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Original article

Climate change as a factor enhancing the invasiveness of alien species

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ABSTRACT

Climate is one of the key factors governing the biological invasions of alien species, thus its change may have significant consequences for the scale of this process. We analyzed the predicted influence of climate change on the invasiveness of alien species in Poland and identified species susceptible to climate change. A total of 60 species of alien plants and 58 animals were assessed through an expert elicitation process. For 79 species climate change was assessed as the factor enhancing the likelihood of introduction, establishment, spread and/or impact in the future. Currently, the majority of these species are not widespread in Poland, and this list includes species totally absent, or present only in cultivation and captivity. Climate change will increase the number of high-risk invasive alien species (IAS) from 38 to 63. Species originating in warmer parts of the world are most susceptible to climate change. The majority of the high-risk IAS are regulated under the EU and Polish legislature. However, no restrictions have been imposed on some of the high-risk IAS. Since climate change will further increase their invasiveness, implementation of legal provisions towards these species is recommended.

KEY WORDS: increased temperature, invasive alien animals, invasive alien plants, risk assessment

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1. Introduction

Climate change and biological invasions are both listed among the factors threatening global biodiversity (IPBES, 2023). At the same time, climate change is perceived as the key factor that may exacerbate the problem of alien species in the future (PYŠEK ET AL., 2020). This is a consequence of the fact that temperature is one of the main factors limiting invasions of alien species (DUKES, 2011). On the one hand, too high temperatures may negatively affect some alien species that were introduced in the past and thrive under the current climate. However, many alien species originate in warm areas of the world, therefore elevated temperatures may allow them to overcome each of the current, climate-related barriers, from introduction to new areas, through establishment to spread, and ultimately – to exerting impacts upon native biodiversity, the local economy and human health. In particular, climate change may influence species introduction rates, establishment, dispersal, and impact (PYŠEK ET AL., 2020).

At the introduction phase, mechanisms behind this process include the increase in variety and volumes of goods that will need to be imported because of climate-induced shortages of their local production. This will result in an increase in propagule pressure of species arriving as stowaways and contaminants

(Hulme et al., 2008), whose introductions were previously limited, or that have never been imported in the past. Higher temperatures may also allow some species to survive their journey to new areas.

The increased odds of survival upon their arrival and increased propagule pressure will enhance the establishment of species that so far have not been able to cross this barrier. The impact of increased temperature will, in the context of survival and reproduction, be particularly pronounced in the case of plants and cold-blooded animals. Their rate of metabolism, and thus development and reproduction, is highly dependent on the temperature of their environment. The changes caused by increased temperatures, will improve the chances that, after colonizing an area, pioneer individuals of a species will reproduce successfully enough to become permanently established, forming a stable population (Walther et al., 2009). Increased reproduction due to climate change will result in expanding populations, and the area it occupies will increase. At this stage, the impact of climate change will be manifested, for instance, by increasing the mobility of individuals (Walther et al., 2009). For example, organisms will be more active at night times or for a longer period of the year, which was not possible before due to too low temperatures. This will allow them to migrate faster and further into new areas, inaccessible in the past, such as northern latitudes and higher elevations (e.g., Battisti et al., 2006). For aquatic organisms, water temperature can also be a barrier to rapid expansion. An increase in water temperature will enable the expansion of tropical alien species from artificially heated waters to waters having naturally lower temperatures (Najberek & Solarz, 2011).

The climate of Poland is characterized by high weather variability and significant changes in the course of the seasons in successive years. Average annual air temperatures range from above 5°C to nearly 9°C (Polish National Strategy for Adaptation, 2013). Since the 1980s the recorded temperatures are getting higher. Since 1951, the total annual temperature increase has been estimated at 2.09°C (IMGW Report, 2023). Variation in air temperature affects the length of the growing season which on average lasts 214 days, ranging from 199 to 233 days (Polish National Strategy for Adaptation, 2013).

In these circumstances, therefore, future climate change may significantly increase the vulnerability of the Polish territory to invasions by alien species. The aim of this study was to assess how the most invasive alien species will respond to climatic changes in terms of the likelihood of their invasion and the scale of their impact in Poland.

2. Materials and methods

The main criterion for species selection was their legal status: all species listed by 2018 as invasive alien species of Union concern (N = 49) and all species listed in the Polish national regulation on IAS (Regulation ME, 2011; N = 33) were included in the analyses. In addition, we included 36 species that were not listed but were identified as the most invasive aliens in Poland (Głowaciński et. al., 2012; Tokarska-Guzik et al., 2012; Tokarska-Guzik et al., 2021). A total of 60 species of alien plants and 58 animals were selected for analyses. All plants represented vascular plants, while animals represented 4 different phyla, including 41 vertebrates, 10 arthropods, 6 molluscs, and 1 ctenophore.

The Belgian protocol Harmonia+ (D'Hondt et al., 2015), was applied for the assessment of species invasiveness. It consisted of 41 questions, including questions on the likelihood of introduction, establishment, and spread, and on the likelihood of impact on environmental targets, plant targets (i.e., cultivated plants), animal targets (i.e., captive-bred animals), human targets (e.g., human health) and other targets (e.g., infrastructure). Each answer was accompanied by a confidence level (low, medium, or high). The protocol was fine-tuned for the local circumstances (and termed Harmonia+^{PL}), including changing species examples in explanatory notes, to make them more comprehensible for the Polish experts. The assessment was done independently by two leading Polish experts, experienced in different aspects of the biology and ecology of the assessed species, or with the relevant taxonomic group. The experts based the assessment on their own experience and on information retrieved from published and online information sources, including existing risk assessments and projections of species distribution under different climate change scenarios. After finishing their own assessments, they compared their answers and worked out a consensus between themselves. Their agreed assessment was then reviewed by the third "super assessor" – another expert experienced in the biology and ecology of the relevant organism. If the original scores were disputed, they were again discussed between the three experts until a consensus was reached. As a final result, numerical indicators (ranging from 0 to 1) were obtained for the probability of invasion (related to introduction, establishment, and spread) and for their invasiveness (related to impacts on the distinguished targets). Species that scored 0.51 - 0.66 for impacts were classified as moderate risk invasive alien species, and species that scored 0.67 - 1.00 – as high-risk invasive alien species.

While this assessment was carried out on the assumption of the current climatic conditions, the last 8 questions in the protocol were directly related to climate. The assessors were informed that the timeframe for the assessment of the climate change influence was the mid-21st century. The assumptions on the magnitude of change were made on the basis of the Intergovernmental Panel on Climate Change (IPCC) and acknowledged the expected changes of atmospheric variables, listed in its 2013 report. The main assumption for the assessment was that the global temperature will rise by 1 to 2°C by 2046-2065. Assuming this scenario, the experts assessed the influence of climate change on their initial estimates of the likelihood of the three subsequent stages of the invasion, as well as on the impact of the species on each of the five target categories. The questions on the invasion stages were as follows: Due to climate change the risk for the organism to overcome: (1) geographical barriers and, if applicable, subsequent barriers of captivity or cultivation will be(…); (2) survival & reproduction barriers will be (…); (3) dispersal barriers & (new) environmental barriers within the area will (…). The questions on the impact were as follows: Due to climate change the consequences of the organism: (1) on wild animals and plants, habitats and ecosystems will (…); (2) on cultivated plants (e.g. crops, pastures, horticultural stock) will (…); (3) on domesticated animals (e.g. production animals, companion animals) will be (…); (4) on humans will (…); (5) on targets not considered in previous modules will(…). Possible answers for each of the above questions included the following options: decrease significantly, decrease moderately, not change, increase moderately, and increase significantly.

To calculate the future invasiveness of each species, its initial invasiveness value was multiplied by the following coefficients: 0.5 for a significant decrease under the changed climate; 0.66 for a moderate decrease, 1.33 for a moderate increase; and 1.5 for a significant increase. For some their initial invasiveness values under the current climate were already high, thus their multiplication reflecting the positive influence of climate change produced values exceeding 1.0, which was beyond the upper limit. In such cases, 1.0 was ascribed as the invasiveness value under the changed climate.

3. Results

Responding to the 8 climate change-related questions for 118 species produced a total of 944 answers on the likelihood of invasion and on the scale of impact. In none of the answers was climate change assessed as significantly decreasing risks of any of these 8 invasion-related parameters. A moderate decrease was assessed only for 12 (1.3%) of the answers. At the same time, a significant increase was assessed for 35 (3.7%), and a moderate increase – for as many as 339 (35.9%) of the answers. The most common answer to the climate change-related questions was that it would not have any impact on the assessed parameters (N = 558; 59%).

At the species level, limiting effects of climate change were assessed only for 4 (3.4%) of the 118 analysed species (Table 1), including 3 vascular plants (*Elodea canadensis, Rudbeckia lacinata* and *Amelanchier spicata*) and 1 crustacean (*Pacifastacus leniusculus*). For all of these species the negative influence was only moderate. No influence of climate change was assessed for 35 (29.7%) of the analysed species. At the same time, climate change was demonstrated to significantly, or moderately, increase invasion-related parameters in two-thirds (N=79; 66.1%) of the analysed species (Table 1). More than half of these species (N=40; 50.6%) were vascular plants, which precisely reflects their prevalence in the total pool of the analysed species. Also, the share of other groups in the pool of the species positively affected by climate change generally followed their share in the total analysed pool, with a substantial representation of mammals (N=11, 13.9%) and lower (between c.a. 2-8%) representations of fish, crustaceans, birds, molluscs, reptiles, insects and amphibians (Fig. 1).

However, it needs to be highlighted that when the positive impact of climate change is analysed separately within each group, then vascular plants are the third least affected group; nevertheless, the share of plants that will be prone to these changes is still very substantial, reaching 2/3 of all analysed plant species. Also, among the two least susceptible groups, mammals and crustaceans, the share of species subject to climate change is very high, reaching 55.0% and 62.5%, respectively. These values for all remaining groups are from 71.4% to 100.0%, however, it needs to be considered that these groups were represented by a low number of species (Fig. 1).

Table 1. List of IAS for which climate change was assessed to moderately or significantly influence their impact upon environmental targets, plant targets (i.e. cultivated plants), animal targets (i.e. captive-bred animals), human targets (e.g. human health) and other targets (e.g. infrastructure). Status in Poland and risk category under current and future climates is indicated. Changes in risk categories are bolded

Species	Organism	Impact of climate change	Risk under current climate	Current invasieness value	Risk under future climate	Future invasiveness value	Status in Poland	IAS list
Ailanthus altissima	plant	significant +	high	1.00	high	1.00	widespread	EU IAS
Alternanthera philoxeroides	plant	moderate +	medium	0.65	**high**	**0.86**	absent	EU IAS
Ambrosia artemisiifolia	plant	significant +	high	1.00	high	1.00	widespread	
Amelanchier spicata	plant	moderate -	medium	0.40	**low**	0.26	restricted	
Asclepias syriaca	plant	moderate +	medium	0.50	**high**	**0.67**	restricted	EU IAS
Aster novi-belgii	plant	moderate +	medium	0.60	**high**	**0.80**	widespread	
Azolla filiculoides	plant	significant +	medium	0.65	**high**	**0.98**	restricted	PL IAS
Baccharis halimifolia	plant	moderate +	medium	0.50	**high**	**0.67**	cultivation/captivity	EU IAS
Bidens frondosa	plant	moderate +	high	0.70	high	0.93	widespread	
Bromus carinatus	plant	moderate +	medium	0.50	**high**	**0.67**	widespread	
Cabomba caroliniana	plant	significant +	high	1.00	high	1.00	restricted	EU IAS
Celastrus orbiculatus	plant	moderate +	high	0.70	high	0.93	restricted	EU IAS
Clematis vitalba	plant	moderate +	high	0.70	high	0.93	widespread	
Crassula helmsii	plant	significant +	medium	0.50	**high**	**0.75**	cultivation/captivity	
Eichhornia crassipes	plant	moderate +	medium	0.40	medium	0.53	cultivation/captivity	EU IAS
Elodea canadensis	plant	moderate -	medium	0.50	**low**	0.33	widespread	
Elodea nuttallii	plant	moderate +	medium	0.60	**high**	**0.80**	restricted	EU IAS
Eragrostis albensis	plant	moderate +	medium	0.40	medium	0.53	widespread	
Gunnera tinctoria	plant	moderate +	medium	0.50	**high**	**0.67**	cultivation/captivity	EU IAS
Helianthus tuberosus	plant	moderate +	medium	0.65	**high**	**0.86**	widespread	
Hydrocotyle ranunculoides	plant	significant +	medium	0.65	**high**	**0.98**	cultivation/captivity	EU IAS
Impatiens glandulifera	plant	moderate +	high	0.75	high	1.00	widespread	EU IAS
Impatiens parviflora	plant	moderate +	medium	0.35	medium	0.47	widespread	
Lagarosiphon major	plant	moderate +	medium	0.65	**high**	**0.86**	cultivation/captivity	EU IAS
Ludwigia grandiflora	plant	moderate +	high	0.75	high	1.00	absent	EU IAS
Ludwigia peploides	plant	moderate +	high	0.75	high	1.00	absent	EU IAS
Lysichiton americanus	plant	moderate +	low	0.10	low	0.13	cultivation/captivity	EU IAS
Microstegium vimineum	plant	moderate +	medium	0.55	**high**	**0.73**	absent	EU IAS
Mimulus guttatus	plant	moderate +	low	0.20	low	0.27	widespread	
Myriophyllum aquaticum	plant	moderate +	medium	0.35	medium	0.47	cultivation/captivity	EU IAS
Myriophyllum heterophyllum	plant	moderate +	medium	0.55	**high**	**0.73**	cultivation/captivity	EU IAS

Padus serotina	plant	moderate +	high	0.75	high	1.00	widespread	
Parthenium hysterophorus	plant	significant +	high	1.00	high	1.00	absent	EU IAS
Pennisetum setaceum	plant	moderate +	medium	0.35	medium	0.47	cultivation/captivity	EU IAS
Pueraria montana	plant	moderate +	high	0.75	high	1.00	cultivation/captivity	
Quercus rubra	plant	moderate +	high	0.70	high	0.93	widespread	
Reynoutria × bohemica	plant	moderate +	high	1.00	high	1.00	widespread	PL IAS
Robinia pseudoacacia	plant	moderate +	medium	0.65	**high**	**0.86**	widespread	
Rudbeckia lacinata	plant	moderate -	medium	0.60	medium	0.40	widespread	
Spartina anglica	plant	moderate +	medium	0.45	medium	0.60	absent	
Spiraea tomentosa	plant	moderate +	high	0.75	high	1.00	widespread	
Ulex europaeus	plant	moderate +	medium	0.55	**high**	**0.73**	restricted	PL IAS
Xanthium albinum	plant	moderate +	high	0.75	high	1.00	absent	
Harmonia axyridis	insect	moderate +	medium	0.50	**high**	**0.67**	widespread	
Vespa velutina nigrithorax	insect	moderate +	high	0.67	high	0.89	absent	EU IAS
Orconectes limosus	crustacean	moderate +	high	0.83	high	1.00	widespread	EU IAS
Orconectes rusticus	crustacean	moderate +	high	0.75	high	1.00	absent	EU IAS
Orconectes virilis	crustacean	moderate +	high	0.75	high	1.00	absent	EU IAS
Pacifastacus lenuisculus	crustacean	moderate -	high	0.75	**medium**	0.50	restricted	EU IAS
Procambarus clarkii	crustacean	moderate +	high	0.83	high	1.00	isolated	EU IAS
Procambarus fallax f. virginalis	crustacean	moderate +	high	0.75	high	1.00	isolated	EU IAS
Arion distinctus	mollusc	moderate +	medium	0.42	medium	0.55	widespread	
Arion lusitanicus	mollusc	moderate +	medium	0.50	**high**	**0.67**	widespread	
Corbicula fluminalis	mollusc	moderate +	low	0.25	low	0.33	restricted	
Corbicula fluminea	mollusc	moderate +	high	0.75	high	1.00	widespread	PL IAS
Sinanodonta woodiana	mollusc	moderate +	low	0.29	**medium**	0.39	widespread	
Ameiurus nebulosus	fish	moderate +	high	0.71	high	0.94	widespread	PL IAS
Neogobius fluviatilis	fish	moderate +	medium	0.38	medium	0.50	widespread	
Neogobius gymnotrachelus	fish	moderate +	medium	0.38	medium	0.50	widespread	
Perccottus glenii	fish	moderate +	high	0.67	high	0.89	widespread	EU IAS
Piaractus brachypomus	fish	moderate +	low	0.25	low	0.33	isolated	
Pseudorasbora parva	fish	moderate +	high	0.75	high	1.00	widespread	EU IAS
Cynops pyrrhogaster	amphibian	moderate +	medium	0.42	medium	0.55	cultivation/captivity	
Lithobates (Rana) catesbeianus	amphibian	significant +	medium	0.58	**high**	**0.87**	cultivation/captivity	EU IAS
Chelydra serpentina	reptile	moderate +	high	0.75	high	1.00	isolated	PL IAS
Graptemys pseudogeographica	reptile	significant +	high	0.71	high	1.00	isolated	PL IAS
Trachemys scripta	reptile	significant +	high	0.67	high	1.00	restricted	EU IAS

Aix galericulata	bird	moderate +	medium	0.50	**high**	**0.67**	isolated	
Alopochen aegyptiacus	bird	moderate +	high	0.92	high	1.00	isolated	EU IAS
Corvus splendens	bird	moderate +	high	0.83	high	1.00	isolated	EU IAS
Psittacula krameri	bird	moderate +	high	0.75	high	1.00	isolated	
Threskiornis aethiopicus	bird	moderate +	medium	0.42	medium	0.55	isolated	EU IAS
Callosciurus erythraeus	mammal	moderate +	medium	0.50	**high**	**0.67**	cultivation/captivity	EU IAS
Cervus nippon	mammal	moderate +	high	0.83	high	1.00	isolated	PL IAS
Muntiacus reevesi	mammal	moderate +	medium	0.50	**high**	**0.67**	cultivation/captivity	EU IAS
Myocastor coypus	mammal	moderate +	high	0.75	high	1.00	isolated	EU IAS
Neovison vison	mammal	moderate +	high	0.67	high	0.89	widespread	
Nyctereutes procyonoides	mammal	moderate +	medium	0.58	**high**	**0.78**	widespread	EU IAS
Odocoileus virginianus	mammal	moderate +	high	0.75	high	1.00	absent	PL IAS
Oryctolagus cuniculus	mammal	moderate +	medium	0.63	**high**	**0.83**	widespread	
Procyon lotor	mammal	moderate +	high	0.75	high	1.00	widespread	EU IAS
Sciurus carolinensis	mammal	moderate +	high	0.75	high	1.00	cultivation/captivity	EU IAS
Sciurus niger	mammal	moderate +	medium	0.63	**high**	**0.83**	cultivation/captivity	EU IAS

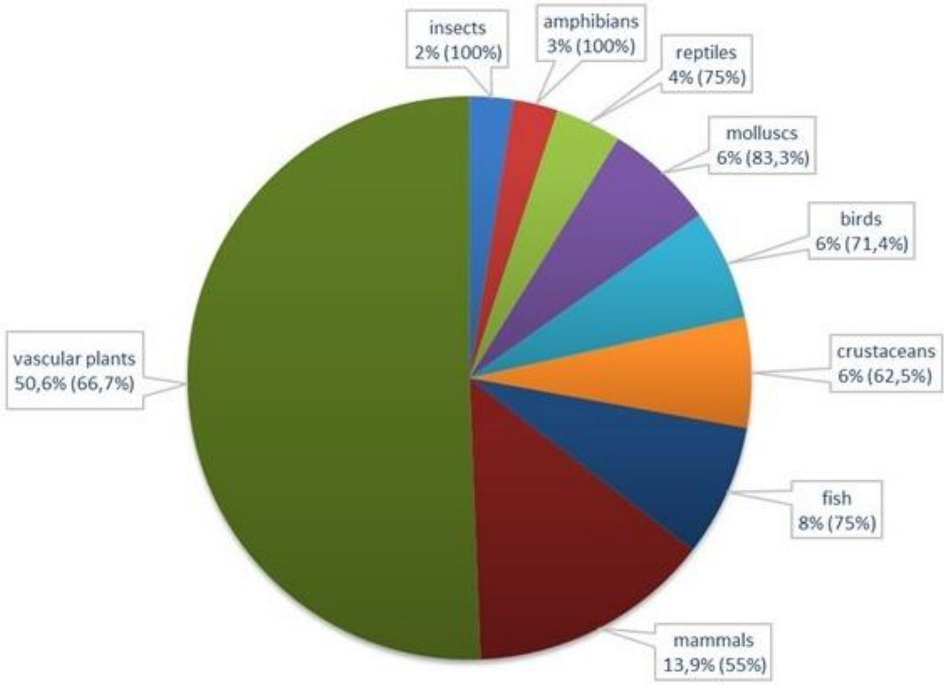

Fig. 1. The percentage shares of systematic groups among the 79 IAS for which significant or moderate influence of climate change on invasiveness was demonstrated (not bracketed values) and percentage shares of species affected by climate change within each taxonomic group (bracketed values)

Among the species favoured by future climate change, the largest group (N = 32; 40.5%) is represented by species that are already widespread in Poland (Fig. 2). It is particularly noteworthy, however, that the second-most represented group (N = 17; 21.5%) are cultivated plants and captive-bred animals, that is, species that have not been recorded in the wild yet. Climate change may also significantly change the invasion scene in Poland for species that currently are only known from a few isolated localities (N = 12; 15.2%) or whose range is restricted only to parts of the territory (N = 8; 10.1%). Moreover, some of the susceptible species (N = 10; 12.7%), including *Parthenium hysterophorus*, *Vespa velutina nigrithorax* or *Orconectes rusticus,* have never been recorded in Poland, even in cultivation, or captivity (Fig. 2).

The assessment of the impact of climate change on the probability of introduction, establishment, and spread of species in Poland indicates that in most cases it will be moderate. Significant influence will be the case for only 2.5% of the species at the stage of their introduction, for 5.9% at the stage of their establishment, and for 5.1% at the stage of their further spread (Table 2). Overall, however, climate change will affect the invasion process for a large proportion of the analysed species, facilitating the spread of 62, the establishment of 49 and the introduction of 41 species.

As in the case of the subsequent stages of the invasion process, the increase in the negative impact on the environmental targets, plant targets, animal targets, human targets, and other targets due to climate change will be mostly moderate (Table 3). Only for 10 (7.9%) species was the increase in impact assessed as significant, including 7 species increasing their impact on the environmental targets (e.g. *Azolla filiculoides*, *Cabomba caroliniana*, *Trachemys scripta* or *Lithobates (Rana) catesbeianus*). In general, however, climate change will increase the impact of a very significant share of the assessed species: from one-fourth of the species affecting the plant targets, to half of the species in the case of the environmental targets.

While the previous analyses of the influence of climate change were based on the qualitative assessment of the influence of climate change, changes in absolute values of invasiveness also provide an interesting insight into this process. The initial assessment procedure carried out on the assumption of the current climatic conditions, assigned the category of high-risk invasive alien species to 38 species for which the value of invasiveness was equal to, or higher than, 0.67. After adjusting this value to account for climate change (see Methods), 25 species previously assessed as medium-risk invasive alien species, advanced to the category of high-risk (Tables 1 and 4). Consequently, a total of 63 alien species were classified as high-risk invasive alien species under the future climate scenario, which constitutes an increase of over 60% in comparison to the current climatic conditions. There was also one species, the mollusc *Sinanodonta woodiana*, that moved from the low to medium-risk invasive alien species category after including climate change in the assessment (Table 1). Amongst the 4 species for which climate change was assessed to be a limiting factor, there is one species that will consequently move from its current high-risk category to the medium-risk category, two species will move from the current medium-risk to low-risk and one species that will remain it its current medium-risk category (Table 1).

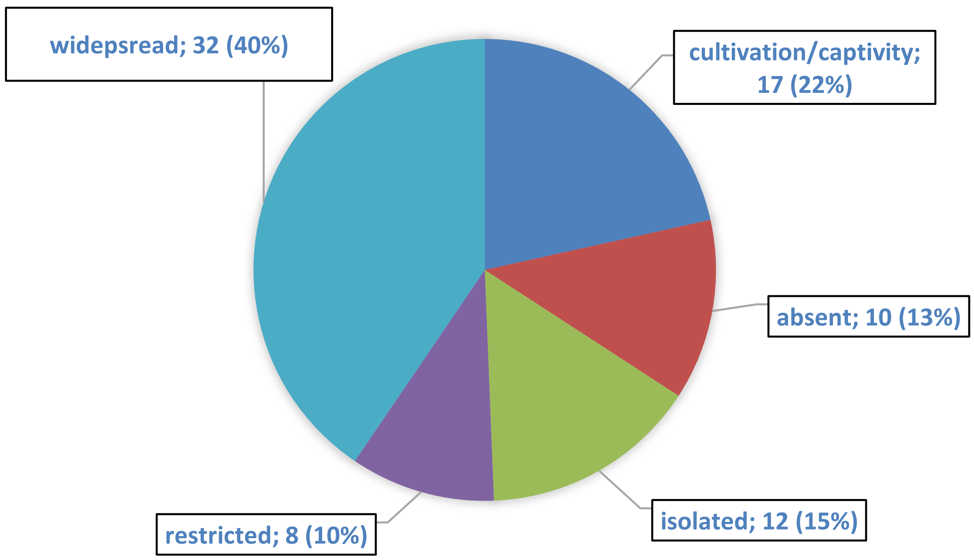

Fig. 2. Numbers and percentage share (in brackets) of IAS susceptible to climate change in different categories of occurrence in Poland. Absent – species not occurring in cultivation, captivity, or in the wild; cultivation/captivity – species present only in cultivation or captivity; isolated – species with single records in the wild or with isolated wild populations; restricted – species occurring in the wild in small part of Poland country; widespread – species occurring in the wild in large part of Poland

Table 2. The number and percentage share of IAS for which the probability of introduction, establishment and spread in Poland was assessed as significantly or moderately increasing according to the Harmonia+[PL] protocol; the total pool of the analysed species was 118, however, as one species may be represented in more than one invasion phase, the total number of cases (as well as %) is higher

Invasion phase	Number of species (% of species)	
	Significant increase	Moderate increase
Introduction	3 (2.5%)	38 (32.2%)
Establishment	7 (5.9%)	42 (35.6%)
Spread	6 (5.1%)	56 (47.5%)

Future climate will render environment as the most severely affected, with as many as 38 alien species demonstrating a severe impact on this target category in the future, compared to twice as low as the current number (Table 4). Cultivated plants, on the other hand, will be least affected by the future changes: only 2 alien plants (*Ambrosia artemisiifolia* and *Quercus rubra*) and one alien mammal (*Sciurus niger*) will severely affect this target category (albeit currently no species was classified this way). Increases in those species affecting animal and human targets were less pronounced, and the level of impact on other targets remained unchanged.

Among groups with a strong representation in the assessed pool of organisms, climate change had the most significant influence on vascular plants and mammals, with 100% and 84% increases in the number of high-risk invasive alien species, respectively, between the current and the future climate (Table 5). Crustaceans, reptiles, and fish were not affected in this respect, although it needs to be remembered that the numbers of species in these groups were low.

Table 3. The number and percentage share of IAS for which the probability of negative impact on environmental targets, plant targets, animal targets, human targets and other targets was assessed as significantly or moderately increasing according to the Harmonia+PL protocol; the total pool of the analysed species was 118, however, as one species may be represented in more than one impact type, the total number of cases (as well as %) is higher

Targets of impact:	Number of species (% of species)	
	Significant increase	Moderate increase
Environmental	7 (5.9%)	62 (52.5%)
Plant (cultivated)	1 (0.8%)	27 (22.9%)
Animal (bred)	3 (2.5%)	44 (37.3%)
Human (incl. health)	2 (1.7%)	37 (31.4%)
Other (incl. infrastructure)	4 (3.4%)	38 (32.2%)

Table 4. Number of high risk IAS affecting each impact targets under the current and future climatic conditions

Targets of impact:	Number of high risk invasive alien species	
	Current climate	Future climate
Environmental	19	38
Plant (cultivated)	0	3
Animal (bred)	16	19
Human (incl. health)	6	9
Other (incl. infrastructure)	12	12
Total	38	63

The native range of species for which climate change will have a moderately, or significantly positive, impact was attributed to continents; some species originated in more than one continent and the ultimate number of range categories was 11; one of them comprised 2 species (*Eragrostis albensis* and *Xanthium albinum*) whose origin could not be unequivocally determined (Table 6). North American species accounted for as much as 40.5% of the species, and 29.1% were from Asia. Each of the remaining areas was the native range for less than 10% of the species. The origins of species positively affected by future climate were compared to the origins of all analysed species. The only 2 areas, for which the number and share of species under future climate are lower than currently, were North America and Asia, which means that some species from these areas will not benefit from climate change. Virtually all species originating in the remaining parts of the world were indicated as beneficiaries of climate change (Table 6).

Table 5. Taxonomy of high risk IAS species under the current and future climatic conditions

Organisms	Number of high risk invasive alien species	
	Current climate	Future climate
Vascular plants	16	32
Mammals	6	11
Crustaceans	5	5
Birds	3	4
Reptiles	3	3
Fish	3	3
Insects	1	2
Molluscs	1	2
Amphibians	0	1

Table 6. Native area of IAS classified as high risk under the current and future climatic conditions

Native area	All analysed species		Species susceptible to climate change		Change in %
	N	%	N	%	
Africa	2	1.7	2	2.5	0.8
Africa/Asia	3	2.5	3	3.8	1.3
Asia	38	32.2	23	29.1	-3.1
Australia	1	0.8	1	1.3	0.4
Europe	4	3.4	4	5.1	1.7
Europe/Africa	1	0.8	1	1.3	0.4
Europe/Africa/Asia	1	0.8	1	1.3	0.4
N America	56	47.5	32	40.5	-7.0
N America/S America	3	2.5	3	3.8	1.3
S America	7	5.9	7	8.9	2.9
Unclear	2	1.7	2	2.5	0.8

4. Discussion and conclusions

Risk assessment systems are rarely analysed in terms of their prediction accuracy, but it is likely that they are limited in their ability (e.g. BARTZ & KOWARIK, 2019; VILÀ ET AL., 2019). Assessing the risk of introduction, establishment, and spread of an alien species, and the consequences of their presence, remains one of the greatest challenges in invasion biology. There are many factors that contribute to this difficulty, including the unpredictability of time, place, pathway and the vector of introduction and gaps in the fundamental knowledge of the biology and ecology of many potential invaders (ROY ET AL., 2017; GONZÁLEZ-MORENO ET AL., 2019). Future climate change further increases the uncertainty of these predictions. Another type of limitation to risk assessments comes from their inherent biases, in terms of the pool of the assessed species (systematics, source region, climates) and in terms of the subjectivity of the assessors.

Nevertheless, despite these shortcomings, risk assessment protocols, such as Harmonia+ (D'HONDT ET AL., 2015), provide a "best guess" on the basis of logical assumptions about a wide range of ecology, plausibility of introduction, and qualitative impacts (BARTZ & KOWARIK, 2019). In the absence of more accurate scientific data, they may tell decision-makers whether they might expect the species to have the potential to enter, establish, spread, and have an impact. This makes risk assessments the key tool for management of biological invasions, including horizon scanning (ROY ET AL., 2019), putting legal restrictions on species for which the risks were assessed to be high (EU REGULATION, 2014) and prioritization of species that should be subject to management (NAJBEREK ET AL., 2022).

Although the results of our analyses need to be taken with due caution, they indicate that in Poland climate change might increase the threat of invasion of most of the analysed species. The most striking result was that virtually none of the 944 climate-related answers implied that future climate change will significantly reduce the risk of any of the 8 assessed parameters related to introduction, establishment, spread and impact. Moreover, merely 1.3% of the answers assessed future reduction as moderate. In contrast, nearly 40% of the answers pointed out that future climate is likely to significantly, or moderately, increase the likelihood of the invasion and/or impact. The conclusion on the facilitating role of climate change on biological invasions holds true even despite the fact that the most common answer to the 8 climate change-related questions was that future climate is unlikely to alter the likelihood of the assessed parameters. This result can be partly explained by the fact that some of the assessed species may indeed remain unaffected by changing climate, whereas others have already advanced in their invasion stage in the past, to an extent that leaves little room for any further increase. Similarly, some of these species received the maximum impact score already under the current climatic conditions, thus this value cannot be increased in the future.

Of particular concern is the fact that as much as 60% of the species that are likely to benefit from climate change in the future are currently either entirely absent from Poland, found only in cultivation, or in captivity, or at the early stages of their invasion in the wild. For these species favourable future climatic conditions may facilitate overcoming each of the three invasion barriers, namely introduction, establishment and spread.

Consequently, climate change may be the major factor changing the invasion scene in Poland for these species particularly advances in the invasion process will translate into increased levels of impact exerted by the assessed species. Although the share of species whose impact is likely to significantly increase was less than 10%, even moderate increases in future will ultimately cause severe impacts from species whose impacts are substantial already under the current climatic conditions. In order to translate qualitative measures of impact that were produced during the assessment into quantitative measures, we used coefficients arbitrarily ascribed to each answer type. In practice, the 0.5 coefficient ascribed to a significant decrease under the changed climate was not used, as this answer was not provided for any of the assessed species. Bearing in mind that the values of the coefficients were subjective, the results of these calculations are alarming: climate change will result in a significant, over 60%, increase in the number of high-risk invasive alien species. It will by no means be compensated by the decrease in their numbers – only one species will move from high-risk to medium-risk invasive alien species.

The most severe impact was found for the environmental targets, and this was manifested both by the highest increase in the share of species that will affect this target and by the highest number of high-risk invasive alien species that will affect it under the changed climate. The assessed impact on the remaining targets was considerably less severe, with the lowest threat posed to cultivated plants.

Drawing conclusions on the groups of organisms that will be most susceptible to changing climate is obscured by their uneven representation in the analysed pool of species. Vascular plants largely prevailed both among all assessed species and among species that will be responding to climate change, while the remaining groups were less numerous in both aspects. However, a significant increase in the number of high-risk invasive alien species was noticeable among mammals.

Uneven representation of species originating in different parts of the world also makes it difficult to indicate native areas that may pose a higher threat in the future as a source of further invasions. However, it is symptomatic that North America and Asia were the only areas for which climate change decreased the percentage share of species in the analysed pool. It is noteworthy that the current climate in these areas (at least in their large parts) is relatively similar to the current climatic conditions in Poland, thus future climate change is not a prerequisite for many species to become effective invaders. On the contrary, the current climate in Poland is a limiting factor for species originating in warm parts of the world, therefore they will benefit from future changes in the climatic conditions.

The results of these analyses highlight the urgent need to intensify efforts to address the threats resulting from the accelerating biological invasion phenomenon due to climate change. The three-stage hierarchical approach, recommended by the Convention on Biological Diversity (COP 6 Decision VI/23, 2002), remains the best overall strategy in this respect. It emphasizes the importance of preventing new introductions as the first line of defense, by, for instance, designing and enforcing appropriate legal regulations. The second line of defense is early detection of introductions and the rapid response to prevent the establishment of the introduced species, particularly through its complete eradication.

These two lines of defense are particularly crucial for species that have never been recorded in Poland, or still occur only in cultivation or in captivity. In the analysed pool these groups are represented by 28 species, including 22 species in the high-risk category. It is encouraging that as many as 18 of these species are listed as IAS of Union concern under the EU Regulation on IAS, and 1 – as IAS of Poland's concern under the national legislation (EU Regulation, 2014; Minister Decree, 2011; Minister Decree, 2022). These legal instruments define restrictions imposed for this species to prevent their introductions, and procedures that need to be followed in case of detection of their introduction. These solutions provide a solid foundation to appropriately address the threats posed by these species currently and in the future. Nevertheless, the ultimate success in this respect will depend on the effective implementation of the legal provisions which need improvement in many aspects (Pietrzyk-Kaszyńska et al., 2023).

The recommended approach towards IAS that are already established but impossible to eradicate, is to implement measures that will contain their further spread or will limit their numbers, or range in the long-term (EU Regulation, 2014). A total of 51 species favoured by future climate fall into this category, including 41 high-risk species. They differ in the stage of their invasion in Poland – from isolated populations, through restricted occurrence, to widespread distribution throughout the country. Legal regulations were introduced towards 12 of these species at the EU level and towards 6 species at the national level. Again, success in limiting threats posed by these species, particularly as a result of climate change, will depend on the efficiency of practical enforcement of the existing legal solutions. It needs to be emphasized, however, that as many as 16 of these species have not been included in the EU, or in the Polish, list of IAS. Among them there are 2 bird species, namely *Aix galericulata* and *Psittacula kramerii*, whose populations are still very localized in Poland. Inclusion of these species in the legal regulations would be a mindful precautionary step towards limiting the risk of their future spread. The remaining 14 species are already widespread throughout the country. This group comprises some of the most invasive alien species in Poland, such as *Neovison vison*, *Quercus rubra* and *Padus serotina*. In the past control of these species was undertaken locally, e.g., in national parks. Under the new legal framework, however, the priority given to controlling the unregulated species will be less binding than obligations to take actions against the IAS of Union, or of Poland's, concern. Consequently, the level of financing the control of the unregulated species is likely to decrease, which will in turn downgrade effects of the past efforts. It is therefore recommended that these species are considered for inclusion in the legal regulations when they are revised.

Finally, it needs to be remembered that due to the dynamic character of biological invasions risk assessments for alien species need to be regularly revisited. Furthermore, the process of intentional and unintentional introductions of alien species is continuing (Pyšek et al., 2020; Tokarska-Guzik et al., 2021). Risk assessment must therefore remain the key element of preventive measures, and the role of the climate change component in such assessments must be appropriately acknowledged.

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