



# An updated assessment of the direct costs of invasive non-native species to the United Kingdom

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**Abstract** Estimates of the economic impact of invasive non-native species (INNS) are important to support informed decision-making and prioritise resources. A detailed estimate of the direct costs of INNS to Great Britain, covering many sectors of the economy and the impacts of many INNS in diverse habitats, was made in 2010 and extended to Northern Ireland in 2013. These estimates are increasingly out of date as a result of changes in distribution and impacts of species, new knowledge, changes in management and newly established INNS. We, therefore, updated the estimated costs for the United Kingdom (UK) for sectors where new information was available and applied an inflation factor to the remaining sectors and species. The results show changes in all sectors and species and the new estimated annual costs to the UK economy is £4014 m, with £3022 m, £499 m, £343 m and £150 m to England, Scotland,

Wales and Northern Ireland, respectively. Overall, we found a 45% increase in comparable costs since 2010, with most estimated costs increased, often more than inflation, although in some cases the costs have decreased as a result of changes in the population size of INNS, such as was the case for rabbits. A comparison with the previously estimated costs revealed that the costliest species and sectors of 2010 remain the same, but the newly established, widely distributed and highly impactful ash dieback is now one of the most costly diseases caused by an INNS. We discuss reasons for these changes and the evolution of costs in comparison to other studies. Overall, these results confirm the enormous cost of INNS to the UK economy and highlight the need for continued efforts to mitigate the impacts of established INNS, whilst also supporting measures to limit the entry and establishment of new, potentially harmful non-native species.

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## Introduction

The impacts of invasive non-native species (INNS) can be manifold, ranging from loss of crops, damaged buildings, and additional production costs, to the loss of livelihoods and ecosystem services (Vilà et al. 2011; Pyšek et al. 2020; Diagne et al. 2021;

Cuthbert et al. 2021). INNS are increasingly abundant in the United Kingdom (UK) and their impact is rising (Cuthbert et al. 2021). The arrival and establishment of these species can have severe adverse economic impacts on a wide range of sectors, such as agriculture, transport and utilities. As of 2019, there were 3224 non-native species in Great Britain (GB), of which 2016 were classified as established (reproducing in the wild) (Joint Nature Conservation Committee 2021). Tackling INNS is a key component to achieving the UK Government's aims under the 25-Year Environment Plan, under the Great Britain Invasive Non-Native Species Strategy (Anonymous 2015) as well as the UK's obligations as a signatory of the Convention on Biological Diversity (<https://www.cbd.int/convention/text/>). Given the limited resources available to address INNS, it is important to determine and quantify the impacts of INNS on different sectors of the economy to enable prioritisation of said resources (Cuthbert et al. 2021; Eschen et al. 2021). Furthermore, the impact of INNS changes over time and repeated assessments may provide insight into the evolution of the impacts, and potentially the effectiveness of INNS management.

The number of introduced non-native species has increased in many parts of the world (Seebens et al. 2017), including in GB (Roy et al.). While there are significant differences in introduction rates among taxa (Seebens et al. 2018), it is clear that measures need to be taken to minimise new establishments, through pathway management, early detection and rapid response, control of the spread of established species and mitigation of the impact of established and widespread species (Eschen et al. 2021; Cuthbert et al. 2022). An estimated 10–12 new non-native species become established every year in GB (Anonymous 2015) and the impact of other, already established species increases, likely including the associated costs in various sectors of the economy. These costs are significant, and it is not possible to control all species, especially if they are widespread or occur in natural areas where management options are limited. This clearly highlights the need to prioritise resources based on a good understanding of INNS and their economic impacts.

There remains a significant gap in our understanding of the size and nature of the economic impacts of INNS, and assessment of the costs is needed to prioritise investment in prevention, intervention and

management of INNS. In 2010, Williams et al. (2010) made an estimate of INNS costs to GB in 2009, which provided assessments of the economic cost of INNS to twelve sectors and detailed examples for three species (Japanese knotweed (*Reynoutria japonica*), signal crayfish (*Pacifastacus leniusculus*) and floating pennywort (*Hydrocotyle ranunculoides*)). In 2013, Kelly et al. (2013) made a similar estimate of the costs for Northern Ireland in 2012, which was based on new information, where available, or extrapolated the figures in Williams et al. (2010) where new information could not be found.

It is important that decisions are made based on up-to-date information and given the evolution of INNS in the UK, a new estimate is needed that will highlight changes. Repeat assessments may provide indications of the efficacy of, or need for improved management interventions. The estimates for the UK that were made over ten years ago are increasingly out of date and the impacts that were quantified have evolved. Williams et al. (2010) included five case studies to demonstrate the (hypothetical) costs of eradication of these species at different stages of invasion; some of these species are likely to have subsequently spread further, increasing associated costs. For example, carpet sea squirt (*Didemnum vexillum*), has become established in more locations (<https://records.nbnatlas.org/>), as has water primrose (*Ludwigia grandiflora*), which is now present in more than twice the number of locations (T. Renals, pers. comm.). Eradication efforts have not succeeded, with a likely associated increase in economic impacts. Other species have established, or the impacts of species already present in 2009 have increased notably. For example, *Hymenoscyphus fraxineus*, the causal agent of ash dieback was first recorded in the UK in 2012, although it was probably present earlier (Wylder et al. 2018), and today causes major economic costs. While a recent study has summarised costs of INNS to the UK (Cuthbert et al. 2021) and revealed that the costs are increasing, this estimate was based only on empirical data from the literature, and thus used a different methodology, yielding results that cannot be regarded as an update of the figure in Williams et al. (2010) that was based on upscaling of costs to the national scale. To date, studies have assessed the patterns of costs and modelled changes across studies of different INNS, in a range of habitats and on various spatial scales (Diagne et al.

2021; Cuthbert et al. 2021). While this approach is the best possible with the available data, an assessment of cost evolution would be most comparable if an assessment was repeated using the same approach for the same region, but to our knowledge this has never been done. The aims of this study were therefore to update the estimates by Williams et al. (2010) and Kelly et al. (2013), to quantify the current direct costs of INNS to the UK and to assess how the costs have changed over the past decade.

## Methods

This work evaluated the annual economic costs of INNS to different economic sectors in the United Kingdom in 2021. As such, it provides an update to the estimate of the cost to Great Britain (Williams et al. 2010) and to Northern Ireland (Kelly et al. 2013). Information to update the estimates was sought through searches of grey and peer-reviewed literature, popular media (all using key words like “cost”, “invasive species”, “INNS”, the names of the sectors and the names of individual species) and by contacting key stakeholders and additional people in our networks to obtain up-to-date cost estimates for selected species and sectors. In addition, information about the distribution of individual species, statistics on sectors and other relevant information were identified as needed to upscale localised estimates to the national or UK scale. This information was used and combined to produce updated estimates for all sectors (see S11). Most of the estimates were updated with new information and only the section on human health costs was solely updated by application of an inflation factor to the 2010 figure using the calculation and data underlying the Bank of England inflation calculator (<https://www.bankofengland.co.uk/monetary-policy/inflation/inflation-calculator>). For example, to calculate the inflation of a cost between 2009 and 2021, the cost in 2009 was multiplied by the 2021 consumer price index, divided by the 2009 consumer price index. However, inflation factors were used in many of the detailed calculations as well, where some figures were adjusted for inflation and other figures were replaced with new data. Therefore, it is impossible to provide an inflation cost separate from the change in the total cost.

There are a number of detailed economic valuation techniques that can be used including partial budgeting, use of replacement and control costs, partial equilibrium models and economy-wide models (Warziniack et al. 2021). Partial budgeting and use of replacement and control costs are the simplest approaches to use. They enable costs to be estimated either at a species level or closed system level e.g. crop production. Partial equilibrium models and economy-wide models allow much broader assessments of costs, but are complex, have heavy data requirements, and are time-consuming. In addition, non-market valuation methods, including stated and preferred preference techniques can be used to estimate non-market or non-use costs, including ecosystem services. As with Williams et al. (2010) the focus here was on use of partial budgeting and replacement and control costs, where species estimates needed to be updated e.g. for water primrose or carpet sea squirt, or new species estimates developed. Where appropriate, some non-market valuation methods, as detailed in Defra’s Enabling a Natural Capital Approach guidance (Department for Environment Food and Rural Affairs 2021), were used to update previous estimates. The timescale of this work did not allow field research to generate original data.

The methods of calculation for the updates were broadly similar to the calculations in Williams et al. (2010) and used available data from grey and peer-reviewed literature, media reports, online databases (for species distribution, areas under specific land use, etc.) and interviews with key informants. Where new data were available, these were used to update the previous calculations, to ensure consistency of approach and results with Williams et al. (2010). Due to time constraints, we did not carry out a survey to collect new data. Instead, we contacted key stakeholders and informants on an as-needed basis. Newspapers also report exceptional costs incurred by various stakeholders as a result of high-impact INNS and we searched the literature to collate reported costs, while taking care not to double count costs reported by different sources. Information from news media was considered a last resort when no other information could be found and was very rarely used in the calculations (S11). We upscaled local or regional costs to the country where possible, using various sources such as national statistics and species distribution data. Thus, the general approach to generating

estimates was one of cost accounting and the exact methodology varied among species and sectors depending on the availability of data.

We made cost estimates for each of the four countries and for the United Kingdom as a whole. While it was impossible to obtain all costs for most of the species and sectors due to a paucity of data, and sometimes a lack of time or resources, we wanted to ensure that no major errors were made. In this study, we included the costs associated with a few fungal pathogens, because although microorganisms are not part of the merit of the GB Non-Native Species Secretariat (NNSS) and these were not included in Williams et al. (2010), some of these have become more important than they were in 2009. In order to be able to compare the estimates resulting from the current study with the previous work, we report cost estimates with and without fungal pathogens below. A panel of experts reviewed the estimates in order to verify their correctness and accuracy. The results presented below and in the Tables are rounded to the nearest £m. Detail of all calculations, including data sources, is provided in SI1.

## Results

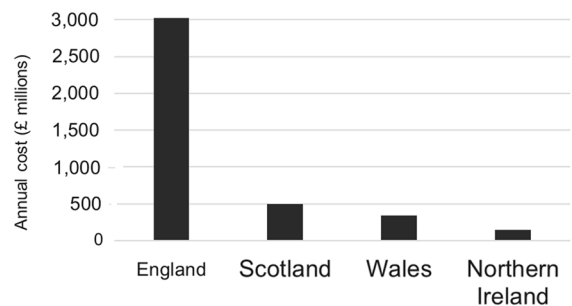
### Annual INNS costs in 2021

The total annual cost of INNS to the UK was estimated at around £4014 m, with the largest fraction of the costs that were split by country attributed to

England (75.3%) and only a small fraction apportioned to Northern Ireland (3.7%) (Table 1, Fig. 1).

There were large differences in the fraction of total estimated costs to the sectors of the economies. The largest fraction of costs across the four countries was allocated to agriculture (57.8%, £ 2321 m), but the fraction of costs to agriculture was higher in England and Scotland than in the other countries (62.1 and 55.8%, respectively; Fig. 2). Fungal pathogens were an important component of the cost to agriculture, accounting for 46.9% of the INNS costs to this sector. The second-largest sector cost was forestry (average 25.2%, £1010 m), which was almost exclusively the result of the newly established *Hymenoscyphus fraxineus*, the causal agent of ash dieback (Table 2).

On average, almost 5% of the costs were attributed to construction, development and infrastructure, with a larger fraction in England (7.6% of total



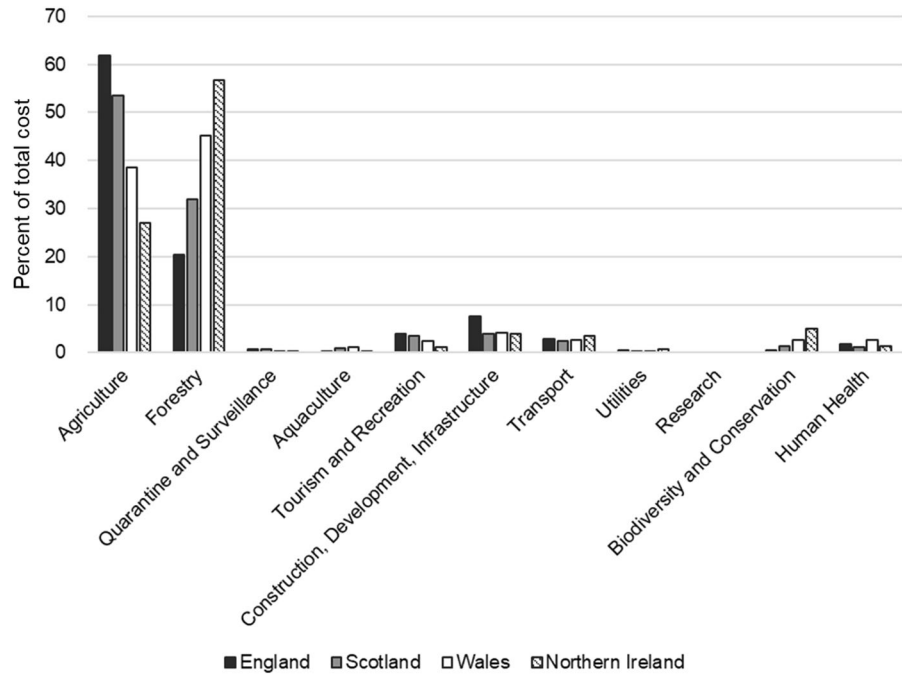
**Fig. 1** The annual cost of INNS to the UK in 2021, by country. The total estimated annual cost to the UK was £4014 m

**Table 1** Annual costs of invasive non-native species to the United Kingdom in 2021 by sector, including the cost of fungi

In £m	England	Scotland	Wales	Northern Ireland	UK
Agriculture	£1878	£278	£124	£40	£2321
Forestry	£614	£145	£167	£85	£1010
Quarantine and Surveillance	£19	£4	£1	£1	£24
Aquaculture	£9	£5	£4	£1	£18
Tourism and Recreation	£107	£19	£8	£2	£136
Construction, Development and Infrastructure	£231	£20	£13	£6	£270
Transport	£84	£12	£9	£5	£110
Utilities	£13	£2	£1	£1	£17
Research	£0	£0	£0	£0	£8
Biodiversity and Conservation	£14	£8	£8	£8	£37
Human Health	£54	£6	£8	£2	£71
Subtotal	£3022	£499	£343	£150	£4014

Numbers are rounded to the nearest £m

**Fig. 2** The fraction of the annual cost of INNS to different sectors of the UK economy in 2021, by country



**Table 2** Annual costs of invasive non-native species to the United Kingdom in 2021 by sector, excluding the cost of fungi

In £m	England	Scotland	Wales	Northern Ireland	UK
Agriculture	£860	£147	£56	£24	£1088
Forestry	£56	£23	£39	£4	£123
Quarantine and Surveillance	£19	£4	£1	£1	£24
Aquaculture	£9	£5	£4	£1	£18
Tourism and Recreation	£107	£19	£8	£2	£136
Construction, Development, and Infrastructure	£231	£20	£13	£6	£270
Transport	£84	£12	£9	£5	£110
Utilities	£13	£2	£1	£1	£17
Research	£0	£0	£0	£0	£8
Biodiversity and Conservation	£14	£8	£8	£8	£37
Human Health	£54	£6	£8	£2	£71
Subtotal	£1447	£246	£147	£53	£1893

Numbers are rounded to the nearest £m

costs to England) than in the other countries. This was due to comparatively higher costs of a few species to England, including Japanese knotweed, grey squirrel, brown rat and signal crayfish (Table A6.6 in SI1). Costs to tourism and recreation accounted for on average 2.7% of the costs per country, with higher fractions in England and Scotland, compared to Wales and Northern Ireland. Hull fouling and waterway management constituted about half of the costs

in this category in all four countries, and in England, the recently established box tree moth (*Cydalima perspectalis*), caused approximately a quarter of the costs related to tourism and recreation at £15.4 m (Table A5.6 in SI1). Transport also accounts for on average 2.8% of the costs, with a higher fraction in Northern Ireland (3.5%) than in the other countries, which was caused by comparatively high costs to shipping (mainly hull fouling; Table A7.5 in SI1).

Costs related to biodiversity account on average for 2.3% of the costs, but these are some of the most challenging costs to capture comprehensively, and this is likely a gross underestimate. The average country costs to the other sectors were less than 2%

When species only covered by the NNSS are considered, i.e. with fungi excluded from the estimate, the total cost was estimated to be £1893 m (£1839 m to GB and £53 m to NI) and the fraction of the INNS cost to UK agriculture was 57.5%. The cost to forestry was 6.5%, with higher fractions in Scotland and Wales than in England and Northern Ireland, which reflects differences in forest cover among the countries. The cost to construction, development and infrastructure was 14.3%, to tourism and recreation 7.2% and to transport 5.8%. The cost to human health was 3.7% and all other sector costs were below 2%.

### Changes 2009–2021

Across all sectors and countries, the estimated annual cost of INNS to the UK increased by 135% from the previous estimates. However, there were large differences in changes among the countries and sectors (Table 3). The cost to forestry increased eightfold, the cost to aquaculture and agriculture increased by 139.5% and 112.7%, respectively, and the cost of most of the other sectors increased roughly in line with inflation (47.6% for GB and

55.7% for Northern Ireland). The cost to biodiversity, which was updated by adding an inflation factor, was lower because research and indirect costs were not included in the updated figure because of a paucity of data. The cost of research is much lower than in Williams et al. (2010), which is partly due to changes in the calculations.

Cost of mammals has decreased as a result of the decline in rabbit population due to the increased distribution of two strains of rabbit haemorrhagic disease virus, although populations of other mammal species have increased, especially deer. The cost of plants has increased, for example due to the increase in the distribution of floating pennywort and Japanese knotweed.

When fungi are excluded from the estimates, the picture looks quite different (Table 2, Table 4), with an overall cost increase of only 44.9%, due to small changes to agriculture and forestry, which now increased by only 58.1% and only 9.3%, respectively. The other sectors are not affected by cost estimates made for fungi. Fungi in forestry have become much more costly, which is almost entirely (>98.5%) due to the new *Hymenoscyphus fraxineus* as well as due to the spread and consequent additional management cost of *Phytophthora ramorum*. The fraction of the changes in economic costs as a result of including fungi in the estimates was larger in Northern Ireland than in Great Britain.

**Table 3** Percent change in annual cost estimates by sector and country, including the cost of fungi. No estimates were made for some of the sectors for Northern Ireland (Kelly et al. 2013) and research costs were not split by country

	England	Scotland	Wales	Northern Ireland	UK
Agriculture	123.7	78.4	74.7	64.2	112.7
Forestry	1240.4	197.4	1015.6	2942.1	800.6
Quarantine and Surveillance	33.1	177.4	-47.3		37.9
Aquaculture	101.1	579.2	75.0	82.1	139.5
Tourism and Recreation	36.1	42.5	38.5	175.5	38.0
Construction, Development, Infrastructure	18.7	196.4	20.7	82.3	25.4
Transport	33.1	27.3	-1.0	-60.6	16.0
Utilities	48.0	77.7	84.9		64.7
Research					-52.7
Biodiversity and Conservation	23.2	30.2	31.0		-8.9
Human Health	42.7	42.7	42.7	25.6	42.2
Subtotal	132.9	101.4	167.6		134.9

The strong increases in the forestry sector are almost exclusively due to *Hymenoscyphus fraxineus*

**Table 4** Percent change in annual cost estimates by sector and country, excluding the cost of fungi. No estimates were made for some of the sectors for Northern Ireland (Kelly et al. 2013) and research costs were not split by country

	England	Scotland	Wales	Northern Ireland	UK
Agriculture	72.9	40.2	−9.3	3.9	58.1
Forestry	23.4	−53.0	160.4	56.0	9.3
Quarantine and Surveillance	33.1	177.4	−47.3		37.9
Aquaculture	101.1	579.2	75.0	82.1	139.5
Tourism and Recreation	36.1	42.5	38.5	175.5	38.0
Construction, Development, Infrastructure	18.7	196.4	20.7	82.3	25.4
Transport	33.1	27.3	−1.0	−60.6	16.0
Utilities	48.0	77.7	84.9		64.7
Research					−52.7
Biodiversity and Conservation	23.2	30.2	31.0		−8.9
Human Health	42.7	42.7	42.7	25.6	42.2
Subtotal	51.4	25.0	23.5		44.9

### Costs of individual species

There were large differences in the costs due to species (and in some cases species groups) to the four countries and the UK as a whole (Table 5). The fungus *Hymenoscyphus fraxineus* was the costliest, followed by Japanese knotweed, rabbit, rats and mice, cockroaches and deer. As a group, fungi were the costliest to the UK, accounting for 52.9% of the total estimated costs, followed by mammals, plants and terrestrial arthropods (21.9%, 15.5% and 7.5% of the total, respectively).

### Discussion

Our results show the high current annual cost of INNS to the UK economy, and reveal how these costs have changed over the past decade (twelve years for GB and nine years for Northern Ireland). When the same species are considered as in the previous estimates (Williams et al. 2010; Kelly et al. 2013), the proportion of the costs incurred by different countries and sectors of the economy is similar and the taxa causing these costs largely remain the same. The cost of rabbits is again the highest, although it has come down due to viral infections that appear to have reduced the wild population size, and the cost of Japanese knotweed is still very high. However, a single species (*Hymenoscyphus fraxineus*) has become one of the most costly species in the past decade, while

some other species, including *Didemnum vexillum*, water primrose and *Phytophthora ramorum*, have become more costly as a result of their expanding distributions.

Overall change in annual cost of INNS to UK, by sector, species and country

Our updated estimate of the cost of INNS to the UK, affecting a range of sectors and caused by a wide range of species, appears to confirm that the costs increase rapidly over time. The increase in costs over the past decade reported here is similar to the increase in costs over the three decades since 1976 reported in recent studies (Diagne et al. 2021; Cuthbert et al. 2021), which reported an increase of roughly one order of magnitude per decade, but higher than the change in costs to the UK reported by Cuthbert et al. (2021) for the period 2016–2019. The authors of the latter paper suggested that the lower rate of increase in the last period was due to a lag in reporting. We found a similar shortage of new research but resolved this through expert consultation and inclusion of data from reports (including the UK Breeding Bird Survey, National Farmers Union mutual report, Defra, DAERA stats etc.) to obtain missing or new data to inform calculations. In other words, inclusion of data from reports increased the evidence base, primarily used for upscaling impacts, but few assessments of economic impact were found in such reports.

**Table 5** Summary of estimated annual cost per species in 2021, arranged by the total estimated cost to the four countries and the UK

Species	England	Scotland	Wales	NI	UK
<i>Hymenoscyphus fraxineus</i>	£556.4	£120.3	£125.9	£80.9	£883.5
Japanese Knotweed	£207.4	£21.8	£11.2	£6.0	£246.5
Rabbit	£88.9	£38.1	£39.7	£3.0	£169.7
Rats and mice	£61.0	£8.4	£5.0	£10.0	£84.4
Cockroaches	£53.4	£6.3	£8.2	£1.9	£69.8
Deer	£47.7	£9.8	£4.6	£0.8	£62.9
Grey squirrel	£32.0	£1.1	£1.1	£2.5	£40.6
Varroa mite	£10.7	£5.4	£5.4	£1.0	£22.5
Box tree moth	£15.4	£0.0	£0.0	£0.0	£15.4
Green spruce aphid	£1.4	£10.3	£2.4	£0.5	£14.5
Zebra mussel	£11.2	£0.2	£0.1	£0.6	£12.0
Slipper limpet	£5.0	£0.2	£2.7	£0.0	£7.9
House mouse control	£5.4	£0.8	£0.0	£0.0	£6.3
Rhododendron	£2.2	£3.1	£0.7	£0.2	£6.2
Signal crayfish	£3.7	£0.6	£1.2	£0.0	£5.5
<i>Phytophthora ramorum</i>	£0.7	£1.5	£1.9	£0.0	£4.2
Geese and swans	£2.8	£0.4	£0.8	£0.0	£3.9
<i>Hydrocotyle ranunculoides</i>	£3.3	£0.0	£0.1	£0.1	£3.4
Killer shrimp	£2.4	£0.0	£0.4	£0.0	£2.9
<i>Thaumetopoea processionea</i>	£1.9	£0.0	£0.0	£0.0	£1.9
Giant hogweed	£0.7	£0.2	£0.4	£0.0	£1.4
Buddleia	£0.4	£0.6	£0.4	£0.0	£1.4
Mink	£0.6	£0.1	£0.2	£0.0	£0.9
Edible dormouse	£0.4	£0.0	£0.0	£0.0	£0.4
Dendroctonus micans	£0.1	£0.3	£0.0	£0.0	£0.4
Quagga mussel	£0.1	£0.0	£0.0	£0.0	£0.1
Topmouth gudgeon	£0.1	£0.0	£0.0	£0.0	£0.1
Parakeets	£0.0	£0.0	£0.0	£0.0	£0.0
Termites	£0.0	£0.0	£0.0	£0.0	£0.0
Himalayan balsam	£0.0	£0.0	£0.0	£0.0	£0.0

Numbers are rounded to the nearest £m

Despite the overall increase in costs, we found large differences among species and between sectors. The variability in changes in costs is due to a combination of variation in the availability of new information among sectors and between INNS, additional INNS, and population dynamics of established INNS. The latter can lead to increased cost estimates if a species is expanding or its abundance increasing (*Hydrocotyle ranunculoides*, *Phytophthora ramorum*), or decreased costs if population size reduces (for example, due to an emerging disease: rabbit) or if management is effective (*Ludwigia grandiflora*, whose spread appears to have slowed). This is an important finding, as it indicates that more studies

that allow disaggregating costs are necessary, and highlights reduced costs that are rarely reported.

Another source of variation in the estimates is due to relatively small changes in the way some estimates were obtained and the inclusion of a few new species and costs. In general, the sources of information and the calculations were comparable to those in Williams et al. (2010), but in some instances, changes were made as a result of lacking information or newly available information. For example, we now included an estimate of the cost of treatment of wood packaging material destined for export (£19.6 m) that is needed to comply with the requirements of the most recent International Standard for Phytosanitary Measures No. 15 (ISPM15) (FAO 2018). The cost



of research is almost half that of the 2009 estimate, which is partly because now the obtained costs were averaged over the period 2017–2021, resulting in an average annual spend by each large organisation in the UK. This approach differed from the approach taken in Williams et al. (2010), where the annual costs of some projects were added up, independent of the year they happened within the given 11-year time period, which resulted in an overestimation of the annual costs. Therefore, the new estimate is likely more accurate.

Assessments of economic impacts are limited in accuracy as a result of, among other factors, the incomplete database, limited comparability of valuation techniques used in published studies and the inability of stakeholders to provide cost estimates or hesitancy to do so. Yet, the value and impacts of cost estimates are significant as indicated by the number of references made to estimates of INNS costs in media, peer-reviewed work and the policy arena. For example, the study by Williams et al. (2010) has been referred to hundreds of times in the scientific literature, in traditional newspapers and in political discourse. The estimates of economic costs of INNS presented in peer-reviewed manuscripts and reports are used as evidence to inform the public, funding agencies and indeed decision-makers about the impacts of INNS and the urgency to manage them, but the scarcity of such assessments means that they are referred to even if increasingly outdated.

At least part of the increased estimated cost is a result of inflation, new species establishing and the appearance of new research. The impact of inflation is difficult to separate from the other factors affecting the changes in the estimated costs, as only the human health cost was adjusted entirely by applying an inflation factor and inflation was applied to parts of other calculations only. Although newly introduced species rarely cause large and widespread costs because of their limited geographical distribution, the case of *Hymenoscyphus fraxineus* illustrates that this is possible and the impact it has on the overall cost estimate. The included estimate was different from other calculations, as Hill et al. (2019) based their work on benefits transfer from stated preference estimates that looked at the value of the treescape and not the impact of a tree disease, whereas our estimates are based on partial budgeting and replacement and control costs. This may have resulted in differences in the estimates,

but it was impossible to make an assessment using the same methodology as for the other species and sectors. Furthermore, fungi were not part of the estimates in Williams et al. (2010) or Kelly et al. (2013) and we therefore presented changes in estimates without fungi too, and these results revealed much lower cost increases than revealed by recent studies of the evolution of INNS costs (Cuthbert et al. 2021).

To our knowledge, this is the first time that detailed changes in INNS costs have been assessed for an entire country. Although Pimentel et al. (2005) updated the estimate they made for the United States a few years earlier (Pimentel et al. 2001), their assessment lacks the level of detail provided in this study. Other studies assessing the evolution of costs of INNS, based on the Invacost database (Diagne et al. 2020), synthesise the changes for many countries and sectors using data reported in many published studies, which may introduce variation as a result of differences in methodology, study area and INNS. Our study is unique, because we updated earlier assessments using the same methodology and the diversity of changes among sectors and species highlights the value of such a detailed approach. Although the overall cost of INNS to the economy has clearly increased, there have been decreases, which can only be revealed by exact repetition of the estimation process. Our assessment also covered a wide range of INNS, not only the most visible or impactful.

At the start of our efforts to update the cost estimates, we screened the internet for new information concerning INNS affecting the sections in Williams et al. (2010) and the INNS for which estimates were made, in order to prioritise those that were most likely to have changed. Little new information about the costs of INNS was readily available, especially in the literature, which appears to be confirmed by the small number of studies from the UK outlined in the Diagne et al. (2020) database. We did use recent papers in our updated estimates, but those rarely stated economic costs. Instead, these provided other information that was used in our calculations and we based many calculations on updated sources of information that were used for the previous estimates, such as industry reports (Williams et al. 2010; Kelly et al. 2013).

From our previous study, we had good experiences interacting with stakeholders, although we were conscious that it often requires time and perseverance to

obtain the required information. Stakeholders, including government institutions such as Forest Research and the Environment Agency, were a key source of information for the update of the estimate, as we expected that many of the costs have not been, and may never be, reported in the literature. One reason for this is that many of the costs are incurred by stakeholders outside the scientific realm and most scientific studies focus on ecological rather than economic impacts. In addition, the current work focused partially on newly established INNS or INNS whose impact has increased recently, and the impact of these INNS are less likely to be reported in the literature, but stakeholders, such as local councils, natural resource managers and decision-makers, may be aware of the incurred costs and it was important to consider their first-hand knowledge. Future assessments of economic impacts of INNS would benefit from better reporting of the impacts and management costs. While the impacts of INNS may not often be recorded separately and not all management costs can be attributed to INNS, our interactions with various institutions across the UK indicate that some of these costs can be retrieved. It would be beneficial for policy makers and managers alike to identify and record the costs.

As with all assessments of the economic impacts of INNS, there was uncertainty about some assumptions and some of the numbers used in the estimates. Parts of our estimates were therefore reviewed by anonymous experts and their comments were taken on board to improve the work. However, this did not resolve all uncertainties: for example, neither of two reviewers of the section on costs associated with rabbits believed the change in population numbers that we obtained from literature, but they had no data to contradict the evidence we used. One reviewer thought that the cost estimate was fine, despite not agreeing with the estimated population change. This highlights the paucity of data, and the importance and potential risk of using expert opinion, when the evidence is unclear. Without additional original research efforts, which are unfeasible for comprehensive studies like this one, better data are unlikely to be obtained. Therefore, the review of estimates by multiple experts may identify uncertainties which may then be resolved prior to publication of the results.

## Conclusions and recommendations

Our research illustrates the usefulness of repeating economic cost assessments for INNS, as INNS are dynamic and their impacts vary. Repeat assessments like this one are important to maintain a focus on the impact of INNS, changes in impacts as a result of new or spreading species, as well as the identification of potential impacts of management or policies. Details in the assessments revealed the lower than expected overall increase in costs, compared to trends described in recent literature (e.g. Cuthbert et al. 2021), as well as the reduction in the costs resulting from the population dynamics of some INNS. Repeat assessments also allow improvements to some estimates as a result of error corrections or use of more accurate or new information. In general, the paucity of new data made it difficult to obtain major updates for most species and sectors, which indicates that there continues to be a need to collect information on the economic impacts of INNS, and to make such standardised information available in open-access databases. Only then will informed decisions about management and resource allocation be possible.

This assessment again shows the important costs of INNS to the UK economy. Few effects of INNS specific management efforts can be seen in these results. However, they highlight the need to continue prevention and early detection, followed by eradication of the highest-risk species prior to establishment (Anonymous 2023). Indeed, these may be the most cost-effective interventions to minimise economic impacts of new INNS (Williams et al. 2010; Epanchin-Niell 2017), especially in environments or situations where limiting the spread or eradication of established species is likely impossible, e.g. in marine environments and in the case of fungal invasions (Giakoumi et al. 2019; Green and Grosholz 2021). Indeed, it is unlikely that the introduction or eradication of *Hymenoscyphus fraxineus*, and containments of its spread once established, could have been achieved. The availability of these up-to-date data on INNS costs, 10 years after the first estimate, allows policy makers to continue to advocate for funding for prevention of the entry of new species where possible, and active control measures to facilitate early and rapid responses to new outbreaks. For example, the active management of *Ludwigia grandiflora* appears to have eradicated almost one third of infestations

while the success of the other eradication efforts is yet unknown. In other situations, such as *Impatiens glandulifera* or *Dendroctonus micans*, eradication and containment are no longer possible and the impact of such INNS needs to be mitigated. Therefore, we recommend strengthening biosecurity to prevent arrival or new and secondary spread of established alien species, including through changing awareness and engagement of the general public, for example through government campaigns like “Be Plant Wise” and “Check Clean Dry”. New treatments and innovations to limit spread through contamination, such as disinfectants or steam treatments (Crane et al. 2019), should be promoted where appropriate. We also recommend continued investment in sustainable, long-term solutions for widespread damaging species, such as classical biological control, which has been shown worldwide to be a cost-effective, safe and environmentally sensitive management option when other methods prove ineffective or are no longer feasible (Heimpel and Cock 2018; Schwarzländer et al. 2018; Seehausen et al. 2021).

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## Declarations

**Conflict of interest** The authors have no relevant financial or non-financial interests to disclose.

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