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Alien species and public health impacts in Europe: a literature review

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Abstract

Impacts of alien species on human health have recently become a major issue in medical research and invasion ecology, but comprehensive assessments of this subject are largely lacking. Here, we provide a literature review of alien species with public health impacts in Europe based on a systematic search in the Thomson Reuters Web of Science. We detected 77 relevant articles, of which 21 were reviews and 56 were original research articles. The taxonomic focus was on vascular plants (n=31 articles) and dipterans (n=25 articles). The original research articles mainly covered the spread of the study species, while early invasion stages (introduction, establishment) as well as impact and management were less investigated. Alien species of health concern in Europe are mostly introduced as contaminants, and mostly originate from climatically similar regions of the Northern Hemisphere. In those cases (36% of all articles) when information on the trend in range and abundance was provided, this trend was mostly increasing. We detected little information on the severity of the impacts (two articles) and the interaction with climate change (three articles). In 15 original articles (28%) specific management measures were suggested, in only one article the socioeconomic costs were assessed. We conclude that European research on human health impacts of alien species is biased towards few species, and that several important aspects such as early invasion stages, severity of impact and its temporal trends, and the scale of the socioeconomic costs caused are poorly understood. Interdisciplinary projects bridging gaps between ecologists medical researchers, socioeconomists and public health authorities are required to link alien species to severity and trends of impacts, which is a crucial requisite for risk assessment and decision making.

Keywords

Aedes, *Ambrosia*, climate change, human health, management, vector

Introduction

Alien species invasions cause a multitude of impacts on environment (Vilà et al. 2010, 2011, Jeschke et al. 2013, Simberloff et al. 2013, Blackburn et al. 2014), and socioeconomy (Pimentel et al. 2000, Pimentel 2002, Gren et al. 2009). In particular, there is evidence for an increasing magnitude of human health impacts by alien species (Kenis and Branco 2010, Vilà et al. 2010, Richter et al. 2013, Conn 2014, Hulme 2014, Mazza et al. 2014), as globalization increases the likelihood for the movement of disease vectors (e.g. *Aedes* spp.), and has facilitated the transmission of tropical and subtropical pathogens to temperate regions (Paupy et al. 2009, Medlock et al. 2012, Bonizzoni et al. 2013). There, alien species may also benefit from climate change (Takumi et al. 2009, Walther et al. 2009, Thomas et al. 2011, Caminade et al. 2012, Dobson et al. 2013), causing additional pressure on human health (Keller et al. 2011, Strayer 2012).

Health impacts of a few alien species have already received much attention in research related to public health and invasion ecology (e.g. Smith et al. 2007, Tsetsartsin et al. 2007). In Europe, common ragweed (*Ambrosia artemisiifolia*) has become notorious for its highly allergenic pollen (e.g. Vilà et al. 2010, Bullock et al. 2012, Richter et al. 2013), giant hogweed (*Heracleum mantegazzianum*) for causing contact dermatitis (Pyšek et al. 2007), and the Asian tiger mosquito (*Aedes albopictus*) for serving as vector of several pathogens (Medlock et al. 2012). However, the human health impacts of many other alien species are far less recognized. Consequently, the taxonomic and geographic biases in understanding the impacts of alien species at large (Pyšek et al. 2008, Hulme et al. 2013) may prevail also for alien species of human health concern and may hinder a balanced understanding of the scale, patterns and trends of these impacts (Hulme 2014).

Based on a literature search, we here provide a review of the state of knowledge and associated research gaps on alien species impacting human health in Europe. In particular, we ask the following questions: (1) What is the taxonomic and geographic coverage of literature on human health impacts in Europe? (2) Which invasion stages (sensu Blackburn et al. 2011, Jeschke et al. 2013) are studied? (3) Where are the regions of origin and what are the introduction pathways of alien species of human health concern? (4) Which knowledge is currently available on issues such as severity and trends of impacts, interactions with climate change, and the scale of the socioeconomic costs?

Material and methods

Inclusion criteria

We included peer-reviewed articles dealing with species alien to Europe or being native in parts of Europe but alien to others that cause negative impacts on human health. We here define alien species as species being 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 (Richardson et al. 2000, Blackburn et al. 2011). For our purposes, we included alien species of direct health impact (e.g. allergenic plants), but also alien vector species (e.g. mosquitos, ticks, sandflies), which carry and transmit infectious pathogens to humans, and alien reservoir species (e.g. mammals), which are long-term hosts of pathogens of infectious diseases (cf. Mazza et al. 2014). In contrast, we excluded (i) emerging pathogens (e.g. virus, bacteria, prions, pathogenic fungi and protozoans – e.g. smallpox, HIV, Anthrax, Candida, Toxoplasma), if they did not arrive with alien species and were exclusively transmitted by native vector or reservoir species, (ii) domestic animals that serve as vectors or reservoirs, (iii) evidence from the native range of the species, (iv) indirect health impacts that might be caused by agricultural pests or species causing traffic accidents and (v) European species that do not fall under the definition of alien species such as those recently colonizing new regions in Europe without evidence that their spread was fostered by human assistance, although it might have been enhanced by climate change or habitat change (e.g. *Ixodes ricinus*, *Cheiracanthium punctorium*).

Literature search

We conducted a standardized and reproducible search in Thomson Reuters Web of Science (formerly ISI Web of Knowledge) in June 2013. Thus, we excluded literature published in other sources (non-indexed journals, books and conference proceedings, reports), which might contain additional relevant information. However, as the rigorous publication criteria applied for indexed publications are not necessarily met by publications in other sources, we consider our conservative approach for inclusion of publications warranted. We applied twelve search strings combining three or four search terms that specified the (i) impacted population (i.e. humans, public health), (ii) the alien species, (iii) the outcome (diseases), and (iv) the geographical focus (i.e. Europe) (Table 1). We did not use scientific or vernacular names of particular species for the search strings nor did we use reference lists of detected articles for further relevant references to avoid bias towards particular taxa. We did not apply any other kind of restrictions, e.g. regarding the year of publication.

Analyses

Titles of detected articles and subsequently their abstracts were screened to eliminate unsuitable articles that dealt for instance with pests and diseases impacting agriculture, livestock or wildlife. After this screening, 115 articles remained. Of these, 15 full texts were not available (these ones were mostly published in local journals in non-English language), 23 were excluded after reading the full version (mainly because the focal species did not fall under our inclusion criteria of being alien) and the remaining 77 were considered for further analyses.

Table 1. Applied search strings. Search strings applied in Thomson Reuters Web of Science (formerly ISI Web of Knowledge, http://thomsonreuters.com/thomson-reuters-web-of-science/) for the literature search in this review.

Population	Geography	Exposure 1	Exposure 2	Outcome
"human (health)"	**"Europe"**	**"alien species"**	**"alien species"**	**"disease"**
health*	europe*	alien*	species	
	europe*	invasiv* species	alien*	allerg*
	europe*	invasiv* species		allerg*
human* health*	europe*	invasiv* species		pathog*
		invasiv*	species	vector* born* disease*
human* health*	europe*	naturali*	species	
human* health*	europe*	establ*	species	
human* health*	europe*	introd*	species	
public* health*	europe*	exotic*	species	
public* health*	europe*	globali*	species	
public* health*	europe*	invasiv* species		parasit*
human*	europe*	exotic*	species	disease*

First, we classified each article as original research article (full length article or short report) or as review article. Then we performed descriptive analyses based on data and meta-data extracted from the included articles. These descriptive analyses dealt with bibliographic information (year of publication), taxonomic and geographic coverage, invasion stages (sensu Blackburn et al. 2011 and Jeschke et al. 2013), and finally, impact and management of review and original articles.

For original articles, we analysed the native range (continents) and the pathways of introduction (following the classification of Hulme et al. 2008) of the species. We did not perform these analyses for review articles, because they often dealt with multiple species (Van der Weijden et al. 2007, Aspöck 2008, Keller et al. 2011, Mack and Smith 2011). Further, we assessed if information on temporal trends in species distribution and abundance and on public health impact were given, if the economic costs were evaluated, and if management measures were suggested. Finally, we assessed if information on the effects of climate change on future spread and impacts of the study species was considered. All articles included and all data used in the analyses are presented in Suppl. material 1.

Results

Number of publications and temporal trends in publication

The 77 analysed articles consisted of 21 review articles and 56 original research articles (42 full articles, 14 short reports). We found a strong increase in the cumulative number of articles published (Figure 1). Interestingly, the 77 included articles were exclusively published recently, i.e. from 2002 onward.

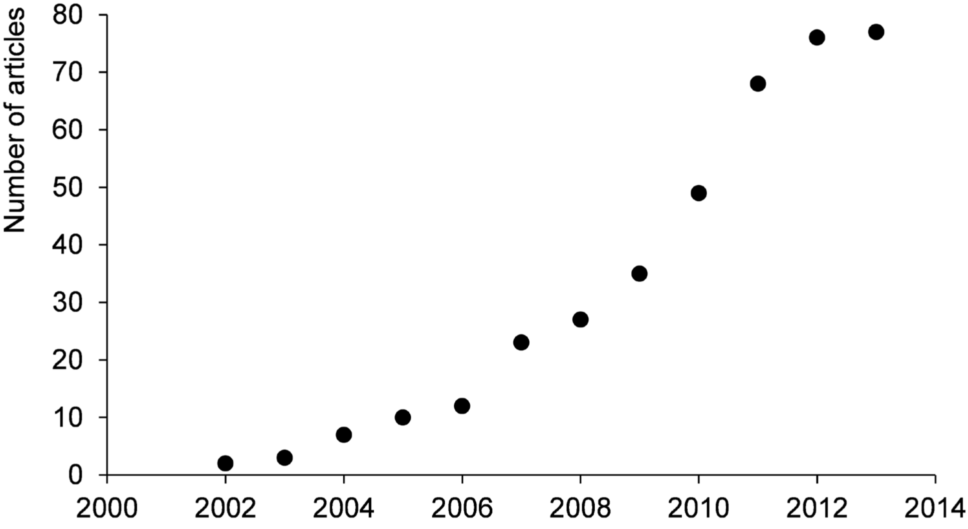

Figure 1. Temporal trend in European publications on alien species of health impact. Shown is the cumulative number of relevant articles detected by our search in Thomson Reuters Web of Science and included in this review (n=77). Note that articles published in 2013 were only partly included in Thomson Reuters Web of Science at the time of our search.

Review articles

With our search, we did not find any review article providing a complete coverage of alien species of human health impact with particular focus on Europe. Eight of the 21 review articles were dealing with dipterans (Table 2), with some of them focusing on a single mosquito species (Gratz 2004, Paupy et al. 2009), others on all alien mosquitos in Europe (Medlock et al. 2012), vectors of Arboviruses (Pfeffer and Dobler 2009), or vectors of West Nile Virus (Koopmans et al. 2007) and Leishmaniasis (Gramiccia et al. 2007, Dujardin et al. 2008, Ready 2010). Four reviews were dealing with vascular plants (Table 2), three with singles species focus (Brandes and Müller 2004, Sauerwein 2004, Gramiccia and Gradoni 2006) one considering all invasive plants of Ireland (Stout 2011). Other reviews focused on the raccoon (*Procyon lotor*; Beltrán-Beck et al. 2012) or presented short summaries on invasive birds (Brochier et al. 2010), amphibians and reptiles (Moutou and Pastoret 2010), or arthropods (Sanders et al. 2010). Aspöck et al. (2002) reviewed all human parasites and Aspöck (2008) all pathogens transmitted by arthropods, but without a dedicated focus on alien species. Further reviews on multiple taxa (Table 2, Suppl. material 2) included human parasites spreading by invasive plants (Mack and Smith 2011), vectors of vector-borne diseases (Van der Weijden et al. 2007), and a comprehensive work by Keller et al. (2011) covering all alien species in Europe, however health impacts played a very minor role in their assessment. The geographic scale of the reviews was mainly European (n=9) or global (n=6) (Table 3).

Table 2. Taxonomic coverage. The taxonomic affiliation of alien species with human health impacts in Europe detected in 77 articles. Shown is the number of alien species with human health impacts, and the number of original research articles and reviews per taxonomic group.

Taxonomic group	No of alien species	Original articles	Reviews	Total no of articles
Vascular plants (Tracheophytes)	28	27	4	31
Flies (Diptera)	6	17	8	25
Mammals (Mammalia)	2	3	1	4
Other arthropods (Arthropoda)	4	1	2	3
Mites and ticks (Acari)	7	2		2
Amphibians (Amphibia) and reptiles (Reptilia)	7	1	1	2
Birds (Aves)	53	1	1	2
Hymenoptera	1	1		1
Jellyfish (Cnidaria)	1	1		1
Multiple taxonomic groups	n.a.	*2*	*4*	*6*

Table 3. Spatial scale of relevant articles. Spatial scale of original and review articles on human health impacts of alien species in Europe.

Scale	Original articles	Review articles	Total
Global	3	6	9
European	6	9	15
Subcontinental	4	3	7
National	24	3	27
Subnational / local	16	0	16
Local lab / field trials	3	0	3

Original research articles

In the 56 included original articles, we found a strong bias in taxonomic coverage of alien species in Europe (Table 2; Suppl. material 2). Most articles were available for vascular plants of human health concern (n=27) and for dipterans (n=17) of human health concern, while only few articles dealt with other taxa such as mammals, ticks (acari), amphibians and reptiles, and birds. The single species most frequently studied were *Ambrosia artemisiifolia* (n=19) and *Aedes albopictus* (n=12) (See Suppl. material 2).

Most of the original research articles dealt with the national and regional scale (Table 3). Western, southern and central European countries had higher coverage by research articles, whereas little information was found for eastern and northern Europe (Figure 2, Suppl. material 3). Invasion stages were represented in an unbalanced manner (G test with Williams correction G=39.02, df=3, p<0.001; Figure 2). Most articles had a strong focus on spread (n=31 original articles), fewer on introduction (n=6), establishment (n=7), and transport (n=2). Similarly, a moderate number of publications studied impact (n=5) or management (n=5). Fourteen articles dealt with two or more invasion stages, impact or management. A large fraction of publications dealing with establishment (71%) and impact (50%) were short reports (See Suppl. material 1).

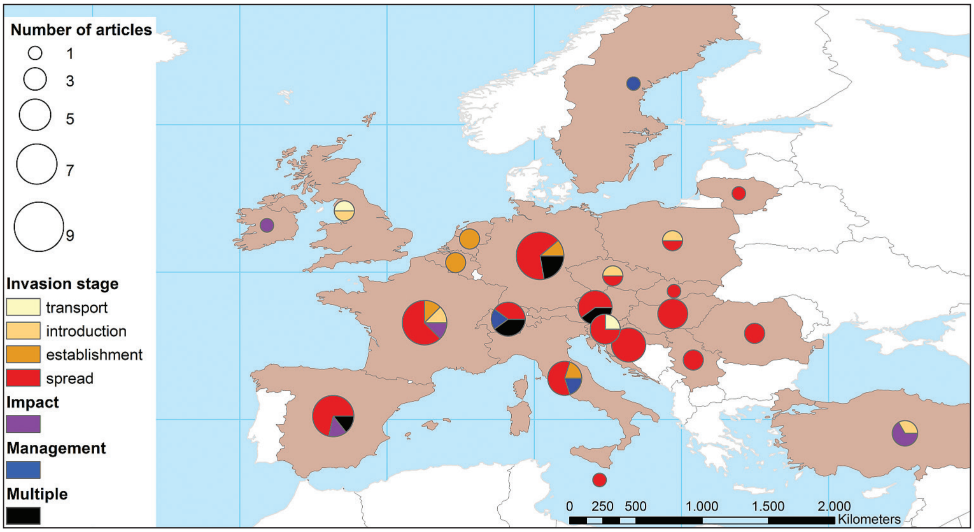

Figure 2. Geographical coverage of the original research articles. The map shows the geographical distribution of the detected original research articles on human health relevant alien species, broken down into invasion stages, impact and management. Articles dealing with several countries were assigned to each study country, whereas articles dealing with the European or global scale were not included in this map.

Geographic origins and pathways of introduction

Most of the 56 included original articles were dealing with alien species native to North America (n=20) and Asia (n=18), less with species from Africa (n=2) and the marine environment (n=2). The 56 articles covered 111 taxa (Suppl. material 2), of which 53 bird species were only listed in a single table of one article because of detected microsporidia infection (Kašičkova et al. 2009) and not considered for further analyses. The remaining 58 taxa also originated predominantly from North America (n=22) and Asia (n=11), but several articles dealing with multiple taxa also considered alien species from the Southern Hemisphere (Figure 3, Suppl. material 2).

Thirty-five articles dealt with contaminants and eight articles with released and escaped species. The two articles on the marine environment dealt with introductions by stowaway (ballast water) and corridors (Lessepsian migration). Fourteen articles dealt with taxa of multiple origins or multiple pathways. Again, the covered species were predominantly introduced as contaminants (total n=21 taxa), however some articles (e.g. Hidalgo-Vila et al. 2008, Hulina 2010) covered several taxa which escaped (n=19 taxa) or were released (n=9 taxa) (Figure 3, Suppl. material 2).

Severity of health impacts, temporal trends, and interaction with climate change

In only two of the 56 original articles (De Haro et al. 2010, Öztürk and İşinibilir 2010) the severity of the impact was quantified and only in one of them the trend in

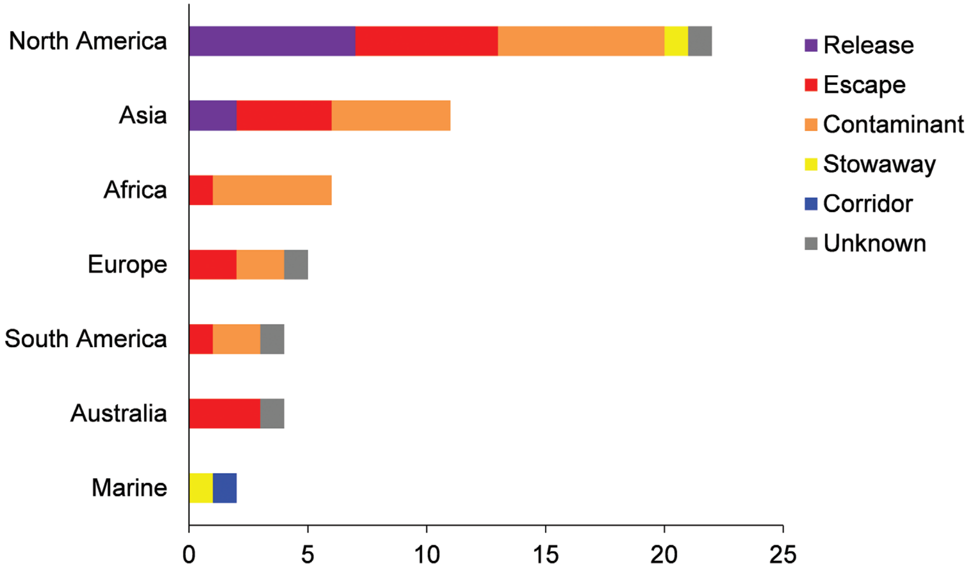

Figure 3. Pathways of introduction and native ranges (continents). Presented for 58 alien taxa of human health concern. Hybridogenous species which have arisen in the native range (e.g. anecophytes) or such native on several continents are not included (See Suppl. material 1).

Table 4. Temporal trends in distribution and impacts. Information on observed or projected changes of species range, species abundance or impact provided in the original research articles on alien species of human health concern in Europe (n=56).

Criteria	Temporal trend				Total
	Not assessed	Decreasing	Stable	Increasing	
Introduction rate	3				**3**
Species abundance	1		1		**2**
Species distribution	18		2	15	**35**
Impact	5		1		**6**
Management effectiveness	4				**4**
Infection rates of vectors or reservoir species	5		1		**6**
Total	**36**	**0**	**5**	**15**	**56**

impact was quantified by showing that no change occurred in the number of hymenoptera envenomations (i.e. stings or bites by a venomous animal including injection of venom) in the areas affected by Asian hornet (*Vespa velutina*) invasion (De Haro et al. 2010). In 36% of all articles, mainly those related to species distribution, also information on temporal trends was provided (Table 4). In most cases there was evidence of an observed or projected increase in distribution or impact (15 out of 20 articles, i.e. 75%), whereas no evidence was provided on decreasing distribution or impacts.

Table 5. Consideration of climate change in original research articles. Climate change effects were mainly discussed or assessed in articles on the spread of health relevant alien species. Only original research articles (n=56) have been analysed.

Invasion stage	**Climate change**		
	Assessed	Discussed	Not considered
Transport		1	1
Introduction		1	5
Establishment		1	6
Spread	3	13	15
Impact			5
Management		2	3
Total	**3**	**18**	**35**

Most of the 56 primary original articles did not consider potential effects of climate change (Table 5). Only three articles (Fischer et al. 2011, Thomas et al. 2011, Caminade et al. 2012) assessed climate change impacts, and further 18 discussed potential impacts of climate change.

Management experience and costs of management or medical treatment

In 15 original articles (27%) specific management measures were proposed, which were usually derived from the presented research. In further 20 articles (36%), general management measures were discussed or proposed. In the remaining 21 articles (38%), management measures were not mentioned. In only one original article the socioeconomic costs were assessed (Gren et al. 2009), in five articles management costs or socioeconomic costs of impact were discussed.

Discussion

We found that the analysed European literature on alien species of human health concern is biased towards few well studied species of only two taxonomic groups, allergenic plants of the family Asteraceae and disease vectors of the order Diptera. On the other hand, we did not detect literature focusing on some taxa of global human health relevance (e.g. snails, bivalves, crayfish) (Mazza et al. 2014), and comparably few information on disease vectors of the subclass Acari, or on vertebrates as reservoirs of alien pathogens. This demonstrates that a few organisms are dominating the literature and that the pronounced taxonomic bias in understanding the impacts of alien species at large (Pyšek et al. 2008, Hulme et al. 2013) also prevails for alien species of human health concern in Europe. This is of concern as lessons learned from few species not necessarily hold true for other species, and thus the risks posed by emerging pathogens may not be fully recognized.

Also the severity of the health impact is poorly covered by the literature, and temporal trends of impacts can almost only be estimated by proxy information. It would be desirable to know to what extent alien species introduced to Europe led to increased rates of disease incidents, but this is difficult, because original hosts or vectors are rarely identified (Hulme 2014). For instance, most articles dealing with the spread of species are explaining the type of impact (e.g. allergenic plant, disease vector), but analytic assessments of trends of numbers of impacted persons hardly occur. Öztürk and İşinibilir (2010) specify 815 hospitalizations after the arrival of the alien scyphomedusa *Rhopilema nomadica* in the Eastern Mediterranean (Turkish coast). One French article reports no increase of total hymenoptera envenomations after the establishment of alien *Vespa velutina* (De Haro et al. 2010), but the reported envenomation data do not differentiate *Vespa velutina* stings from those of native hymenopteran species, and the study therefore cannot be considered as evidence for no impact. This lack of quantitative information on severity and trend of impacts is problematic, because species impact and its severity is crucial for risk assessments (D'hondt et al. 2015) and commonly considered as the best criterion for prioritizing its management (e.g. Blackburn et al. 2014). In this context it is also important to note that estimates of monetary costs of alien species on human health in Europe are scarce, although such figures are decisive to steer decision making (Kettunen et al. 2009, Vilà et al. 2010). Kenis and Branco (2010) mention that economic studies on the impact of alien arthropods worldwide are numerous, with most of them have been undertaken in North America, South Africa and Oceania (Born et al. 2005), but less so in Europe.

Spatial patterns and temporal trends

The risks posed by alien species of human health concern are not equally distributed across Europe. Currently, evidence on human health impacts in Europe has mostly been documented in central and southwestern Europe, whereas little evidence is available for other European regions (Fig. 2). Whereas for northern Europe this lack of evidence most likely truly reflects a lower level of impacts, it is probable that it reflects for southeastern Europe a poor documentation of impacts. For instance, the first record of *Aedes albopictus* in Europe has been made in Albania (Adhami and Reiter 1998), but most articles are dealing with countries such as Spain (Eritja et al. 2005), Italy (Neteler et al. 2011) and the Netherlands (Takumi et al. 2009). Similarly, the highest infestation levels of common ragweed, the alien plant species with the strongest human health impacts in terms of costs and people affected (Vilá et al. 2010), are found in the Pannonian Basin of eastern Europe (Chapman et al. 2014), whereas most articles are from France (Dessaint et al. 2005, Genton et al. 2005, Fumanal et al. 2007, Chauvel and Cadet 2011). Thus the detected East-West divide seemingly does not reflect health impact, but mirrors research intensity. It is less biased towards Western Europe than in other medical and environmental research topics such as infectious diseases (Bliziotis et al. 2005, Durando et al. 2007), public health and preventive and environmental medicine (Soteriades and Falagas 2006), and farmland bird biodiversity (Báldi and Bátary 2011).

Although often lacking direct evidence, the European literature on alien species relevant to human health suggests that the magnitude of the impacts is increasing. This is mainly concluded indirectly from widespread evidence of increasing ranges and abundances of the species (Essl et al. 2009, Paupy et al. 2009, Walther et al. 2009, Keller et al. 2011, Neteler et al. 2011, Thomas et al. 2011, Caminade et al. 2012, Follak et al. 2013, Mazza et al. 2014). Velocity and rate of future spread are often dependent on the trajectories of globalization and climate, as these drivers act in concert in fostering the spread of most alien species of human health concern. Whereas climate change modulates habitat suitability, globalization increases propagule pressure and therefore the likelihood of introduction and establishment and thus range filling. Many species which are currently limited by temperature in Europe are projected to expand into currently climatically unsuitable regions mostly to the north (Chen et al. 2011). This projected northward and upward shift of most alien species under climate change will modify the location of those regions which are affected most by alien species of human health concern. For instance, the allergenic plants annual mugwort (*Artemisia annua*) and *Ambrosia artemisiifolia* are expected to increase their range and abundance due to rising temperatures (Essl et al. 2009, Follak et al. 2013). Thermophilic alien mosquito species, such as the yellow fever mosquito (*Aedes aegypti*) are assumed to establish in Mediterranean Europe (Thomas et al. 2011). Alien mosquito vectors from temperate Asia (e.g. *Aedes albopictus*) are projected to spread throughout central and northern Europe under climate change, whereas in the most arid parts of southern Europe the climatic suitability for their establishment might deteriorate (Eritja et al. 2005, Fischer et al. 2011, Caminade et al. 2012), as these species require ephemeral standing water bodies for their reproduction cycle. Additionally to range shifts due to climate change, habitat shifts might increase potentially suitable habitat as shown for *Ambrosia* and for mosquitos (Essl et al. 2009, Becker et al. 2010).

The increasing numbers of publications published per year might be an indirect indication of increasing relevance of health impacts of alien species in Europe. Interestingly, the detected literature on human health impacts and biological invasions published in refereed journals has been surprisingly recent as we found with our search criteria no publication which was published before 2002. Many of the alien species with human health impacts are either relatively recent arrivals (e.g. *Aedes albopictus*, *Ae. japonicus*, *Ae. koreicus*, *Ochlerotatus atropalpus*) (Medlock et al. 2012) or have strongly spread in the last decade (e.g. *Ambrosia artemisiifolia*) (Bullock et al. 2012, Chapman et al. 2014). Consequently, the attention devoted by scientists, funding agencies and the wider public has increased only recently. Furthermore, some of our selected keywords (e.g. "alien*", "invasiv*") are only rarely used in older literature. In addition, we have included only publications published in journals indexed in the Thomson Web of Science. This conservative approach, which we have chosen to ensure consistency in selecting the literature, excludes a substantial fraction of literature published in other outlets. Finally, there is a well-known publishing delay between conducting the research and publishing the results (publication lag) (Björk and Solomon 2013).

Regions of origin and the role of pathways

Most alien species of human health concern in Europe are native to North America or to East Asia, including the most common studied species, *Ambrosia artemisiifolia* (North America) and *Aedes albopictus* (East Asia). The predominance of species from these two regions, with climates similar to Europe, reflects their high relevance as source regions for alien species in Europe in general (Lambdon et al. 2008, Roques et al. 2010).

Recently, an emphasis on the contributions of specific pathways to the rates of invasion, and on the temporal changes in pathway importance has emerged (e.g. CBD 2014, Essl et al. 2015). In our review, the contaminant pathway was the most important for alien species of health concern. This is in agreement with general introduction patterns of alien arthropods to Europe that are mainly associated with horticultural trade and unintentional escapes of pests (Rabitsch 2010). However, the dominance of introductions as contaminants likely mirrors the favorable species traits of the most relevant taxonomic groups. Diptera of the genus *Aedes* spp. have drought-resistant eggs able to withstand long journeys and enter Europe associated with used tires or Lucky bamboos, which are imported from Asia (Medlock et al. 2012). For common ragweed, medium- and long-distance spread are driven by human agency (e.g. bird feed; EFSA 2010), whereas local population growth and short-distance spread are dependent on natural seed dispersal (Bullock et al. 2012).

Invasion stages and implications for management

While most articles focus on spread, the first invasion stages such as transport, introduction and establishment are poorly covered, a pattern that is even more pronounced for articles assessing temporal trends. The difficulties to gain research funding for basic monitoring activities and that research targeting early invasion stages may not allow for quantitative analyses resulting in research articles, but only FOR descriptive short notes, are probably important reasons for this result (Pietzsch et al. 2006, Scholte et al. 2009, Versteirt et al. 2009).

The publication bias in favor of spread and against early invasion stages indicates that the precautionary principle is not sufficiently embedded in scientific inquiry, as incipient invasions can be easier controlled (Bohren et al. 2006, Galzina et al. 2010, Neteler et al. 2011, Fernández-Llamazares et al. 2012, Hulme 2014, Mazza et al. 2014). Similarly, articles assessing management effectiveness are underrepresented (Bayliss et al. 2012). It should be taken seriously that many studies recommend a comprehensive surveillance of the studied species, which is a prerequisite for rapid management response (e.g. Paupy et al. 2009, Takumi et al. 2009, Versteirt et al. 2009, 2012, Galzina et al. 2010, Capelli et al. 2011, Fischer et al. 2011, Kalan et al. 2011, Marsot et al. 2013, Thomas et al. 2011, Fernández-Llamazares et al. 2012, Medlock et al. 2012). An appropriate tool to avoid invasions already at the earliest stage is certainly the application of trade restrictions, as proposed e.g. for the pet trade (Hidalgo-Vila et al. 2008, Moutou and Pastoret 2010), but as highlighted in Mazza et al. (2015), online trade is poorly regulated and some species, such as the Indo-Pacific lionfish *Pterois volitans*, are sold despite being potentially harmful to humans. A crucial role for guiding European policy on invasive alien species will be exerted by the new European Regulation 1143/2014 (EU 2014), which entered into force in 2015; this legislation, however, focuses on biodiversity impacts and human health will only be considered as aggravating factor.

In terms of management, genetic techniques to eradicate mosquitos (strains with wingless females, transgenic strains) have recently received much attention (Paupy et al. 2009, Sutherland et al. 2011, 2014, Alphey et al. 2013). Some methods developed for mosquitos spread genes through a population despite the genes conferring a reproductive disadvantage, and are meanwhile also explored for alien plants (Hodgins et al. 2009). In principle, the use of such genetic methods may reduce the need for periodic releases of carriers of the desired traits. Beyond effects on the target alien species, the potential side-effects such as unintended dispersal of target species to other localities, horizontal gene transfer, and unforeseen ecological persistence of heritable control elements, have not been investigated in detail (Sutherland et al. 2014).

Gaps in knowledge and research priorities

We found substantial gaps in the literature on human health impacts of alien species in Europe. Most conspicuously, taxonomic and geographic coverage are biased towards few well-studies species and regions while early invasion stages and severity and trends of impacts are poorly studied. Finally, the role of climate change was rarely integrated in predictive assessments. For this study, we have extracted the available articles from the most important literature database for natural sciences. Additional literature on human health impacts of alien species will be available in complementary repositories for medical research publications (e.g. Pub Med). A test run with the search string »“alien species” AND “public health” AND “Europe”« resulted in 38 articles, with the large majority of them being not relevant to this review or redundant to articles that we obtained with our principal search in Web of Science. To ensure repeatability and to avoid that outcomes are biased regarding their relative taxonomic and geographic coverage, we did not perform specific searches at specialist sources, for particular species, or snowballing in reference lists of detected articles. We are aware that this approach may have negatively affected the comprehensiveness of the review. However, such systematic search effort covering several environmental and medical databases, relevant specialist sources, as well as the most relevant scientific and vernacular species names should be a promising alternative for obtaining a more comprehensive set of articles on the topic (Bayliss et al. 2015).

The existence of disciplinary frontiers in publishing and archiving may limit the exchange and uptake of knowledge on human health impacts of alien species generated in different scientific fields. This situation will hopefully improve, e.g. by the “One Health” initiative, an interdisciplinary approach for combating threats to the health of animals, humans, and the environment (Dantas-Torres et al. 2012, Conn 2014). Currently, research projects combining ecology and medical research on and management of alien species hardly exist in Europe. However, this kind of interdisciplinary research would be desirable to assess the direct implications and possible indirect consequences of alien species risks posed for human health now and under foreseeable changing environmental conditions (Conn 2014, Bayliss et al. 2015). Therefore, interdisciplinary projects bridging gaps between ecologists, medical researchers, socioeconomists and public health authorities such as the on-going EU-funded Atopica-project (www.atopica.eu), which focuses on common ragweed, are exemplary and should be taken as a model.

Conclusion

Knowledge on human health impacts of alien species in Europe is still scattered. The review articles detected in this synthesis cover particular species or species groups, whereas a complete coverage of alien species of human health impact in combination with a strong focus on Europe was lacking (but see Hulme 2014 for a recent essay on this topic). Detected original research articles were biased towards few species, mainly vascular plants and dipterans. Alien species of health concern in Europe are mostly introduced as contaminants of products originating from climatically similar regions of the Northern Hemisphere such as North America and Asia. Original articles most commonly deal with the spread of species, while knowledge gaps prevail for early invasion stages, severity and trends of impacts, interactions with climate change, and the scale of the socioeconomic costs. Research projects combining invasion ecology and medical research on alien species would be desirable to assess the consequences of alien species risks posed for human health now and under foreseeable changing environmental conditions. Comprehensive surveillance and monitoring for alien species of health concern are prerequisites for risk assessments and urgent management response and an important baseline for assessing the impact of alien species on severity and frequency of diseases and other types of health impacts.

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Supplementary material 1

Literature on human health impacts by alien species in Europe used in this review (n=77 articles)

Authors: Stefan Schindler, Bernadette Staska, Mildren Adam, Wolfgang Rabitsch, Franz Essl

Data type: categorized literature

Explanation note: Literature on human health impacts by alien species in Europe used in this literature review (n=77 articles). Given are article type, full citation, authors, publication year, journal (source) name, species under concern, taxonomic group, spatial scale, country / region, invasion stage-impact-management, climate change impact, criterion, trend in criterion, severity of impact, trend of impact, management measures, costs, origin, and pathway of first introduction.

Supplementary material 2

Alien species studied in the 56 original articles.

Authors: Stefan Schindler, Bernadette Staska, Mildren Adam, Wolfgang Rabitsch, Franz Essl

Data type: categorized species list

Explanation note: Alien species studied in the 56 original articles, their regions of origin (continents) and their introduction pathways.

Supplementary material 3

Spatial scale and location of the original and review articles

Authors: Stefan Schindler, Bernadette Staska, Mildren Adam, Wolfgang Rabitsch, Franz Essl

Data type: Table summarizing geographical coverage of the considered literature

Explanation note: Spatial scale (global, continental, subcontinental, national, subnational, Local lab/field trials) and location of the original (n=56) and review (n=21) articles.