Non-native vascular flora of the Arctic : Taxonomic richness, distribution and pathways

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Non-native vascular plants in the Arctic

Abstract:

We present a comprehensive list of non-native vascular plant species known from the Arctic, explore their characteristics, analyze the extent of naturalization and invasion among investigated regions, and examine pathways of non-native plant introductions. The presence of 341 non-native species in the Arctic was confirmed, of which 188 are naturalized in at least one of 23 regions, while 11 taxa are invasive in three regions. In several Arctic regions there are no naturalized non-native species recorded, whereas in the majority of Arctic regions the number of naturalized species is low. Biogeographic analyses of the non-native vascular plant flora identified three main clusters within the Arctic: American, Asiatic and European. Among all pathways, seed contamination and transport by vehicles have contributed the most to non-native plant introduction to the Arctic.

Key words: alien species, Arctic, invasive species, non-native species, pathways, vascular plants

Introduction

Non-native species are amongthe most significant contributors to global of biodiversity loss, ecological disruption, and economic loss (Dukes and Mooney 2004; Pimentel et al. 2011; Simberloff et al. 2013). Although non-native animals generally receive more attention from the public than plants, non-native plants have a higher likelihood of causing irreversible ecosystem impacts (Vila et al. 2011). Many non-native plant species play a positive role in agriculture, horticulture, and aquaculture without causing adverse ecological effects; a subset of intentional and unintentional introductions, however, cause substantial ecosystem disruption (see Williamson and Fitter 1996). The risks and impacts of biological invasions are growing globally and almost all biomes have faced substantial introduction and establishment of non-native biota (Simberloff et al. 2013).

The Arctic is one of few areas worldwide where ecosystems remain minimally affected by non-native species (Lassuy and Lewis 2013). Limited large-scale human disturbance, low human population size, light traffic, extreme climatic conditions, and short growing seasons likely act as constraints on non-native plant invasion in the Arctic and adjacent regions (Carlson and Shephard 2007; Alsos et al. 2015). However, climate change (Urban et al. 2016) and increasing industrial activities (Reeves et al. 2012) are particularly acute in the Arctic (Descamps et al. 2016), possibly diminishing many of the constraints to the importation and establishment of non-native plant species. Milder climatic conditions and longer growing seasons coupled with anthropogenic disturbance may facilitate a shift in the composition of the non-native flora in the Arctic.

Inventories of non-native plant taxa (e.g. Pyšek et al. 2017) constitute an indispensable element of any research focused on understanding the nature and pace of biological invasions and they are necessary for informed natural resource management actions. Comprehensive non-native plant inventories have been compiled and published for many regions, especially in lower latitudes (Pyšek et al. 2017; Vinogradova et al. 2018). The situation in the Arctic, however, is different. Apart from a fewnotable exceptions (Wasowicz et al. 2013; AKEPIC 2018; NBIC 2018), the non-native flora of the Arctic is still not well known and catalogues of the non-native flora in many regions have never been published. Improving our knowledge of the composition of the non-native flora in the Arctic will contribute to our understanding of the current state of the flora and will serve as a baseline for monitoringfuture changes.

Most catalogues and analyses of non-native plants are based on political borders rather than natural ecoregions as boundary-delimiting factors (e.g. Seebens et al. 2017).

While this approach has obvious practical value (i.e., it is usually straightforward to determine if a taxon has been recorded within a political unit with a clearly defined boundary), it is problematic for characterizing the non-native flora of the Arctic. CPolitical boundaries of several Arctic nations, states, and territories extend into boreal or even temperate biomes, such as . in Alaska (Carlson and Shephard 2007) and the two provinces and three territories in Canada that comprise both Arctic and boreal ecozones. As such, catalogues of non-native taxa in these politically-defined areas may include species found only in their southern, non-Arctic portions, with no indication of the ecozone in which each non-native taxon has been recorded. Species lists compiled for administrative regions that include the Arctic ecozone but also extend beyond it can thus significantly distort understanding of plant invasions in the Arctic, if it is assumed that all non-native taxa in a list are present in the Arctic. We approached this limitation of many previous local studies by accepting the natural boundary of the Arctic as defined by vegetation (i.e., Circumpolar Arctic Vegetation Map; Walker et al. 2005) rather than by political boundaries.

Ecological disruption caused by invasive non-native plant species requires three basic steps: transportation of propagules, population establishment, and a subsequent increase in population size. Increasing attentionis being directed at the first step in invasion: managing pathways of non-native propagules (Ruiz and Carlton 2003; Conn et al. 2008; Davies and Johnson 2011). In general, the pathways of invasive species mirror the movements of people, and the movement of people and their goods are closely tied to commerce and trade; the volume and rate of globally traded goods has increased dramatically in recent decades, facilitating the transport of non-native species (Hulme 2009). The Arctic is not an exception here and increased shipping within the region has been recorded over the past 40 years (MOSJ, 2018).

Non-native plant species may arrive to a new region by one of six primary pathways: intentional release, escape from confinement, transport contaminant, transport stowaway, corridor, or unaided (Hulme et al. 2009; CBD 2014). Globally, the majority of non-native plant species have been introduced intentionally (Dodet and Collet 2012), and most plants follow either an escape from confinement or intentional release pathway (Hulme et al. 2009). Some groups of species, such as shrubs and trees, have been almost entirely intentionally released (Reichard and Hamilton 1997). Container-grown ornamentals, hay and straw, and agricultural seed harbor substantial amounts of non-native plant seeds (e.g., 585 weed seeds/kg of hay and straw bales in Alaska) (Conn 2008; Conn et al. 2010; Conn 2012). Footwear of travelers is also a significant pathway of viable non-native seeds, including to high latitudes. For example, the average visitor to the arctic archipelago of Svalbard transports approximately four seeds, with 40% of visitors transporting at least one species (Ware et al. 2011).

The global Arctic is a partially inter-connected area with geologically recent ice-free exposure of terrains into which many plant species have naturally migrated and colonized of post glaciation (Abbott and Brochmann 2003; Alsos et al. 2007). The geology and partially connected geography leads to high similarity of the native arctic floras, even on different continents (Hultén 1958). Regional relationships among the non-native components of the arctic flora, however, have not been explored.

In the present paper we: (**1**) provide an account of non-native plant introductions to the Arctic, (**2**) explore the basic taxonomic and biogeographic characteristics of the non-native flora, (**3**) compare the extent of non-native plant naturalisation and invasion among analysed regions, and (**4**) analyze the pathways of non-native plant introductions.

Material and methods

Study area

Our definition of Arctic followed the borders of the Circumpolar Arctic Vegetation Map (Walker et al. 2005). The total investigated land area was ca. 5 438 000 km^2. We subdivided the Arctic into 23 regions that largely correspond to the floristic regions used by the PanArctic Flora Checklist (PAF; Elven et al. 2011) (Table S1). Iceland, Jan Mayen, Svalbard, and Franz Joseph Land were treated as separate regions in our study due to their geographic isolation and differences in the composition of their non-native floras.

Lists of non-native plant taxa

We then classified non-native plant species in each region into [how many?] different categories: native/ non-native, casual, naturalized, invasive, [best to list them all I think]. Definitions of these terms can be found in Table S1. Species were classified as native or non-native in each region separately because species native in some Arctic regions are non-native or invasive in other regions (e.g. Lupinus nootkatensis is native to the W Alaska Arctic region but is an established and aggressively expanding adventive in Iceland).

We compiled regional lists of non-native plants in the Arctic, based on herbarium collections, non-native plant databases, literature records, and unpublished data. Our starting point for this compilation was the list of non-native taxa included in the Panarctic Flora Checklist (Elven et al. 2011), which includes many non-native species that fall outside the limits of the Arctic used for this study; . Only records that fell within the geographical limits of the present study were considered. In many cases we confirmed voucher specimens and reviewed primary literature supporting reports on non-native plants in the Arctic. Source data for each evidence point is provided in Table S3.

We classified each non-native species according to invasion status into “casual” and “naturalized” (Richardson et al. 2000 and Pyšek et al. 2004, for definitions see table S2).

Naturalized taxa were further subdivided into “invasive” and “transformers” (sensu Richardson et al. 2000, table S2).

When available, systematic invasiveness ranking values were used to set thresholds for determining invasive and transforming e.g., invasiveness ranks of > = 60 in Alaska and Yukon (Carlson et al. 2008). To standardize scientific names, each non-native plant inventory was compared with Catalogue of Life (http://www.catalogueoflife.org/) and for each species only a name accepted by the Catalogue of Life was retained.

Pathway of introduction analysis

Within each region pathways of introduction of each species were identified based on the available evidence, including personal observations, notes from herbarium specimens, data available from local databases). We used the pathway categorization accepted by the Convention of Biological Diversity (CBD 2014), consisting of six major categories: (1) Release in nature, (2) Escape from confinement, (3) Transport - contaminant, (4) Transport - stowaway, (5) Corridor, (6) Unaided. Within each category a number of subcategories were used (see the caption of Fig. S1 for a complete list). An additional ‘unknown” category was used, when there was no information available to assign a species to a pathway. Each species in each region was assigned to at least one pathway; multiple pathways for the same species were possible, when our data clearly suggested introduction through multiple pathways. The number of introductions by each pathway was calculated for each regional and the entire Arctic for three groups: (1) all non-native plant species, (2) naturalized species, and (3) invasive species.

Multivariate analysis

Detrended Correspondence Analysis (DCA) was employed to investigate overall similarity/dissimilarity of the non-native flora among Arctic regions. All calculations were conducted using the decorana function in R 3.5.1. (R Development Core Team 2018).

Analysis was based on a data matrix containing information from regions with more than 10 tnon-native species >10. Regions with less than 10 non-native species were excluded from this analysis because … We used principal component analysis and correspondence analysis to confirm the results of DCA (data not shown). Results of these analyses were largely in agreement with the results presented in the paper.

Results

We documented 341 non-native vascular plant taxa in the the Arctic taxa (see Table S1 for the complete list of species, details on their invasion status and distribution in investigated regions). There are 188 taxa naturalized in at least one floristic region, and 153 arecasual in one or more regions. The total share of non-native species in Arctic flora is 8.6%[1] .

We excluded 38 taxa from the non-native flora of Arctic that have been referenced previously, due to erroneous reports or because these species fell outside the geographical limits accepted in this study (they should be classified as sub-Arctic).

The 341 non-native taxa recorded for the Arctic belong to 39 families and 180 genera (see Table S2). The greatest number of non-native plant species in the Arctic belong to Poaceae (51 taxa), Asteraceae (48) and Brassicaceae (45). The genera richest in Arctic non-native species are Poa (8), Ranunculus (7), *Rumex* (12 taxa), *Trifolium* (7) and *Vicia* (7).

Chenopodium album is the most widespread non-native species in the Arctic (recorded in 13 of the 23 regions we investigated), followed by *Stellaria media* (recorded in 11 regions), and *Fallopia convolvulus* (recorded in 11 regions). Most non-native species have very limited distributions in the Arctic (Fig. 1). The number of species that are naturalized follows a similar pattern, with the majority of naturalized species occurring in one or a few regions. *Stellaria media* is the most widely naturalized taxon (10 regions) followed by

[1] There are 1981 plant taxa native (excluding borderline species) according to Daniëls et al. (2013). See Table S1 for detailed regional data.

Chenopodium album, *Draba nemorosa*, *Puccinellia hauptiana* and *Trifolium repens* - all of them naturalized in nineof the 23 regions investigated).

The total richness of non-native plant species varies greatly among regions, ranging from zero (in Ellesmere Land – Northern Greenland and Franz Joseph Land) to 206 (in Kanin-Pechora) (Fig.2 A). The average number of number of plant taxa per region is 40.39 ± 48.57 (median = 19). There is a similar pattern for naturalized species (Fig. 2 B). No naturalized non-natives are recorded from three regions: Wrangel Island, Ellesmere Land – Northern Greenland, and Franz Joseph Land, while 120 species are naturalized in Kanin-Pechora. The average number of naturalized non-native plant taxa per region is 21.30 ± 26.75 (median = 13).

Plant invasion in the Arctic is limited both geographically (Fig. 2 C) and in terms of the number of invasive species present overall (Table 1). Only three regions have species recorded as invasive or transformers: North Alaska - Yukon Territory, Western Alaska, and North Iceland. In almost all cases these same species were present and regarded as casual or naturalized non-natives in other regions (with the exception of *Prunus padus* that was restricted to North Alaska - Yukon), but were not determined to be invasive.

Eleven taxa are considered invasive or transformers in at least one region (Table 1); most are located in North Alaska - Yukon Territory - 8 species, and Western Alaska - 5 species (two species are present in each of these regions). Two invasive species are present in the Arctic part of Iceland. Most Arctic invaders belong to Fabaceae (4 taxa), Asteraceae (2) and Poaceae (2). The three remaining species belong to Apiaceae, Plantaginaceae and Rosaceae. Three taxa are classified as transformers and they all belong to Fabaceae. The predominant life form in this group is chamaephyte (73%).

The results of detrended correspondence analysis (DCA) of non-native species composition of Arctic regions identifies three geographically clustered major units:

American, Asian and European (Fig.3). The non-native floras of North American Arctic regions are more similar, while the Asiatic parts of the Arctic (consisting of nine Siberian-Arctic regions) differ in terms of non-native flora composition. In our analysis Northern Iceland shows unique characteristics and forms a separate group (European). Svalbard archipelago (SF) groups with Northern American regions.

We also examined the pattern of diversity of non-native species per km^2 in investigated regions (Fig. 3). The value of this index ranges from 0 (Franz Joseph Land and Ellesmere Land - Northern Greenland) to 0.014 (N Iceland). The average value of this index is 0.001 ± 0.031. When the number of non-native species recorded for a region are scaled proportionally to the land-mass, regions such as North Iceland, Jan Mayen, Northern Fennoscandia, Kharaulakh and Svalbard display high (above average) densities of non-native species (Fig. 3).

Analysis of introduction pathways revealed that all major pathway categories have contributed to the introduction of non-native plant species into the Arctic. However, the significance of this contribution varies greatly among pathway categories (Fig.5). *Escape from confinement* is responsible for introduction of 48 % of invasive vascular plant taxa. *Transport-stowaway* was the second most active pathway for invasive taxa (37 % of all introductions) and most active for pathway for naturalized taxa - contributing to the importation of 19% of naturalized species). *Unaided spread* and spread through *corridor* do not play any significant role in the Arctic.

Further analyses of the pathway subcategories (see Figure S1) revealed that *Seed contaminant* is the most active introduction pathway (when the total set of non-native species was analyzed) and contributes to 14% of all introductions. *Vehicles (car, train, etc.)* is the second most active pathway and contributes to 14% of all introductions. Forty nine percent of introductions are assigned to an "unknown" category, due to lack of sufficient data. The remaining pathways contribute to ca. 32% of all introductions, but the contribution of each pathway is usually equal or lower than 5% (Figure S1).

The analyses indicate that the most active pathway for naturalized taxa is *Vehicles (car, train, etc.)* and contributes to 11 % of all introductions. *Seed contaminant* is the second most active pathway (8%), followed by *People and their luggage/equipment (in particular tourism)* (5%) and *Transport of habitat material* (5%). Pathway of introduction is unknown in 49 % of all non-native vascular plants in the Arctic (Figure S1).

A different picture emerges when only invasive taxa are analyzed. Here, *horticulture* is the most active pathway contributing to 26% of all introductions of invasive species. *Agriculture and Machinery/equipment* are a less active, contributing to 15% of introductions each. Pathway *People and their luggage/equipment (in particular tourism)* is responsible for 11% of all introductions, while *Vehicles* and *Research and ex-situ breeding* contribute to 7.4% of introductions each (Figure S1). Only 4% of all introductions in this category was classified as unknown.

Discussion

We present a comprehensive treatment of Arctic non-native vascular plant richness, naturalization and invasion status using a defined natural geographic delimitation and standardized terminology. Our study reflects the most up-to-date knowledge on non-native and invasive plants in the Arctic and represents a new baseline that will allow better understanding of future changes in the non-native flora of Arctic. Currently, most non-native species in the Arctic are confined to human settlements, roads and infrastructure, but with increasing propagule pressure and higher temperatures these plants might be able to invade areas outside their current distribution limits. Data presented in the current paper differ from previous assessments in terms of the number of non-native species recorded in the Arctic. For example, Arctic Biodiversity Assessment (Daniëls et al. 2013) listed only 190 non-native species (both casual and naturalized) present in the Arctic. In some regions (e.g Kanin-Pechora) the number of naturalized aliens was substantially underestimated: 52 naturalized aliens in Daniëls et al. (2013) vs. 120 taxa in the present study. What is more, the number of casual taxa in many regions with along history of human settlement recorded in earlier work was surprisingly low: e.g. only two casual introductions listed from N Iceland and Jan Mayen by Daniëls et al. (2013) vs. 62 taxa listed by us.

Non-native plants can be divided into two groups: “old” non-natives or archaeophytes and “new” non-natives or neophytes (see Table S2 for definitions), which have been introduced more recently. We excluded “old” non-natives from our study due to insufficient data and unclear status. In some regions, however, where the distinction between “new” and “old” non-natives is not straightforward due to the lack of evidence, some “old” non-natives may be present in our lists.

By combining pan-Arctic data we were able to provide a robust picture of the most successful non-native vascular plants in the Arctic. We identified a set of species widely naturalized in the region: *Stellaria media*, *Chenopodium album*, *Draba nemorosa*, *Puccinellia hauptiana*. However, in many cases geographically clustered regions share unique assemblages of non-native species. Our data suggest that the non-native flora of the Arctic is not uniform and that clear clusters of regions with similar alien flora can be recognized. Factors that could potentially contribute to this differentiation includedifferent species source pools and isolation in terms of historical patterns of trade.

By organizing ? our data in a geographic context we were able to identify regions where the processes of non-native plant naturalization and invasion are advanced (e.g. Alaska, N Iceland, European part of Russian Arctic). We determined that hotspots of plant naturalization and invasion only partially match geographically: invasive species were recorded only in two regions with confirmed occurrence of over 20 non-native taxa. We did not record invasive species from regions with the highest number of naturalized species (Kanin-Pechora, Western Greenland, Polar Ural - Novaya Zemlya). These results suggest that in many of these regions new invasive plant species are likely to emerge in the near future. Another possibility is that in some regions invasive species are present but not yet recorded, given logistical challenges of field exploration across the Arctic.

Our results indicate that the number of non-native plant species in the Arctic is low and that few species are currently perceived to be causing significant ecological alterations. This confirms the general observation that the proportion of non-native species in the polar regions is generally lower than elsewhere (Frenot et al. 2005; Alsos 2015). This pattern in the distribution of non-native species in general (and non-native plant species in particular) may reflect low propagule pressure in the Arctic (caused by low human activity) and the cold climate, which may prevent survival and reproduction of many non-native taxa. In fact, a very large number of non-native species in the Arctic are restricted to hot springs in the Alaskan Arctic (Pilgrim Hot Springs on the Seward Peninsula) and to the extreme southern boundary of our area of interest with longer growing seasons; no non-native species have been recorded in the colder regions of northern Alaska despite large settlements and significant commerce (Carlson et al. 2015). The rate of temperature increase in the Arctic has been so far the highest in a global context and it seems that this trend will also continue in the predictable future (Urban et al. 2016). This fact has major consequences for all Arctic ecosystems leading to changes in species phenology (Alsos et al. 2013; Alsos et al. 2015) and influencing natural distribution patterns (Elmhagen et al. 2015). Although the effect of climate change on non-native species will be complex and multi-directional (Bellard et al. 2013), we expect that the distribution of non-native plant species in the Arctic will be impacted by these major environmental changes. It seems reasonable to assume that climate niche availability for both naturalized and casual non-native plants will increase. This may in turn lead to increased persistence of casual species and promotion of naturalization and invasion. Indeed, recent studies carried out in Iceland indicate that the number of non-native plant taxa is increasing sharply (Wasowicz et al. 2013; Wasowicz 2016) and that some highly invasive species have been recorded either from the Arctic or from the bordering sub-Arctic regions (Carlson and Shepard 2007; Gederaas et al. 2012; Lassuy and Lewis 2013; Wasowicz et al. 2013; AKEPIC 2018). These observations suggest that climate change is already impacting wide areas of the sub-Arctic, where the potential pool of future Arctic invaders is constantly increasing. On the other hand, there is an opposite trend for many non-native species to disappear when inhabited places are abandoned and human activities ceased (Alsos et al. 2015). However, such changes are local and do not necessarily ? lead to the complete disappearance of a species from the territory.

We determined thatplant invasion in the Arctic is currently limited to a local scale and that there are no universally successful invaders able to become invasive in many Arctic regions.

Examining the exact factors driving the patterns of non-native plant richness in the Arctic was beyond the focus of the present study. However, some general conclusions can be drawn from our data. It seems to be quite clear that regions with a long history of human settlement and relatively high population density are among the most impacted by non-native plant species.

A comprehensive picture of important pathways by which non-native plant species are introduced to the Arctic emerged from our study, highlighting unintentional dispersal by *escape from confinement* and *transport-stowaway* pathways. The identification of these pathways is important in developing biosecurity measures on local and regional scales. It may also help in developing strict international biosecurity measures that do not yet exist in the Arctic.

The Arctic wilderness is becoming a major tourist attraction, rapidly increasing the significance of anthropogenic disturbance as a pathway for non-native species. In some areas of the Arctic, the increase in the number of visitors is high and unprecedented. For example, in Svalbard the number of tourists has increased sharply over the last decades, and the number of places visited by cruise passengers going ashore has increased sharply from 53 in 1996 to 174 in 2016 (MOSJ 2018). In Iceland the number of international visitors has grown from 72,600 per year in 1982 to over 2,000,000 per year in 2017 (Freðamálastofa 2018). The recent increase in the number of visitors and human population will likely contribute to increases in the number of introductions through different pathways.

Non-native and invasive species are only one of the many factors that are currently putting pressure on Arctic terrestrial ecosystems. It has been difficult to say how these pressures affect terrestrial ecosystems in the Arctic due to the complex nature of the region and its size. The Circumpolar Biodiversity Monitoring Program (CBMP) aims to overcome these limitations by developing four coordinated and integrated Arctic Biodiversity Monitoring Plans. In order to effectively monitor the impact of non-native species on the Arctic flora the introduction-naturalization-invasion continuum should be used as a conceptual framework (Richardson Pyszel 2012). Close monitoring of populated places, harbours, roadsides and other tracks for plant propagule transportation is recommended in order to detect new non-native species arriving into the Arctic. Monitoring of heavily disturbed and semi-natural plant communities will be crucial in detecting taxa that are becoming naturalized and about to start producing self-sustaining populations. The same areas are crucial for detecting early stages of invasion, which may allow for timely reaction to prevent further spread of the taxa becoming naturalized and invasive.

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