reasons because they are better suited to the changing climate of Great Britain. The major group in this category will be horticultural plants imported for the establishment of low maintenance, low water use “mediterranean-style” gardens e.g. succulents, cacti etc.
4. Non-native species that are currently contained in anthropogenic environments e.g. gardens, buildings, glasshouses. Warmer winter temperatures are expected to increase the probability that the non-native leaf miner (*Liriomyza huidobrensis*), a pest in glasshouses, will overwinter in Great Britain (Baker *et al.* 1996). The German cockroach (*Blattella germanica*) is a common nuisance insect usually found indoors in buildings in Great Britain, however climate change may facilitate the establishment of this species outside as commonly occurs overseas under more suitable environmental conditions (Defra 2009). Widely traded pets and aquarium fish, such as the African pygmy hedgehog (*Atelerix albiventris*) or red shiner (*Cyprinella lutrensis*) pose a higher risk of escape from captivity and subsequent establishment following climate warming (Natural England 2009). A significant source of future established non-native species will be plant species escaping from domestic gardens. The magnitude of this risk is high given that there may be as many as 70,000 taxa (species, subspecies, cultivars and varieties) grown in the gardens of Great Britain. However, the identity of these high risk species has not been explored in detail.

Climate change and the establishment of existing casual non-native species.

The distinction between new introductions and casual species is not always clear, since many species predicted to become new introductions may often occur sporadically in the wild. The distinction is primarily in the regularity of such occurrences, which reflects that most casual populations are maintained by propagule input from a local source and if this source is widespread then the species, even though casual, may also be widely distributed. There are several widely distributed casual non-native plants that fail to overwinter due to low temperatures and these species may be likely to establish more persistent populations following climate change (Preston *et al.* 2002). These include contaminants of bird seed e.g. ragweed (*Ambrosia artemisiifolia*), garden escapes e.g. pot marigold (*Calendula officinalis*) and feral crops e.g. oilseed rape (*Brassica napus* subsp. *oleifera*). It is also possible that several species of mammal that have established casual populations following escape of release from captivity may also face increased opportunities of population persistence under climate change e.g. Mongolian gerbil (*Merriones unguicula*), crested porcupine (*Hystrix cristata)* and golden hamster (*Mesocrice auratus*). Similarly, the red-eared terrapin (*Trachemys scripta*) although not breeding in the wild occurs in substantial populations that have persisted for several years and climate change could facilitate breeding in this species and its subsequent establishment in Great Britain (Natural England 2009). The Colorado potato beetle (*Leptinotarsa decemlineata*) is not established in Great Britain as a consequence of control programmes targeting outbreaks. However, as the climate warms, an increasing area of Great Britain is predicted to become suitable which mean eradication campaigns will become less effective (Baker *et al.* 1998). However, in the absence of detailed assessment, which would include knowledge of the role of climate in species performance and the relative importance of other constraints on establishment, any predictions regarding casual species should be viewed cautiously. For example, the limited distribution and establishment of rainbow trout (*Oncorhynchus mykiss*) in Great Britain has led to the suggestion that it is climate limited but the available evidence suggests that this is not the case but that a variety of other factors prevent this species from establishing widely (Fausch 2007).

Climate change and the spread of established non-native species.

The importance of climate on species distribution has long been acknowledged (Walther *et al.* 2009) and thus it is intuitive to expect changes in species ranges as a result of climate change. Although changes in wind patterns and ocean currents have the potential to alter rates and directions of the spread of non-natives both into and within Great Britain, most invasive non-native species exhibit high rates of dispersal often as a result of their movement by humans (Hulme 2012a). Thus it is likely that it is the effects of climate change on environmental suitability rather that than species dispersal patterns, that will shape the spread of established non-native species. Current perspectives regarding how climate change might affect the distribution of established non-native species are drawn primarily from four sources:

1. Bioclimate models that use existing climate-distribution relationships in the native, invaded or both native and invaded ranges to project potential distribution in Great Britain under current and future climates. These techniques have been applied to model future distributions in Great Britain of non-native marine crustaceans (Gallardo *et al.* 2012)), molluscs (Jones *et al.* 2013) algae (Reid 2009), freshwater fish (Britton *et al.* 2010), terrestrial plants (Beerling *et al.* 1995) and insects (Baker *et al.* 1996). Without exception, these models predict an increase in the potential range occupied by non-native species. A critique of such top-down approaches is that they necessarily emphasise the role of climate in species distributions and ignore other features that might constrain a species range even where the climate is favourable e.g. salinity tolerance (Ashton *et al.* 2007; Groener *et al.* 2011) or do not adequately model multi-species interactions e.g. synchrony with bud

burst in the spring for insect defoliators. Thus at best, these models should be viewed as estimates of the maximum potential rather than realised range species may attain following climate change. For example, when socioeconomic factors are also included in such models they further support the view that socioeconomic factors are critically important in the spread of invasive species across Europe (Gallardo 2014) and also specifically in Great Britain (Gallardo & Aldridge 2013).

2. Ecophysiological studies have been undertaken to assess how a species responds to climate variables in terms of their performance and demography. The performance of several non-native species in Great Britain is temperature sensitive including fecundity in mammals (Bell & Webb 1991); fish (Fobert *et al.* 2011)), birds (Shwartz *et al.* 2009)); growth of marine algae (Hales & Fletcher 1989); survival in amphipods (Cowling *et al.* 2003; Ashton *et al.* 2007)) and growth, survival and fecundity in plants (Willis & Hulme 2002). In most cases, temperature increases expected as a result of climate change will improve the performance of these taxa, however it should be noted that relationships with temperature may be non-linear e.g. giant hogweed (*Heracleum mantegazzianum*) and the performance of some species in some locations may be pushed beyond their optimum by climate change (Willis & Hulme 2002).
3. Interpretations of changes in species distributions that are consistent with recent changes in temperature or precipitation. To date, only a few studies have linked recent spatio-temporal changes in non-native species distributions to climate variables. For example, range expansions of several non-native species in Europe over the last 30 years are correlated with trends in local climate both in coastal Mediterranean areas (Sobrino Vesperinas 2001) as well as continental alpine sites (Walther *et al.* 2002). However, the observation of recent increases in the prevalence of a non-native species and subsequent correlation with contemporary warming trends may not always indicate causation. Although bioclimate undoubtedly sets the maximum potential bounds around species distributions, unlike many native species, the distribution of non-native species may not be at equilibrium with the local or regional climate ((Hulme 2003, 2006). It is in the nature of invasive plant species to increase in prevalence (Pysek & Hulme 2005) and the recent introduction history of non-native species has meant that the population expansion of many species in the 20th century happens to coincide with marked global warming. Models based entirely on intrinsic demographic processes can often simulate these range expansions without recourse to climate drivers (Pysek & Hulme 2005).
4. *A priori* expectations regarding the likely response of non-natives to climate change. The non-native flora and fauna may be represented proportionally more by species that a) are better suited to future climates e.g. low-latitude species that would potentially benefit from a warmer and drier environment; b) comprise life-forms that are known to benefit from future climates e.g. geophytes, thermophiles; and/or c) possess life-history traits that facilitate the rapid tracking of climate change across a region e.g. short generation times, marked dispersal ability. Such expectations form the primary basis for the horizon scanning predictions of the consequences of climate change on non-native species in Great Britain (Defra 2009; Natural England 2009). However, alternative approaches to horizon scanning that did not explicitly examine

climate effects identified a wide range of potential future invasive species to Great Britain that are likely to arrive independently of climate change (Roy *et al.* 2014)

While these different lines of evidence are commonly used to highlight the role climate change will play in the expansion of non-native species in Great Britain, none of these approaches on their own are sufficient to support such predictions. An integrative approach is needed that sets out clear hypotheses regarding the expectations of why a species will respond to climate change that can be matched to ecophysiological knowledge and used to subsequently assess whether this information is consistent with observed changes in species distribution. Only where there is correspondence between these three elements can any confidence be placed in bioclimate based projections of future species ranges. Unfortunately, this comparative framework has not been widely adopted. An exception is the detailed analysis of the role of climate change in the spread of bluetongue virus in Great Britain which combined comprehensive studies linking vector and pathogen temperature requirements to spatial patterns of range change associated with climate shifts (Purse *et al.* 2008). Indeed, it might be expected that predictions of future range expansion of temperature sensitive yet effectively dispersed (either through a vector or wind/water) pathogens of widespread hosts e.g. thermophilic rust fungi, may be more reliable than for other non-native taxa that are likely to be constrained by other features of the environment (West *et al.* 2012). Thus an expectation is that several crop pests and diseases will become more widespread under climate change. However, the situation may not be so simple for other taxa. For terrestrial vascular plants, compared to native species, non-native species are generally found in warmer and drier parts of Great Britain (Hulme 2009a) and their flowering phenology responds more strongly to warming (Hulme 2011). These attributes lead to the expectation that they should also be more likely increase their ranges in Great Britain following recent warming (English Nature 1994). However, recent changes in species distributions do not correlate with either of these factors and appear far more sensitive to changes in land-use and eutrophication (Hulme 2009a; Hulme 2011). Thus, for vascular plants at least, projections of future distributions based on bioclimate alone are unlikely to be reliable. This is not to say that there are no species likely to increase their range as a result of climate change, for example we might expect species adapted to warmer climates such as the evergreen shrub, cherry laurel (*Prunus laurocerasus*), and succulent Hottentot fig (*Carpobrotus edulis*) to benefit from climate warming (English Nature 1994). However, we cannot as yet predict how the distribution ranges, rate of spread and behaviour of these species is likely to change in the future. The extent to which these findings also apply to other taxa is unknown and adds considerable uncertainty to predictions of shifts in distribution of non-native species as a result of climate change.

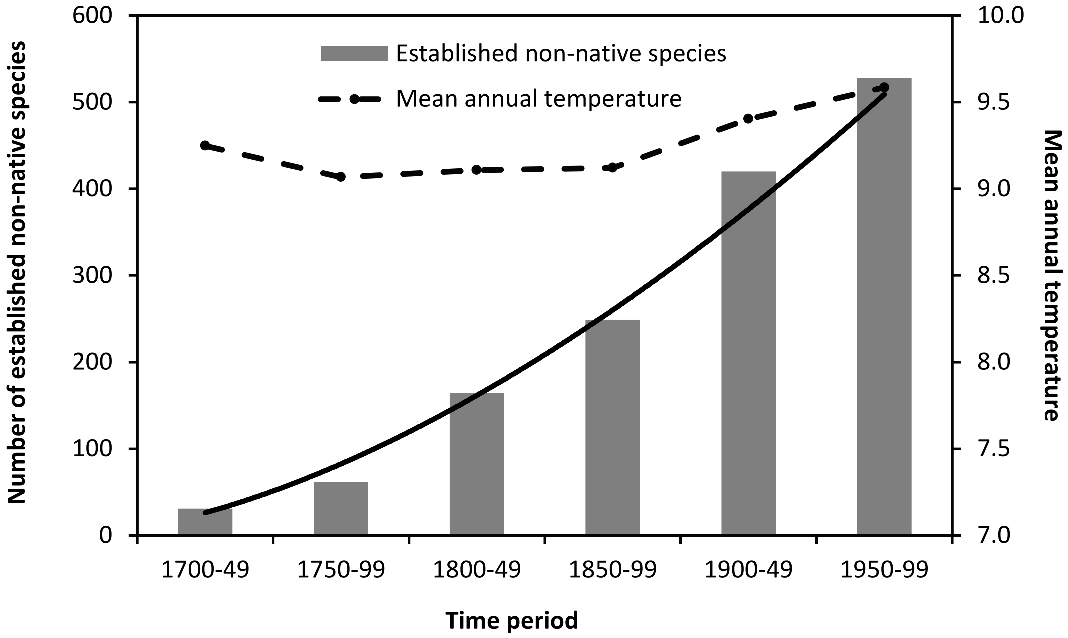
Climate change and the impact of invasive non-native species.

The impact of non-native species will be a function of their per capita effect, local abundance and geographic distribution (Parker *et al.* 1999). Much of the emphasis to date on invasive non-native species and climate change has been on the changes to their geographic distribution. Wider distributions would certainly increase the frequency with which negative impacts might be observed and the total costs of managing problem species. This will be particularly true of non-native crop pests that are likely to expand their ranges northwards e.g. turnip sawfly (*Athalia rosae*). Local abundance can be expected to increase in sites where expanding non-native are currently rare or absent. However, temporal assessments of changes in non-native vascular plant richness show that while climate may increase their abundance, their overall representation in plant communities often remains low (Maskell *et al.* 2006; Keith *et al.* 2009) such that negative impacts of most non-native plants species on native plant richness is negligible. However, similar temporal data on non-natives dominating plant communities are not available for Great Britain. In contrast, the effect of climate on species interactions which might determine their per capita effect are less studied. For vascular plants, the evidence is that experimental warming had a much greater impact on native than non-native species, with the latter disappearing from warmed plots (Buckland *et al.* 2001). Competition between the non-native pumpkinseed (*Lepomis gibbosus*) and native perch (*Perca fluviatilis*) did not increase under warmed treatments and did not support the view of adverse effects occurring following climate change (Fobert *et al.* 2011). Alternatives to these experimental approaches include using long-term performance data to infer likely impacts of climate change on competitive interactions. Compared to the native ash (*Fraxinus excelsior*), growth of the non-native sycamore (*Acer pseudoplatanus*) with which it competes in deciduous woodlands was slower and photosynthetic rates lower under dry conditions suggesting the non-native may be less competitive and even decline under climate change if summer droughts become more frequent (Morecroft *et al.* 2008). Long-term phenological records highlight that non-native vascular plants are responding more strongly to climate change than natives by flowering several days earlier per degree of warming (Hulme 2011). As a consequence of these relative changes in flowering phenology, the likelihood of hybridisation between the non-native white (*Silene latifolia*) and native red (*S. dioica*) campion is greatly increased while that between the non-native pale (*Linaria repens*) and native common (*Linaria vulgaris*) toadflax is reduced (Fitter & Fitter 2002). Thus there is not much quantitative evidence to suggest per capita effects of non-native species will be greater under climate change although it is certainly possible that freshwater and terrestrial invertebrate predators and herbivores could become more active and thus have more impact on native species. A further possibility is that climate change increases the susceptibility of species and ecosystems to invasions. However, there is considerable uncertainty as to how general such indirect effects may be.

Climate change and non-native species: conclusions.

Although much has been written about the potential impacts of climate change on non-native species, there is currently only limited evidence that might help indicate whether this issue will become worse under climate change. The problem is that independently of climate change, we can expect the distribution and local abundances of non-native species to increase. The UK National Ecosystem Assessment identified non-native species to have a very rapid increase in impact in marine ecosystems while increasing impacts were also recognised in coastal margins, urban environment, freshwaters, woodlands, and enclosed farmlands with impacts only remaining the in mountains and moorlands as well as semi-natural grasslands (Winn *et al.* 2011). While it is likely that certain species will respond more to future climates than others, the future composition of non-native species as a whole will probably reflect other drivers e.g. land use change, and globalisation of trade. Indeed, the factors that drive the richness and distribution of the non-native species problems of the future may have been set in motion by historical factors several decades in the past and not reflect contemporary processes at all (Essl *et al.* 2011). It is therefore imperative that rather than making general statements about non-native species increasing under future climates based on their traits or biogeographic origin, research should aim to identify the specific species and particular circumstances likely to be responsible for changes in their per capita effects, local abundance and range. Differences should be expected in the response to climate change by native and non-native species. The dynamics of non-native are likely to be influenced by residence time (the date since naturalisation) especially if inherent lag-phases exist (Pyšek & Hulme 2005), propagule pressure (how many individuals occur), human mediated long-distance transport, and anthropogenic habitat modification. These additional factors will undoubtedly influence the responsiveness of non-native species to climate and since it is likely that non-native species will continue to be introduced, spread and increase in abundance, correctly predicting the drivers of change will be essential for adaptive management in the face of environmental change(Hulme 2005).

Figure 1. Increasing trend in the number of established non-native species in Great Britain in each of six 50 year periods (data from Roy *et al.* (2012) in relation to the mean annual temperature of each period (data from the central England Temperature record). A power relationship is plotted to highlight the strong increasing relationship in the numbers of established non-native species.



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