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Environmental Evidence

SYSTEMATIC MAP

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Evidence for changes in the occurrence, frequency or severity of human health impacts resulting from exposure to alien species in Europe: a systematic map

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Abstract

Background: Alien species are frequently considered a serious environmental threat but negative impacts on human health through injury, allergy, or as vectors of disease sometimes have the most dire consequences for human livelihoods. Climate change and the increasing magnitude and frequency of introductions of species across geographic barriers as a result of international trade are likely to change their establishment, spread, abundance, physiology or phenology, potentially also altering their human health impacts. Yet despite receiving increasing attention in the scientific literature, there have been few attempts to quantify recent changes in human health impacts. Here we report the findings from a systematic map of the literature identifying evidence of any change in the occurrence, frequency or severity of impacts of alien species on human health in Europe over the last 25 years.

Methods: We conducted a systematic search of the ecological and medical literature using English language search terms to identify potentially relevant studies. Search results were assessed against inclusion criteria published in an a priori protocol at title, abstract and full-text to determine their suitability for inclusion in the review. Repeatability was checked at each stage by comparing a subset between reviewers and testing for inter-rater agreement using Cohen's kappa test. Studies deemed relevant at full text were coded against bibliographic, inclusion and study design criteria to create a searchable database of evidence.

Results: Searches retrieved over 15,700 results yet only sixteen cases met criteria for inclusion in the systematic map. Most of this evidence represents first records of impacts from different areas, and in particular first reports of transmission of exotic diseases by introduced mosquito species.

Conclusions: There is currently limited published evidence demonstrating a change in the occurrence, frequency or severity of human health impacts caused by alien species in Europe over the last 25 years. Relevant studies relate to only a few species, often report specific cases and rarely link health impacts with ecology, distribution or spread of the species. Difficulties in attributing human health impacts, such as stings or allergies, to a specific alien species likely complicate attempts to measure changes, as may differences in professional interests between the environmental and health professions. Future studies could helpfully compare spread or abundance with reported, rather than potential, health impacts. Better cooperation between invasion ecologists and health professionals working in affected areas are likely to be necessary to improve the evidence base on this topic for the future.

Keywords: Allergens, Biological invasions, Bites, Dermatitis, Disease, Public health, Stings

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Background

Alien species are frequently considered a serious environmental threat but some have impacts detrimental to human health through injury, allergy, or as vectors of disease ([1–3]; Table 1). Climate change and increasing propagule pressure due to international trade are likely to change the spread, abundance, physiology or phenology of alien species [4–6], potentially also altering their human health impacts [1]. Many alien species will likely benefit from climate change as some ecological traits provide high plasticity and therefore support adaptation capacities to cope with changing conditions [6–8]. Global change may lead to new public health concerns as alien species expand their range or enter new areas, or may alter the severity of health impacts by changing the physiology or quantity of potential allergens or irritants produced (Fig. 1). It is therefore important to consider if and how the health impacts of alien species are changing over time to inform effective public health policies for the future.

To date, there have been few attempts to systematically identify or quantify the extent of alien species impacts on human health. A recent review by Schindler et al. [1] found that most articles describe the types of health impacts without quantitative assessment of numbers of people affected. Further, research on this topic appears biased towards a few species, hindering a balanced understanding of the scale, patterns and trends of these impacts [1, 3]. This bias towards a small number of species is problematic as the information may not be generalisable to other species, meaning that emerging risks to public health may not be fully recognised [1]. Without this information, it will prove challenging to prepare appropriate and timely environmental or public health responses to emerging threats in the face of climate change.

Despite receiving increasing attention in the scientific literature, there have been few attempts to quantify recent changes in the human health impacts of alien species. To address this, we report the findings from a systematic mapping of the literature identifying evidence of any change in the occurrence, frequency or severity of impacts of alien species on human health in Europe over the last 25 years.

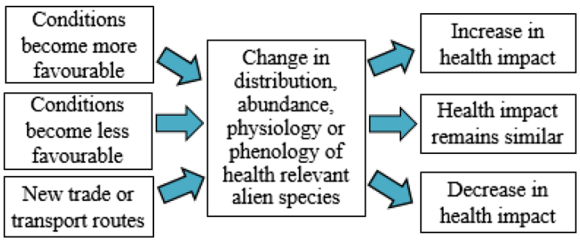

Fig. 1 Components of global change drive changes in the distribution, abundance, physiology or phenology of health-relevant alien species, with resulting implications for their health impacts

Objective of the review

The review objective was to use systematic mapping methodology as described in the a priori protocol [9] to identify the current state and distribution of evidence relevant to the review question. Specifically, this map aims to collate studies that quantitatively report changes in human health impacts from alien species in Europe over the last 25 years. The evidence base is used to identify areas suitable for future systematic reviews and key knowledge gaps.

Primary question: What evidence exists for changes in the occurrence, severity or frequency of human health impacts resulting from exposure to alien species in Europe?

The question consists of the following components:

Population: Any human population resident in Europe

Exposure: Contact with species alien to all or part of Europe

Table 1 Types of health impacts associated with contact with alien plants and animals considered within the remit of this systematic map

Type of contact	Example impacts associated with alien plant species	Example impacts associated with alien animal species
Impacts arising from direct contact	Skin blistering resulting from contact with *Heracleum mantegazzianum* sap	Bites e.g. from *Aedes albopictus*; stings from *Vespa velutina*
Impacts arising from indirect contact	Allergic rhinitis resulting from contact with pollen from *Ambrosia artemisiifolia*	Pseudo allergic reaction to urticating setae produced by *Thaumetopoea processionea*
Impacts arising from the transmission of pests or pathogens by the alien species	n/a	Malaria from introduced mosquito bites; Lyme disease transmitted by ticks spread by *Eutamias sibiricus*

Comparator: No contact or more/less frequent or severe contact

Outcome: Change in the occurrence, frequency or severity of health impacts in human populations since 1990

Methods

This systematic map was conducted in accordance with the CEE Guidelines for Systematic Review and Evidence Synthesis in Environmental Management Version 4.2 [10] to methods specified a priori in a previously published protocol [9]. Following publication of the protocol, study inclusion criteria were subsequently refined to improve consistency in reviewer screening, as detailed in the Study inclusion criteria section below.

Searches

A comprehensive search of multiple information sources attempted to capture an un-biased sample of both published and grey literature, using terms and sources identified during scoping and tested for comprehensiveness using a sample of relevant known studies [9]. All searches were conducted in 2015 by HB, MA and SS. Full details of all of the searches, including dates, sources, platforms, terms, numbers of results generated and destination of retrieved records are reported in Additional file 1.

Search terms

Search terms relating to both alien species and their human health impacts were used to identify potentially relevant studies. Due to the different search functionalities of the sources used the exact search strings deployed varied across databases. Full details of each search string, including any wildcards, Boolean operators (e.g. AND or OR), nesting (brackets), phrase searching and limits used, are provided in Additional file 1. Exposure search terms included in combination: "invasive species"; alien; "non-native"; exotic; "introduced species"; "non-indigenous" and weed. Outcome search terms included in combination: allerg*; hay-fever; asthma; dermatitis; bite; biting; sting*; toxic*; poison*; venom*; irrita*; disease; outbreak; epidemic; parasit*; vector; host; reservoir; "human health" and "public health". Although the use of subject headings such as MeSH was considered, they were not used during the searches for this systematic map. However, this could be addressed in future updates or in other maps using similar search sources.

Search sources

The systematic map searches encompassed eight online bibliographic databases (Web of Science; MEDLINE; CINAHL; CAB Direct including CAB Abstracts and Global Health; EMBASE; SCOPUS; TOXNET including DART (Developmental and Reproductive Toxicology); Armed Forces Pest Management Board Literature Retrieval System), Google Scholar to help identify grey or recently published literature, and a range of specialist sources relating to either health or alien species (see Additional file 1 for full details of all sources searched). Alien species databases were searched using the species names identified in the protocol and cited references screened for potentially relevant articles.

In addition, recent issues of three alien species journals not yet indexed in Web of Science (NeoBiota, Management of Biological Invasions and Bioinvasion Records) were hand searched by screening at title all articles to identify any potentially relevant to the systematic map topic. Online early articles (prior to allocation in an issue) as well as the most recent three issues of two other journals (Biological Invasions and Aquatic Invasions) were also hand screened to account for time lags in articles being indexed in the bibliographic databases.

Supplementary searches

References contained within review articles identified either during scoping or during the screening of the systematic map search results were checked for additional relevant studies that may have been missed.

Reference management and recording

Results of the bibliographic database searches and the first 100 hits from the Google Scholar searches were exported into RefWorks reference management software. Search results were later transferred to EndNote referencing software to allow for offline screening and enhanced sharing of files between the project team. All other search results were screened online at title and any potentially relevant results were recorded in a spreadsheet.

Study inclusion criteria

Study inclusion criteria were defined as part of protocol development, and were subject to refinement during article screening to ensure consistency between reviewers. The refinement expanded on the reasons for exclusion detailed in the final sentence under exposure. Studies were included in the systematic map database if they met the following inclusion criteria:

Population: Any human population resident in Europe.

Exposure: Contact with species alien to Europe or being native in parts of Europe but alien to others that cause negative impacts on human health. Here we

define alien species as species transported by direct or indirect human agency beyond the biogeographic limits of their past or present geographic ranges into areas in which they do not naturally occur [11, 12]. For the purposes of this map, we included alien vector species (e.g. mosquitos, ticks, sandflies), which may carry and transmit infectious pathogens to humans, and alien reservoir species (e.g. mammals, birds and reptiles), which are intermediate or long-term hosts of pathogens of infectious diseases (categories 1b, 2a, 2b and 2c under the framework identified by [3]). We excluded pathogens, pets, domestic or exotic animals that have direct impacts (e.g. bites from exotic snakes in captivity) or that serve as vectors or reservoirs, poisonous species imported for consumption and European species that do not fall under the definition of alien species above.

Comparator: No contact or less frequent or severe contact. Any time series or spatial comparison.

Outcome: Change in the occurrence, frequency or severity of health impacts in human populations since 1990 [9].

Study design: All study designs were included that provided sufficient data to meet the other systematic map inclusion criteria, as long as the study period took place including or since 1990. Studies published after 1990 but completed prior to this date were not included.

Tests for consistency

Tests for consistency between reviewers were conducted at the title, abstract and full text stages of article screening.

A subset of 100 titles randomly generated using the Excel random number generator function were assessed by three reviewers prior to title screening to ensure that the inclusion criteria would be applied consistently (HB, SS and MA). Scores were compared using Cohen's Kappa test [13], and inter-reviewer scores were fair-to-moderate (0.232, 0.441 and 0.513 between reviewer-pairs; 56% overall reviewer agreement). All titles without agreement across all three reviewers were discussed to determine which should be included or excluded; disagreements generally resulted from either a difference of opinion as to how generally the criteria should be applied or a difference in reviewer knowledge (for example if a reviewer was unsure of whether a location or a species met the inclusion criteria they might keep in an article for further checking that had been excluded by the other reviewers). This resulted in a refined understanding of the inclusion criteria, as reflected above.

A second set of 100 references, randomly generated in the same way as the first set, were also assessed at title by the same reviewers to measure whether inter-rater agreement had improved following refinement of the criteria. Kappa scores were good (0.658, 0.718 and 0.650) with 82% complete agreement between reviewers, suggesting an improvement in consistency as to how the inclusion criteria were applied.

A further set of 100 randomly selected abstracts were assessed independently by all three reviewers and inter-rater agreement again scored using Cohen's kappa test. Reviewers were in complete agreement over 63% of the abstracts (either scored Y/Y/Y or N/N/N). Kappa scores were moderate to good (0.518; 0.733 and 0.579 between reviewer-pairs).

All articles selected as meeting the review inclusion criteria at full-text and subjected to study coding were assessed independently by two reviewers to check for consistency and any discrepancies discussed with a third reviewer if agreement could not be reached. Any articles that were identified for full text assessment but were either unavailable to the review team or were excluded for failing to meet the inclusion criteria at full text are listed in Additional file 2, along with reasons for their exclusion. The number of studies included or excluded at each stage of the systematic mapping process were recorded in a flowchart.

Study quality assessment

Included studies were not critically appraised using an existing study quality tool as data resulted from unintentional exposures to the alien species rather than as a result of intentional experimental manipulation. However, details relating to the study that could be used to infer quality (for example, study type, study design, spatial scale, comparators and timescale as applicable) were coded as part of the systematic mapping process. Simple descriptive statistics relating to these details were generated in Excel to provide an overview of the quality of the available evidence.

Data coding strategy

All studies assessed at full text that were deemed to meet the systematic map inclusion criteria were subject to data extraction and coding by one reviewer and checked by a second to minimise errors and ensure consistency. Map codes were devised by the reviewers and were piloted during a data extraction test to ensure they were suitable for the types of information required. Initially, study coding was trialled using Google Forms as per Bottrill et al. [14], however a specially designed spreadsheet generated in Microsoft Excel was used for the final review so that reviewers could work offline. Studies were coded for four types of information (Table 2). Data for categories 1–3 (i.e. bibliographic information, information relating to the inclusion criteria, and information relating to the study) were retrieved from the included studies (where presented), but data for the fourth category (i.e. additional information relating to the species of concern including geographic origin and pathways of introduction) were retrieved by the reviewers from the databases EASIN (http://easin.jrc.ec.europa.eu/use-easin/species-search), NOBANIS (https://www.nobanis.org/) and DAISIE (http://www.europe-aliens.org/) if available. For some categories, multiple codes were applied (for example, where a species is believed to have been introduced along multiple pathways).

Table 2 Categories used for coding studies included in the systematic map at full text

Category	Type of data
1. Bibliographic information	a. Publication type b. Year
2. Information relating to the inclusion criteria	a. Population i: Human population affected b. Population ii: Location of exposure c. Population iii: Location of reported impact d. Population iv: Activity of population at exposure e. Exposure i: Taxonomic group of the alien species f. Exposure ii: Species name (binomial) of the alien species g. Exposure iii: Biome at location of exposure h. Exposure iv: Habitat at location of exposure i. Outcome i: Type of human health impact (disease or pathogen transmission/allergen or irritant) j. Outcome ii: Specific condition (type of injury, allergy, dermatitis, disease) k. Outcome iii: Change in human health impact (occurrence/frequency/severity)
3. Information relating to the study	a. Study type (e.g. patient case study, RCT) b. Study design (sampling size, etc.) c. Spatial scale of reported impact d. Comparators e. Timescale f. Other factors affecting the outcome
4. Additional information relating to the species of concern	a. Geographic origin (native range) b. Pathway(s) of introduction (following the classification of Hulme et al. [45])

Study mapping

Once relevant studies were assessed, coded and checked by a second reviewer, the data were included in a searchable spreadsheet detailing each of the coded variables. Simple descriptive statistics relating to key trends in the final dataset were generated in Excel for presentation in the final systematic map report.

Results

Review descriptive statistics

A flow chart showing the number of studies identified, included and excluded at each stage of the systematic mapping process is provided in Fig. 2. The bibliographic database and Google Scholar searches yielded a total of 15,776 search results. Of these, 2472 were removed as duplicates using the automatic duplicate removal function in EndNote. The remaining 13,304 results were screened at title, abstract and then full text against the inclusion criteria and additional duplicates (undetected by EndNote) were removed manually. Results from the other searches (of the specialist sources and hand searches of recent journal issues) yielded over 550 results and were screened at title level online. Although more than 200 articles were selected for assessment at full text, with 43 unobtainable and a number available in non-English languages, only sixteen cases were included in the final systematic map of the evidence (Additional file 3).

Mapping the quantity of papers relevant to the question

There is currently little evidence demonstrating a change in the occurrence, frequency or severity of human health impacts resulting from exposure to alien species in Europe. The evidence base predominantly constitutes data on arthropods, plants and algae taken from journal articles published since 2001 (Table 3), and much of the available evidence represents first reports of illness or injury resulting from exposure to alien species. Five studies provide the first reports of transmission of exotic diseases (two of Chikungunya virus and three of dengue fever) by non-native mosquito species of the Aedes genus (*A. albopictus* and *A. aegypti*) established within Europe [15–19]. Two adults were infected with dengue in France in 2010 [16], and around 17 in Croatia following identification of dengue fever in a returning German tourist the same year [17]. An outbreak of dengue fever in Madeira, Portugal in 2012 (the first dengue epidemic reported in Europe since 1928) affected at least 1800 people within a

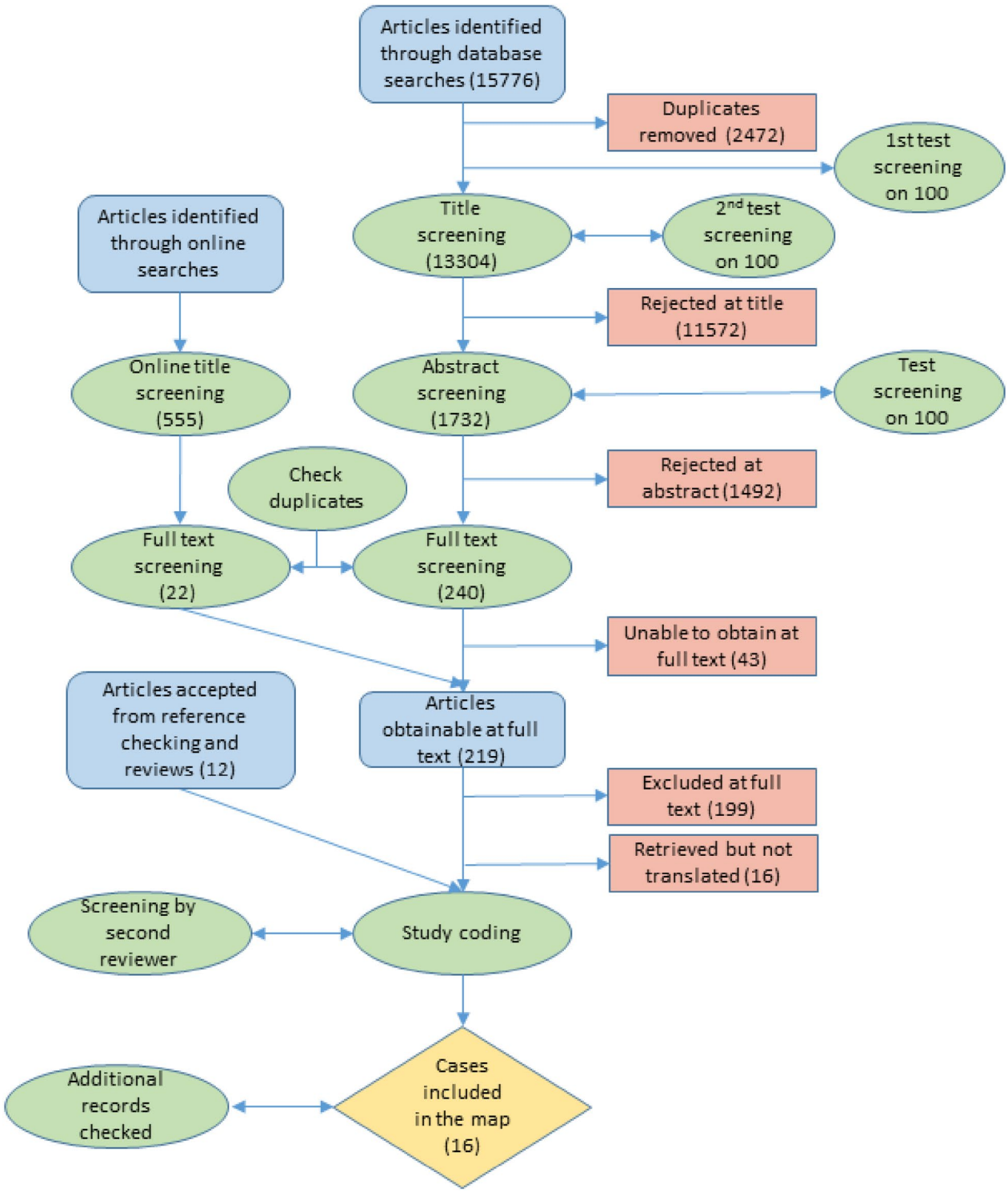

Fig. 2 Flowchart showing the number of articles captured and included or excluded at each stage of the systematic mapping process

matter of months [15]. In 2007 in Ravenna, Italy, an outbreak of Chikungunya virus perhaps introduced by a visitor from India affected two villages, leaving over 200 ill and one dead [18]. Two cases were identified in France in 2010, in young girls who were bitten during a sleepover near an imported case of Chikungunya virus [19].

Table 3 Summary of studies demonstrating a change in the occurrence, frequency or severity of human health impacts resulting from exposure to alien species in Europe

Species	Impact	Location	Description	References
Aedes aegypti	Disease transmission—dengue fever	Madeira	Outbreak with 1891 cases of dengue fever in 2012 following introduction of *A. aegypti* in 2005	[15]
Aedes albopictus	Disease transmission—dengue fever	France	Two cases of Dengue fever presented in adult males in France with no recent history of international travel. *A. albopictus* has been established since 2004	[16]
Aedes albopictus	Disease transmission—dengue fever	Croatia	Two cases of dengue fever in Croatia, one in a German tourist and a second in a local resident, were identified in 2010. Serological assessment suggested at least seven other recent cases. *A. albopictus* was first recorded in Croatia in 2004	[17, 46]
Aedes albopictus	Disease transmission—Chikungunya virus	Italy	Over 200 cases in two contiguous villages in Italy. In most cases the disease was fairly mild, with one reported death. The virus was identified in *A. albopictus* suggesting local transmission	[18]
Aedes albopictus	Disease transmission—Chikungunya virus	France	Two female children developed Chikungunya after being bitten at a sleep over near to an imported case, suggesting local transmission	[19]
Aedes japonicus	Nuisance behaviour	Switzerland	Several reports of biting and nuisance behaviour identified as recently established *A. japonicus*	[30]
Ambrosia artemisiifolia	Allergy—increasing sensitisation	Austria	Of 13,719 atopic patients diagnosed between 1997 and 2007, the frequency of ragweed pollen sensitization increased from 8.5% in 1997 to 17.5% in 2007	[25]
Ambrosia artemisiifolia	Allergy—increasing sensitisation	Italy	Increase in the proportion of patients aged <20 years becoming allergic to ragweed was observed in a study of 665 patients over 15 years, from 0% 1990–1996 to 18% during the last 10 years	[26]
Ambrosia artemisiifolia	Allergy—increasing sensitisation	Germany	Twenty *A. artemisiifolia* scouts (tasked with finding and eliminating the weed) were assessed, and despite close contact to *A. artemisiifolia* over a median of 13.8 months, none of the participants became sensitized or allergic to it	[27]
Arthropods—mosquitoes, multiple	Nuisance biting	UK	No evidence of nuisance biting attributable to alien mosquitoes over a 10 year period according to a survey of local authorities	[29]
Ostreopsis ovata	Respiratory problems and skin irritation	Italy	First cases reported in 2003/2004, in 2005 around 200 people affected by respiratory symptoms resulting from exposure to sea spray containing toxins from *O. ovata*	[21, 22] * after [24]
Ostreopsis ovata	Respiratory problems and skin irritation	Spain	Multiple cases resulting from exposure to *O. ovata* toxins	[23] and Barroso García et al. [47] as cited in [24]
Ostreopsis ovata	Respiratory problems and skin irritation	France	Five out of nine recorded blooms between 2006 and 2009 led to symptoms in divers, swimmers, and shoreline inhabitants, with a total of 47 patients presenting symptoms	[24]
Thaumetopoea processionea	Itchy dermatitis	UK	Numerous cases of itchy rashes reported to the environmental health officer associated with *T. processionea* caterpillars on nearby oak trees	[20]
Vespa velutina	Stings	France	A survey of French poison centres in 20 Departments showed no increase in the number of reported hymenoptera stings following the introduction of *V. velutina*	[28]
Vespa velutina	Stings	France	One case report where a patient suffered severe symptoms after being stung by *V. velutina* 12 times on the head	[28]

Although these studies represent outbreaks occurring at a relatively local scale, the number of individuals affected ranged from 2 to more than 2000. Another impact arising from contact with alien animal species is contact dermatitis. The first localised reports of dermatitis associated with contact with caterpillars of the oak processionary moth *Thaumetopoea processionea* follow the accidental introduction of the species to London (UK) from continental Europe on imported trees [20]. Local residents and management workers were affected.

Evidence also suggests that harmful blooms of alien unicellular algae such as *Ostreopsis* species are causing significant health impacts along European coasts, with cases reported from Italy [21, 22], Spain and France [23, 24]. Numbers affected ranged from only a handful of cases to over two hundred depending on the outbreak. Those affected were beach users involved in a range of recreational activities including swimming and diving, and suffered from both respiratory problems and skin irritations following contact that regressed over time [24].

Not all studies present first reports of impacts. Several large-scale long term studies of individuals with allergic symptoms demonstrate changes in sensitisation levels to *Ambrosia artemisiifolia* among the general population across Europe, indicating that levels of sensitisation are rising and the proportion of young people sensitised is increasing [25, 26]. However, Brandt et al. [27] found no sensitisation or allergy development in a sample of 20 ragweed workers resulting from exposure to *A. artemisiifolia*.

Other studies demonstrated no significant change in impacts over time. De Haro et al. [28] reported no increase in the number of hospitalisations resulting from envenomations following the introduction of *Vespa velutina* to France, although evidence that at least one envenomation has occurred exists, and similarly, Medlock et al. [29] reported no calls to local authorities resulting from nuisance biting caused by non-native mosquito species in England (all calls were for native species). However, in Switzerland, reports of nuisance biting from the mosquito *Aedes japonicus* were reported following introduction [30].

The main pathways of arrival of the alien species with health impacts included in this map are as contaminants or as stowaways, originating from Asia, North America and Africa.

Mapping the quality of papers relevant to the question

Most papers included in the systematic map present numbers of patients affected by an illness or outbreak resulting from environmental exposure to an alien species and so many of the features associated with a well-designed scientific experiment are lacking. For example, temporal and geographical scales tend to reflect the extent of the outbreak and comparators are rarely reported. Studies that assess longer term impacts (e.g. *Ambrosia* [25, 26]) tend to report longer time periods and larger geographic areas but are still reliant on recorded data of impacts. These data reflect only those individuals contacting relevant agencies or reporting symptoms (e.g. to allergy centres), and so anyone affected that did not seek medical attention, or conversely, anyone exposed who did not experience symptoms, will not be represented. Many studies were excluded because there was no attempt to include a temporal comparator.

Discussion

This systematic map expands the existing evidence base demonstrating an impact of alien species on human health and complements recent reviews on this topic (e.g. [1, 3]) by focusing on evidence for changing health impacts related to changes in distribution and abundance of alien species. Despite clear risks to human health from a number of alien species (there are multiple cases of skin burns following exposure to the sap of *Heracleum mantegazzianum* reported in the literature, for example [31]), there is little evidence demonstrating changes in the occurrence, frequency or severity of human health impacts resulting from exposure to these species in Europe. Much of the evidence contained within this map refers to cases of illness or injury that demonstrates an impact where it has not been reported previously, rather than demonstrating any temporal change. The lack of evidence suitable for inclusion in this systematic map appear to be in part due to challenges in linking ecological factors such as abundance or spread with actual human health impacts (as opposed to potential health impacts as inferred by pollen loadings or vector competence). This indeed implies rather complex study designs, because at first temporal change in species distribution or abundance and temporal change in impact must be assessed, and additionally it is required that these two temporal changes are set into relation with each other and evidence must be provided for the relation among them (Fig. 3). However, lacking evidence probably also reflects a lack of central recording for injuries caused by alien species, and reflects difficulties in attributing impacts to a specific species e.g. in the case of allergies, stings, or in identifying the specific vector where there are a range of native and introduced candidate species, and this may complicate attempts to measure changes. It is likely that many cases are attributed at a broad level (e.g. an allergy to pollen) and that assessment of causal species (of which there may be multiple affecting any given individual) is not worth pursuing by primary care practitioners as it would be unlikely to affect the course of treatment required.

Perhaps the greatest threat to human health in Europe currently posed by alien species is the transmission of exotic diseases by non-native arthropods. Some pathogens have the potential to significantly affect large numbers of citizens within relatively short time frames, as demonstrated for example by the outbreak of Chikungunya fever in Italy (e.g. [32]). Despite a relative lack of evidence within this map on allergenic plant species, sensitivity to *A. artemisiifolia* appears to be increasing in Europe. There is much data available in the literature (for example on pollen loads and season lengths) that suggests the spread of this allergenic species will continue to increase the burden on health care systems resulting from the treatment of long-term allergic conditions. Other health impacts are likely to result from either potentially high contact but temporally and geographically restricted events associated with seasonal abundance of species with cyclic populations, or ad hoc events resulting from random encounters such as envenomations by *V. velutina*. Increased monitoring and reporting is critical to establish baselines in impact data and identify any geographic and temporal trends.

For many health-relevant alien species, knowledge gaps must be interpreted as lack of accessible data rather than providing evidence of no impact. It may be the case that evidence exists but it is not accessible using standard systematic reviewing or mapping methodologies, and that alternative methods (for example, compiling data from press reports or accessing national medical records or databases) must be used to increase the information available in this area. For many alien species, existing evidence of health impacts did not fit the inclusion criteria for this map (for example ad hoc case reports referring to injuries sustained following contact with *H. mantegazzianum* as mentioned above) and this may be a suitable topic for a future evidence map to help quantify the health impacts of alien species. Regardless, a lack of baseline data on the health impacts of alien species is concerning as without this evidence it is difficult to establish how much of a risk these species pose to human health currently and in the foreseeable future and therefore to determine an appropriate management response. Further, without a better understanding of which species pose a tangible threat and where, it is difficult to justify or target awareness raising measures for relevant primary care workers, meaning that patients may not receive an accurate or as rapid diagnosis as possible.

Although there is relatively little direct evidence of trends in health impacts of alien species in Europe, there is much related literature that did not fit the criteria for inclusion in this systematic map but which may provide valuable information to help inform decisions. Examples of this indirect evidence not contained within the map include:

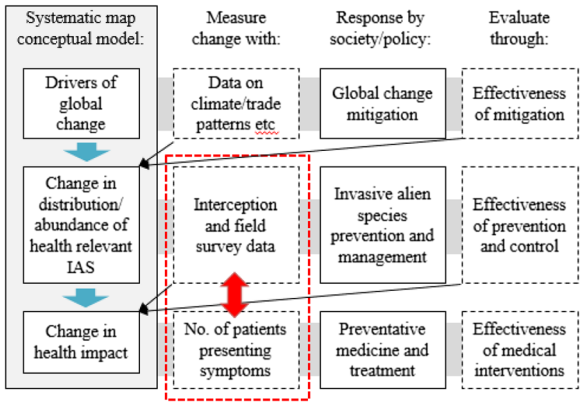

Fig. 3 Drivers of global change cause changes in the distribution and abundance of health-relevant alien species, with resulting implications for human health (relevant data highlighted in *red*). Responses by society and policy aiming at the mitigation of global change and the management of alien species are currently increasing, but still not implemented in sufficient amount to halt global change and invasions of alien species. Thus, medical treatment of alien species health impacts is often required

- Individual case reports. Although these case reports provide valuable evidence that a given species is having an impact (e.g. [31]), they do not represent the magnitude of effects or whether changes are occurring, and as ad hoc events do not provide an accurate baseline against which to measure future changes. An exception is where a case report represents the first report of an impact from a new area as it shows that the alien species is present where it previously was not. This information was included in the map.
- Studies looking at vector competence. Evidence that specific species can carry and transmit particular diseases (or evidence for feeding on different hosts) is likely to be valuable when assessing the potential risks posed by introduced vector species but does not provide evidence of an impact and so has not been included here.
- Studies looking at levels of sensitivity or reactivity to allergenic substances without a comparator. For example, studies showing the prevalence of sensitivity to *A. artemisiifolia* would not be included unless there was evidence that levels of sensitivity had changed over time or due to exposure.
- Studies on captive animals. There are studies providing data on the human health risks associated with captive animals, and predominantly exotic pets, for example salmonella transmission (e.g. [33]) or snake bites (e.g. [34]). However, the circumstances under which health may be affected when dealing with a captive animal may be very different from the circumstances in which the species may be encountered

in the wild, meaning that the risk of injury or disease transmission is likely to be different.

- Impacts caused by exotic diseases that have been contracted by humans returning from endemic areas, unless there appears to have been subsequent local spread by alien species (e.g. [35]).
- Impacts resulting from the introduction of free-living microorganisms that may pose a threat to human health when accidentally imported. For example, a number of harmful microorganisms have been transported internationally in ballast water (e.g. [36, 37]).
- Impacts resulting from intentional ingestion of alien species. For example, *Datura stramonium* is sometimes consumed recreationally for its hallucinogenic effects, and has been implicated in hospitalisations both within Europe [38] and elsewhere (e.g. [39, 40]). Although the number of voluntary poisonings resulting from *D. stramonium* consumption in France appears to be increasing [38], the reasons for this are complex and may relate to increasing popularity among recreational drug users rather than abundance in the wild.
- Studies that deal with health-relevant alien species, but not with their explicit health impacts, even if some covered topics such as management costs or impacts of global change.

Given the limited evidence base available, it is difficult to currently assess the extent of the impacts of alien species on human health, let alone determine whether global change is driving changes in the occurrence, frequency or severity of human health impacts and, if so, in which directions. Better linking between data on spread/abundance and human health impacts over time (and ideally from the point of introduction onwards for species that are not yet established or still spreading) are required to explore this issue further, and are likely to require collaborative approaches between the environmental and the health communities. The taxonomic and geographical biases in the available data make it difficult to draw broader conclusions about changes in health impacts as they may not transfer across species or regions. For established alien species that are widespread, studies correlating health impacts against abundance or comparing different climatic conditions (such as annual rainfall) or management regimes on health outcomes may be valuable in helping to determine their impacts. For more recently introduced species, studies mapping health impacts may help to monitor spread, focus awareness raising activities aimed at minimising exposure, and provide justification for action aimed at containing the species within a restricted area if eradication is not possible. However, this research suggests that these types of studies are still relatively rare in the scientific literature.

Limitations of the map

Systematic reviews and maps aim to undertake comprehensive searches using bibliographic databases, but it is impossible to undertake exhaustive searches of all potentially relevant sources due to resourcing and language constraints. Even within the results retrieved for this systematic map, there are a number of studies that were unobtainable or published in languages other than English, and so have not been included in the final evidence base. As with any systematic review or map, it is also possible that some relevant studies may have been missed during the searching or screening processes as a result of human error, unclear reporting by the primary authors or use of different terminology from that used here. Further, studies in which relevant species are grouped generally with other (native) species are unlikely to have been detected without specific reference to the search terms identified here. However, this map provides the most comprehensive collection of evidence on this topic to date, and highlights some important limitations that need to be addressed to develop this evidence base in the future.

Revisiting the conceptual model

We believe the conceptual model originally presented in our protocol, although simplistic, to be generally correct. However, we expand it out to include the different types of data that relate to each of the components (Fig. 3) and highlight knowledge gaps and opportunities for future research. The topic of this systematic map (in red in Fig. 3) suggests that there have been relatively few studies directly linking either changes in the abundance or spread of alien species with the human health impacts with which they are associated. However, other areas identified within our conceptual diagram—effectiveness of management of either species or health impacts—are potential topics for further study. For example, data exist on the effectiveness of management of *A. artemisiifolia* (e.g. [41–43]) and on the effectiveness of treatments for allergies caused by Ambrosia pollen and may prove valuable areas to pursue in future systematic reviews.

Future updating of the map

Now that the first systematic map on this topic has been completed, future updates to the map should be relatively straightforward. However, given the lack of suitable data identified on this topic at the current time, there are no plans to conduct an update in the near future. Running and title screening the searches in the core databases over a restricted time period should provide an idea as

to whether there is much potential evidence being published and should be undertaken before an update is commenced.

Conclusions

There is some evidence for changes in the human health impacts of alien species within Europe over the last 25 years. However, compared to the relevance of the topic for human well-being (e.g. [44]), there are few studies demonstrating changes in health impacts over time mapped to changing spread or abundance of the alien species. Relevant studies relate to only a few species, often report specific cases or outbreaks, and rarely link health impacts with ecology, distribution or spread of the species, or with public health. Difficulties in attributing human health impacts such as stings or allergies to a specific species likely complicate attempts to measure changes, as do different research interests between ecologists and health professionals. Better cooperation between invasion ecologists, health professionals and others working in affected areas are likely to be necessary to improve the evidence base on this topic for the future.

Implications for policy/management

There is a clear need for better recording/reporting of impacts to determine whether particular alien species present a human health issue or not, to identify any trends (such as changes in impacts) and to inform policy and management appropriately. We recommend that a precautionary approach is adopted towards species likely to pose a threat to human health, and particularly for those species with demonstrable health impacts noted elsewhere. Prevention, detection and rapid response should be prioritised for species of highest concern and risk not yet present and preparations made to raise awareness among relevant professionals (e.g. doctors, environmental managers) and publics most likely to encounter the species (e.g. swimmers, gardeners as appropriate) to facilitate identification and minimise impacts resulting from exposure. For species already present in an area, more thorough assessment of the scale of impacts to date would be valuable in justifying the case for management (or otherwise), and in helping to inform other areas not yet affected by the potential impacts. Depending on the species of concern, alternative forms of data such as vector competence or population sensitivity may be necessary to underpin prioritisation or management decisions until suitable evidence regarding absolute trends in health impacts have been established.

Implications for health professionals

Better awareness of the issue of alien species with potential health impacts among health professionals may be desirable to aid in diagnosing and, in relevant cases, reporting. In particular, knowledge of emerging threats from species that have been recently introduced or are likely to arrive (so called 'alert species') could aid in tracking spread, assessing impacts and prioritising management. Understanding seasonal, temporal and geographical changes in the frequency or severity of symptoms associated with specific species (if possible to determine) could also aid in diagnosis and appropriate treatment. This may require a mechanism by which impacts can be reported and recorded to contribute to an evidence base in this area, similar to those used for notifiable diseases. For now, we strongly advocate that health professionals report unusual health impacts relating to alien species in the scientific literature.

Implications for research

Researchers could helpfully aim to link reported human health impacts with ecological aspects to expand the evidence base on this potentially important topic, rather than studying one or the other in isolation—in particular studies matching data on spread or abundance over time to recorded health impacts would be beneficial (i.e. linking data contained within the red box in Fig. 3), rather than using proxy measures or inferring links. Longer term datasets will prove important in assessing any potential changes in impacts, even if just to compare levels of sensitisation or impact on the population. For example, studies reporting sensitisation rates to *Ambrosia* or impacts resulting from exposure to harmful algal blooms could usefully include data from multiple years to see whether levels change over time. Also, related areas (for example vector competence) may provide a useful tool for assessing risk but a better understanding of how these translate into actual health impacts is necessary, particularly where actual impacts may differ due to different physical, environmental or climatic conditions between different parts of the affected range. This requires collaborative working between both research communities but may also open up new funding avenues for researchers wishing to conduct studies at the interface between ecology or biogeography and human health.

Additional files

Additional file 1. Full details of searches conducted.

Additional file 2. List of studies excluded at full text with reasons for exclusion.

Additional file 3. Spreadsheet of included studies.

Authors' contributions

HB, SS, AP, FE and WR developed the review protocol. HB and MA conducted the searches. HB, SS and MA screened the search results, undertook full text

assessment and coded relevant studies for inclusion in the map. HB, SS and AP drafted the review manuscript with input from MA, FE and WR. All authors read and approved the final manuscript.

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Competing interests
The authors declare that they have no competing interests.

Availability of data and materials
Data generated or analysed during this study are included in this published article and its additional information files. A file containing all 15,776 detected articles is available from the corresponding author on request.

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