Received: 7 September 2020 | Accepted: 10 February 2021

DOI: 10.1002/2688-8319.12056

Ecological Solutions and Evidence | BRITISH ECOLOGICAL SOCIETY

RESEARCH ARTICLE

Moving out of town? The status of alien plants in high-Arctic Svalbard, and a method for monitoring of alien flora in high-risk, polar environments

Jesamine C. Bartlett[1] | Kristine Bakke Westergaard[1] | Ingrid M. G. Paulsen[2] | Ronja E. M. Wedegärtner[3] | Florian Wilken[4,5] | Virve Ravolainen[2]

[1] Norwegian Institute for Nature Research, Trondheim, Norway

[2] Norwegian Polar Institute, Tromsø, Norway

[3] Norwegian University of Science and Technology, Trondheim, Norway

[4] Eidgenössische Technische Hochschule Zürich, Zürich, Switzerland

[5] Universität Augsburg, Augsburg, Germany

Correspondence
Virve Ravolainen, Norwegian Polar Institute, Hjalmar Johansens gate 14, 9296, Tromsø, Norway.
Email: Virve.Ravolainen@npolar.no

Funding information
Svalbard Environmental Protection Fund, Grant/Award Number: 17/50; The Governor of Svalbard; The Ministry of Climate and Environment/The Norwegian Polar Institute

Handling editor: Sarah Dalrymple

[Correction added on 16 April 2021, after first online publication: the spelling of the name of the second author has been corrected throughout the article.]

Abstract

1. Rising human activity in the Arctic, combined with a warming climate, increases the probability of introduction and establishment of alien plant species. While settlements are known hotspots for persistent populations, little is known about colonization of particularly susceptible natural habitats. Systematic monitoring is lacking and available survey methods vary greatly.
2. Here, we present the most comprehensive survey of alien vascular plant species in the high-Arctic archipelago of Svalbard to date, aimed at (i) providing a status within settlements; (ii) surveying high-risk habitats such as those with high visitor numbers and nutrient enrichment from sea bird colonies; (iii) presenting a systematic monitoring method that can be implemented in future work on alien plant species in Arctic environments; and (iv) discuss possibilities for mapping alien plant habitats using unmanned aerial vehicles.
3. The systematic grid survey, covering 1.7 km^2 over three settlements and six bird cliffs, detected 36 alien plant species. Alien plant species were exclusively found in areas of human activity, particularly areas associated with current or historic animal husbandry. The survey identified the successful eradication of *Anthriscus sylvestris* in Barentsburg, as well as the rapid expansion of *Taraxacum* sect. *Ruderalia* over the last few decades.
4. As there is currently no consistent method for monitoring alien plant species tailored to polar environments, we propose a systematic methodology that could be implemented within a structured monitoring regime as part of an adaptive monitoring strategy towards alien species in the Arctic.

KEYWORDS
arctic conservation, EDRR, evidence-based management, non-native species, species distribution, UAV

1 | INTRODUCTION

Humans have acted as agents of ecological change for millennia, through the introduction of species to new regions and habitats, and lately also through anthropogenic climate change and habitat loss (Sala, 2000). Introduced species are considered alien when they are '*introduced outside its natural past or present distribution by humans*' (IUCN, 2020). Combined, alien species and a rapidly warming planet are two of the most pertinent issues impacting terrestrial polar ecosystems today, with climate change likely to escalate alien species' establishments throughout the regions (CAFF-PAME, 2017; Meltofte et al., 2013). Alien species are among the most significant contributors to global biodiversity and ecological disruption, with pest species causing substantial economic loss, and invasive alien species (IAS), as defined by the IUCN, outcompeting natives, leading to declines in species richness (CAFF-PAME, 2017; Simberloff et al., 2013). IAS risk compromising terrestrial ecosystems that are used for sustenance and are of cultural importance to local and indigenous people of the Arctic (CAFF-PAME, 2017; Ebbert & Byrd, 2002). Recently, the rising instances of alien plant occurrence and establishment have reiterated the call for urgent and effective action that is necessary to protect the Arctic from IAS (Wasowicz et al., 2020).

The establishment of alien species in polar regions is generally lower (in absolute terms) than the rest of the world, as cold climates limit survival and reproduction, whilst historically low human activity limits the propagule pressure (Frenot et al., 2005; Wasowicz et al., 2020). Therefore, alien species establishments usually occur in distinct habitats that offer some relief from the harsh polar environment: For instance, in Svalbard, soils enriched with nutrients from animal husbandry are 'hotspots' for alien species (see Coulson et al., 2013; Liška & Soldán, 2004). The Arctic is one of the fastest warming regions on the planet, and an ameliorated climate will expand potential habitats for both native and alien species alike (Meredith et al., 2019). We can therefore reasonably assume that the degradation of harsh climates as a natural barrier to establishment will instigate a rise in alien species throughout the region (Lassuy & Lewis, 2013). Remote Arctic archipelagos like Svalbard have geographic barriers to natural dispersal, yet, in recent years, alien species introductions via anthropogenic pathways are on the rise both globally (Seebens et al., 2018), and into Svalbard and the polar regions in general (e.g. Huiskes et al., 2014; Ware et al., 2012). Once introduced, zoochory and wind dispersal act as further pathways: Sea ice and even driftwood are considered factors in the long-distance dispersal of vascular plants to, and within, the Arctic (Alsos et al., 2016), and with a large population of birds, seed dispersal by both epi- and endozoochory may also act as a pathway around Svalbard. Bird cliffs may be particularly suitable natural habitats for alien species establishment, where not only do zoochory vectors and tourists congregate (Eeg-Henriksen & Sjømæling, 2016; Ravolainen et al. 2020), but soils are nutrient rich as a result of guano build up (Zwolicki et al., 2013). The impacts of a new alien species can potentially become detrimental to local biodiversity (Benediktsson, 2015), and typically, alien species are more likely to succeed over native species in changing environments (e.g. Johnson et al., 1993) and affect whole ecosystems (Simberloff et al., 2013; Vilá et al., 2011). There are no systematic surveys of alien plant species presence in any sites in Svalbard, rather incidental observations and unsystematic walks around settlements.

A recent inventory of Svalbard documented 98 alien vascular plant species, of which 19 were considered naturalized, and therefore received quantitative ecological impact assessment (Elven & Westergaard, 2018b; Sandvik et al., 2019). Svalbard is one of the most accessible areas within the Arctic, meaning it is at a higher risk of further anthropogenic introductions. Established alien plant species in Svalbard are only reported in areas associated with human activity, and transient species only recorded in natural habitats (Alsos et al., 2015). Despite increasing human activity and an ameliorated climate, there are no biosecurity measures implemented throughout the Arctic region, and a lack of systematic monitoring protocol for alien species in general. In Svalbard, only one plant species (*Anthriscus sylvestris*) from one settlement has had focus eradication attempts as a measure to prevent spread to natural habitats (Lutnæs et al., 2017; Sandvik et al., 2019). The first records of alien species on Svalbard were documented in 1883, over 200 years after the first whaling stations were established (Gyllencreutz, 1884). The first survey of alien species in Svalbard was conducted in 1941 (Hadac, 1941) and occurrences have been irregularly noted as part of more comprehensive studies of native flora throughout the 20th century (e.g. Elvebakk, 1989; Hadac, 1944; Rønning, 1964, 1972). In the last few decades, intermittent studies evaluated the occurrence of alien species in Svalbard in some settlements, but methods of survey have varied among studies (e.g. Alsos et al., 2015; Arnesen et al., 2016; Elven & Elvebakk, 1996; Liska & Soldán, 2004).

In recent years, the Norwegian government at the Ministry of Climate and Environment has tasked the Governor of Svalbard, the Norwegian Polar Institute and the Norwegian Environment Agency to monitor alien species occurrence and their potential spread into natural habitats (Norwegian Ministry of the Environment, 2007). Whilst, the 'Circumpolar Biodiversity Monitoring Programme' (CBMP; a working group endorsed by the Arctic Council and the United Nations Convention on Biological Diversity) aims to develop Arctic Biodiversity Monitoring Plans, and identifies alien species as a 'focal ecosystem component' (Christensen et al., 2013). The Arctic Invasive Alien Species strategy and action plan (ARIAS) states that now is the time for urgent action in order to protect the Arctic from IAS (CAFF-PAME 2017). The first line of defence against alien species establishment is through effective and well-implemented biosecurity practices (Bartlett, Radcliffe, et al., 2021; Hughes et al., 2015). Early detection and rapid response (EDRR) management is the only realistic defence against IAS that has established (Waugh, 2009): Establishing systematic and regular monitoring methodologies that are tailored to polar habitats will enable early detection and reporting of alien species introductions, thereby instigating management actions in a timely manner suitable to the vulnerable Arctic environments, and answering the call of several national and international committees.

The aim of this work is (i) to map the status of alien vascular plant species in settlements of Svalbard and high-risk natural habitats such as tourist landing sites at bird cliffs, and (ii) to discuss and improve

FIGURE 1 Location of survey sites and number of alien species found in each. Inset – location of Svalbard in the Arctic

survey methods by (a) synthesizing and evaluating methods previously used in alien plant species recording in Svalbard and (b) developing and implementing a systematic monitoring method that surveys for both spatial–temporal presence and absence of alien plant species. (iv) We also present a pilot dataset and discuss possibilities for mapping alien plant species and assessing potential habitats using unmanned aerial vehicles (UAVs). We discuss the surveys and synthesis in light of an overall adaptive monitoring strategy.

2 | MATERIALS AND METHODS

2.1 | Selection of survey sites

Surveys for alien vascular plant species in Svalbard were undertaken throughout August of 2017, by a team of three to five people. Nine sites were selected based on existing information on alien species occurrence, likelihood of species establishment based on human activities and potential secondary wind dispersal and zoochory via birds (Figure 1). Previous alien vascular plant species occurrences were identified through literature and the 'Artskart' database in June 2017 (https://artskart.artsdatabanken.no, Supporting Information S1a). Sites were prioritized for the nine species registered as reproductively viable in Svalbard *Alchemilla millefolium* and *Alchemilla subcrenata*; *Anthriscus sylvestris*; *Barbarea vulgaris*; *Ranunculus acris*; *Rumex acetosa*; *Tripleurospermum maritimum*; *Poa annua*; *Taraxacum* sect. *Ruderalia*; *Stellaria media* (Alsos et al., 2015; Elven & Elvebakk, 1996; Liska & Soldán, 2004). Bird cliffs with relatively easy access by boat from the settlements, good landing sites and high visitor numbers in recent years were considered as high-risk sites, and selected based on records of visitor numbers over the years 1996–2015 in collaboration with the Governor of Svalbard (The Governor of Svalbard, unpublished database). Accordingly, the settlements of Barentsburg, Pyramiden and Ny-Ålesund were surveyed, along with bird cliffs at the following locations: Skansbukta; Bjørndalen; Alkhornet; Ossian Sarsfjellet; Stuphallet; Fjortende Julibukta. Longyearbyen had been subject to a separate survey in the year prior as part of a commission by the Governor of Svalbard, the results of which will be discussed in addition to our survey sites (Arnesen et al., 2016).

2.2 | Survey design

To obtain a systematic method for recording presence, absence and approximate abundance of species and identifying species' diversity and distribution in settlements and 'high-risk natural habitats'

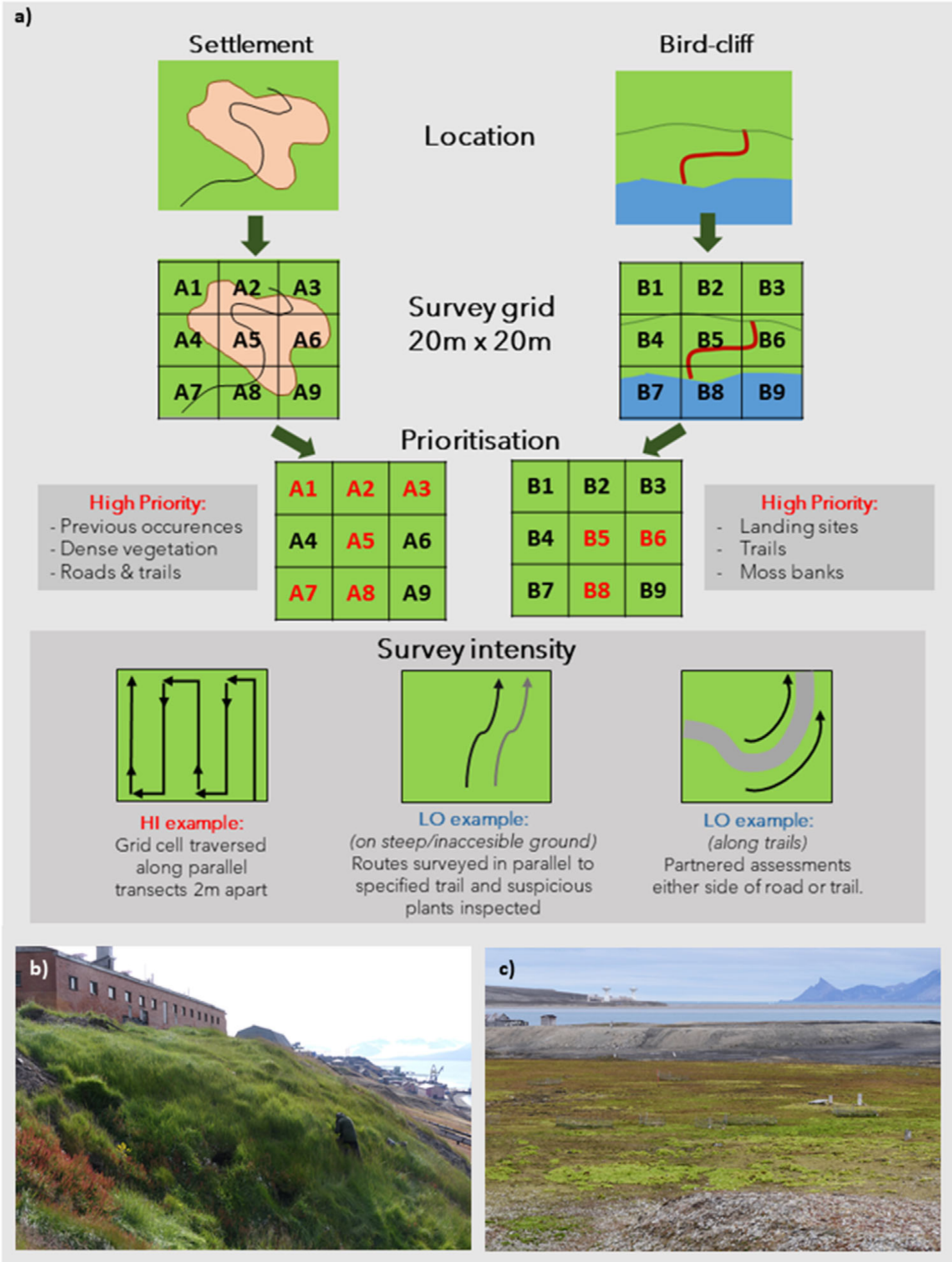

FIGURE 2 (a) Survey methodology, where the lines for 'Location' graphics are as follows: black, roads; red, trails from boat landing sites; green, contour lines (i.e. cliff). When a grid is laid over, these trails and so forth become high-priority (HI) sites (red text), with all other cells surveyed with the 'LO' methodology (black text). Examples of the survey intensity options are shown. (b) Example of dense vegetation requiring high-intensity surveying (Barentsburg: photo KB Westergaard). (c) Example of open vegetation where low-intensity surveying is appropriate (Ny-Ålesund: photo KB Westergaard)

(immediately around settlements, and bird cliffs), a grid with 20 m × 20 m cells (pixel) was created over each study area using ArcMap 10.4.1 (ArcGIS® software by Esri). Each pixel was assigned a unique identification code to ensure reproducibility and quality control throughout data analyses. Due to the geographical scale of the task, survey pixels were pre-classified, through literature reviews and previous observations, into either 'high-intensity' (HI) or 'low-intensity' (LO) surveys (Figures 2, S1a & S1b). One person was engaged for a month to assess previous data for the selection of 'HI vs. LO' sites. Cells that also included boat landing sites, 'town' centres, roads or trails, and thus high levels of ground disturbance and/or human activity (e.g. Lembrechts et al., 2016), were also given HI treatments. HI treatments were also applied to areas of dense vegetation (Figure 2b), or nutrient-rich moss banks under bird cliffs. Figure 2 shows examples of hypothetical surveying in and around settlements, and bird cliffs.

HI pixels were staked at the corners and surveyed in 2-m parallel lines, to ensure that transects were evenly traversed (Figure 2a). For LO pixels, routes were walked along paths, roads or around areas of known

TABLE 1 Methods of recording abundance of individual alien plant species within a 20 m × 20 m pixel, for the 2017 surveys. Differing methods used given the variety in abundance and growth forms between plant species

Species	Recording abundance method	Reasoning
Achillea millefolium; *Ranunculus repens*	Number of patches, patch diameter (m)	Individual plants are indiscrete: *Achillea millefolium* conjugates into turfs through rhizomatous shoots. *Ranunculus repens* distributes through prostate running stems creating mats.
Festuca rubra	Percent cover of pixel in 25% increments	Forms lawns
Taraxacum spp.	<50 = individual plants counted >50 = individual plants estimated	High abundance
All other species	Individual plants counted	Discrete/low abundance species

occurrences in order to obtain a good overview of each pixel. In both cases, the presence or absence of alien vascular plant species within each pixel was noted and the routes walked and recorded using GPS tracking. Observer GPS track and occurrence data were stored and overlaid on all surveyed pixels. Alien vascular plant species in a pixel were identified and abundance of individual plants recorded, with the exception of highly abundant or carpet forming species where a timely identification of individual plants was not possible. In these instances, a classification system with differing systems of either cover or individual plant number was made, depending on the species characteristics (see Table 1). Where identification of species in situ was not possible, herbarium samples were taken for formal identification to the Arctic University Museum of Norway.

2.3 | Evaluation of survey methods in previous studies

To critically evaluate survey methodologies, all literature relevant to the occurrence of alien vascular plant species on Svalbard over the last century was reviewed. Particular attention was given to the methods used, and locations surveyed. Our literature review included published peer-reviewed original papers and review papers, as well as grey literature. A total of 15 such manuscripts were reviewed spanning 1941–2018 (Table 2). Due to methodological inconsistencies between these surveys, we avoided direct analysis of abundance change but rather present what species have abundance data. Information was also taken from the two most comprehensive reviews on Svalbard in the decade prior to this study: the 'Alien species list 2012' inventory for Norway (Gederaas et al., 2012) and Alsos et al. (2015).

2.4 | Pilot test of UAVs as a survey tool

UAV data have been successfully used to map invasive alien plant species in study areas located outside polar regions (see review by Dash et al., 2019). During the summer of 2019, a UAV survey was carried out in an area of high-density invasive alien plant species in Barentsburg, in order to assess the suitability of UAV technology for mapping and monitoring their spread in polar regions. UAV-based imagery (RGB: red–green–blue photographs for photogrammetry) that meets the demands of the 'HI' monitoring to detect individuals of selected plant species and multi-spectral images for plant activity mappings were taken that cover landscape variation (surface reflectance images of specific wavelengths to assess light absorption characteristics of plants that relate to leaf chlorophyll content; Curran et al., 1990; Filella et al., 1995). The UAV photogrammetry setup consisted of a commercial camera (Alpha 6000, Sony, Japan) with a wide angle lens (12 mm APS-C–19.2 mm relative full frame; Touit 2.8/12, Zeiss, Germany) that is linked to a global navigation satellite system for high-accuracy image georeferencing (Zhang et al., 2019). The RGB photogrammetry measurements were carried out at 3–5 m flight altitude for high resolution (0.25 ha plot scale, 1-mm resolution) that allow for a visual plant species classification. The multi-spectral imagery (RedEdge MX, MicaSense, USA) was taken at a flight altitude of 30–40 m and consists of five wavelength bands from visible up to near infrared (NIR; wavelength range 475–840 nm). NDVI (normalized difference vegetation index; Rouse et al., 1974) was calculated based on the red and NIR band of the multi-spectral UAV data. The NDVI-based plant activity maps were then compared to ground mappings of *Festuca rubra* carried out simultaneously to the UAV surveys.

3 | RESULTS

3.1 | Status in settlements and high-risk natural habitats

A total of 4260 pixels were surveyed, covering an area of over 1.7 km^2 between the nine sites. The 36 alien vascular plant species were found only within the settlements of Barentsburg, Pyramiden and Ny-Ålesund (Figure 1), and were present in 12% of all surveyed pixels. Pyramiden had 20 species within 27% of pixels surveyed, with a maximum of five species in any one (Figures 3a and S3). Barentsburg was the most diverse site, with 22 alien vascular plant species, 32% of all pixels with alien species presence and a maximum of eight species in any one (Figures 3b and S2). And Ny-Ålesund had three alien vascular plant species, occurring one per pixel, within 0.8% of pixels (Figures 3c and S4). Some areas could not be mapped due to topography (too steep), contamination (open sewage system, Ny-Ålesund) or restrictions due

TABLE 2 Review of all publications concerning Svalbard's flora that have included reports on alien vascular plant species

Author	Location	Year	Survey method	Peer Rev.
Hadac, 1941	Bellsund, Longyearbyen, Hotellneset, Kapp Smith, Kapp Thordsen, Ny-Ålesund, Nordjysten, Wijdefjorden, Lågøya and Trygghamna	1941	Incidental observations	Y
Sunding, 1961	Longyearbyen and Ny Ålesund	1960	Incidental observations	Y
Engelskjøn, 1986	Bjørnøya	1967 & 1983	35 m transect and incidental observations	Y
Liska & Soldán, 2004	Barentsburg and Pyramiden	1988	Not stated – assumed to be incidental observations	Y
Rønning, 1996	All Svalbard	N/A	Literature reviews and incidental observations – does not describe distributions	Y
Rønning, 1964	All Svalbard	1952–1961	Literature reviews and incidental observations – does not describe distributions	Y
Elven & Elvebakk, 1996	All Svalbard	N/A	Literature review and evaluation of unpublished reports and notes	Y
Hagen & Prestø, 2007	Longyearbyen	2007	Literature review and key areas of biological importance identified in incidental observations (for planning reasons – commission by local council)	N (Research report, Norwegian Institute for Nature Research
Alsos et al., 2015	Longyearbyen, Barentsburg and Pyramiden, Advent city and Hiorthhamn plus 17 stations and lit review of all Svalbard – 77 sites	2007–2013	Literature review and 2–6 h long surveys – no specifics given	Y
Roalsø, 2012	Longyearbyen and Barentsburg	2012	25 transects (20 m) established in seven sites based on records of alien plant species. Transects start in the centre of the source of introduction. 1 m quadrats established every 5 m. Supplementary random recordings also made when plants found on non-transect incidental observations	N (MSc thesis)
Gederaas et al., 2012	All Svalbard	2012	Literature review	Y
Belkina et al., 2013	Pyramiden	2013	Various quadrats (but also not always square). 2 m for low veg; 4 m for tall veg; 10 m for spp. poor anthropogenic vegetation or scattered plants. % cover of species recorded and Braun-Blanquet scale used. Sites classified into 14 different habitat types.	N (Research report, Russian Academy of Sciences)
Thomassen et al., 2017	Arctic	2017	Literature review	N (Research report, Norwegian Institute for Nature Research)
Arnesen et al., 2016	Longyearbyen	2016	Transects along roads, and visits to 'hotspots' of dog yards, the stable, airport, etc.	N (Biological survey by consultancy 'Ecofact' for local government)
Artsdatabanken, 2018	All Svalbard	2018	Literature review	Y

Note: Table details the locations, survey year and survey method, where these are stated. It is noted whether the publication was published in a peer-reviewed journal (Peer Rev.) or was part of an internal or government report or thesis that was not subject to peer review.

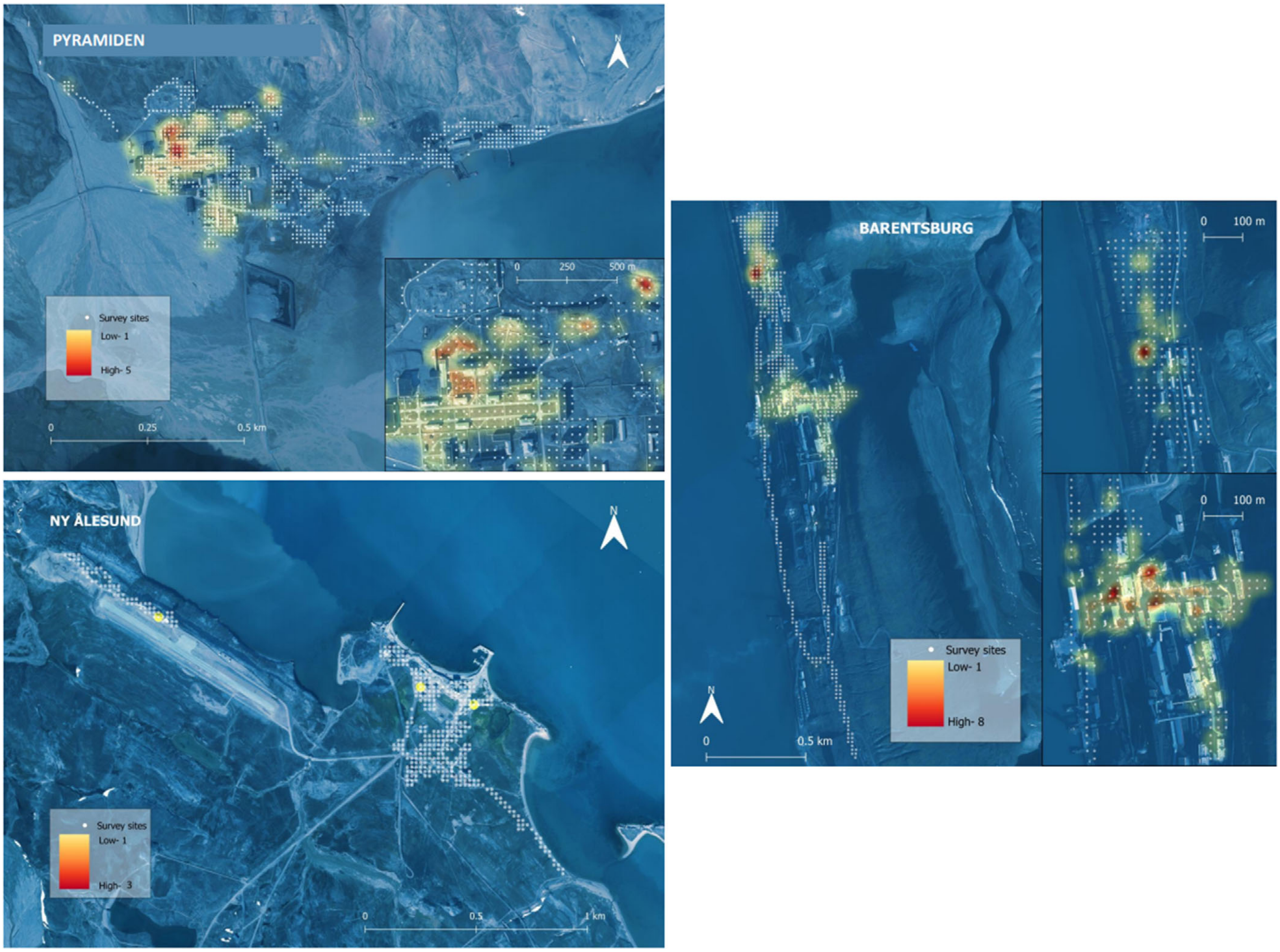

FIGURE 3 Number of alien plant species per pixel (grid cell) within sites. (a) Pyramiden, maximum species per pixel = 5. (b) Barentsburg, maximum number of species per pixel = 8. (c) Ny-Ålesund, maximum species per pixel = 1

to construction. Full details of sampling effort, and distribution and abundance of individual species in the settlements (including Longyearbyen, after Arnesen et al., 2016), can be found in Supporting Information S1–S5. The surveys showed that *Taraxacum* sect. *Ruderalia* was an order of magnitude more abundant than *Poa pratense*, *Festuca rubra*, *Achillea millefolium* and *Barbarea vulgaris* that were the next most abundant species, respectively (Supporting Information S6). Four species were noted to be sexually reproductive: *Achillea millefolium*, *Barbarea vulgaris*, *Alchemilla subcrenata* and *Tripleurospermum maritimum*, (Supporting Information S6); however, it was not in the routine to consistently check for reproductive status. A full list of species found and location is shown in Table S6.

Six bird cliffs (2158 pixels) were successfully surveyed, and no alien vascular plant species were found at any of the sites. The number of surveyed pixels ranged from 134 at Ossian Sarsfjellet to 1106 at Alkhornet reflecting the size of the bird cliffs and to some degree accessibility on site.

3.2 | Evaluation of survey methods in previous studies

Our literature review of all papers and reports on alien vascular plant species in Svalbard since 1941 found no repeated studies that involved systematic monitoring (Table 2). Furthermore, we found that many studies had no standardized surveying protocol or scientific methodology: Out of the 15 manuscripts and databases evaluated, only four involved some element of in-field systematic survey methodologies, of which three are unpublished or not peer-reviewed. Of the 11 that do not have any level of systematic surveying, five are incidental observations where plants are recorded as and when they are found, and six are literature reviews. Thus, 40% of all literature on Svalbard alien vascular plant species are reviews of prior literature. We found only one peer reviewed publication that used systematic survey methodologies (Belkina et al., 2013), and most studies were focussed on the easily accessible settlements of Longyearbyen and Barentsburg (Table 2).

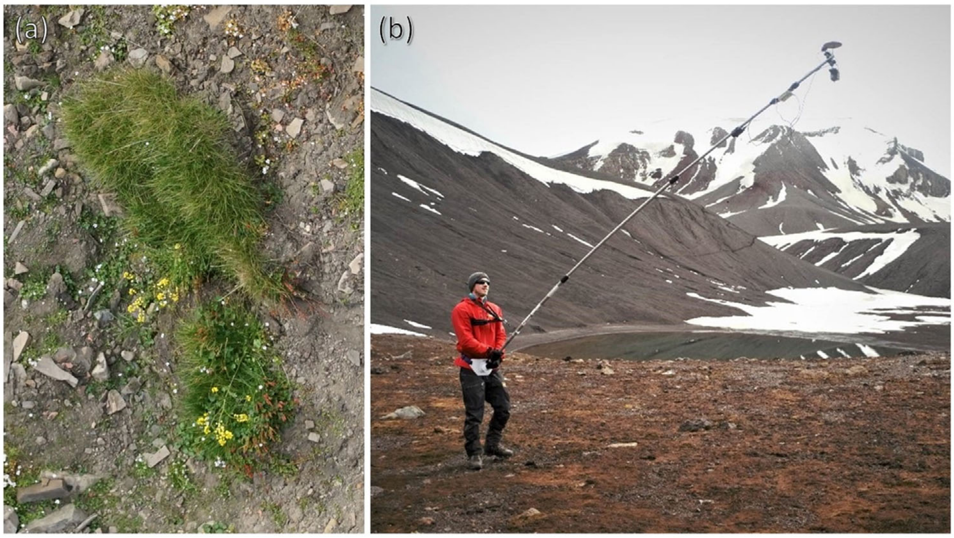

FIGURE 4 (a) Barbarea vulgaris in Barentsburg in 2019, as viewed from 4 m above ground altitude as an example for the HI photogrammetry resolution (photo: F. Wilken). (b) Example of the suggested manual photogrammetry set up (photo: D. Wasner)

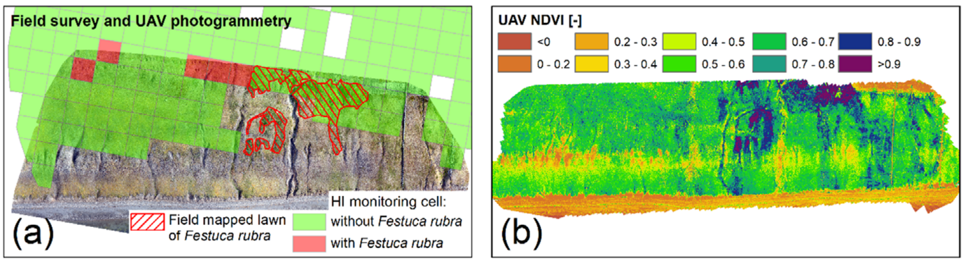

FIGURE 5 (a) UAV photogrammetry and corresponding high-intensity (HI) field mappings of Festuca rubra (20 m × 20 m spatial resolution and detailed delineation, acquisition time summer 2017 and 2019, respectively). (b) UAV NDVI vegetation activity (2 cm × 2 cm resolution; acquisition date 3 August 2019) based on multi-spectral imagery

3.3 | Test of UAVs as a survey tool

The test flights showed that the HI proximal sensed photogrammetry data can be interpreted against the background of local knowledge on potential plant species. Individual plants with larger flowers (minimum diameter ca. 1 cm), or unique colour or shape (Figure 4a), which is the case for some of the alien plant species (e.g. *Achillea millefolium*, *Alchemilla subcrenata*, *Barbarea vulgaris* and *Ranunculus repens*) and native species (e.g., *Bistorta vivipara*, *Carex rupestris*, *Cerastium arcticum*, *Oxyria digyna*, *Salix polaris* and *Saxifraga cernua*) can be detected. Using a photogrammetry setup, which would normally be UAV mounted, on a belt and telescopic pole system instead means that the data acquisition can be simultaneously carried out during the HI field survey (Figure 4b). The HI photogrammetry images were fused to a precisely georeferenced orthophoto (georeferencing error <10 cm) that enables an accurate spread documenting alien plant species.

The multi-spectral UAV data indicated distinct plant productivity patterns at the study site that also reflected in a large NDVI range from approximately 0.4 up to 0.95. At the animal husbandry site in Barentsburg, the highly abundant/lawn-forming species *Festuca rubra* showed distinctively higher productivity compared to native plant communities at that site (Figure 5a). These *Festuca rubra* lawns did show a strong connection between the spatial patterns of high-NDVI areas and the detailed *Festuca rubra* HI mapping (Figure 5b).

4 | DISCUSSION

The present study is among the most comprehensive surveys of alien plants in the Arctic to date, and represents a new baseline for future monitoring that can inform environmental impact assessments and management action. Answering the call from the Conservation of Arctic Flora and Fauna's (CAFF) working group CBMP (Christensen et al., 2013) and 'ARIAS' (CAFF-PAME, 2017), we present a successfully implemented survey methodology for alien vascular plant monitoring in Svalbard, and its potential to form part of an adaptive monitoring strategy anchored in existing national, and regional strategies in

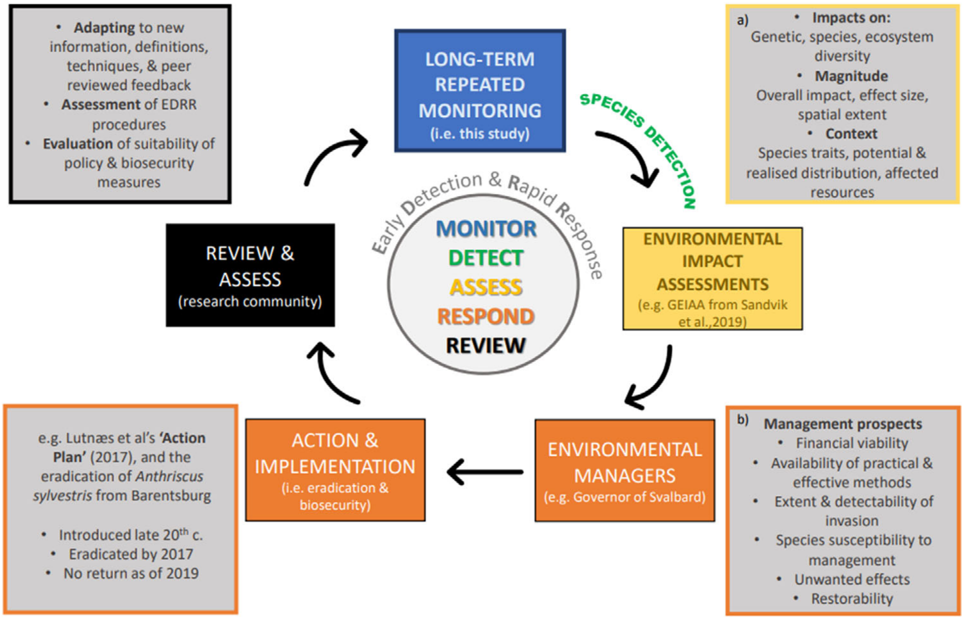

FIGURE 6 The recommended Early Detection and Rapid Response flow for an adaptive monitoring strategy, with examples from Svalbard. Box (a) and box (b) follow suggestions after Bartz and Kowarik (2019)

Norway (Elven & Westergaard 2018a, 2018b; Lutnæs et al., 2017; Sandvik et al., 2019) (Figure 6). The suggested monitoring methodology is not exclusive to Svalbard, and can be adapted to any polar or tundra area to monitor the presence and dynamics of alien vascular plant species. The finding of a severe lack of systematic methods or method descriptions in previous surveys highlights the urgency to develop a transparent and repeatable methodology.

4.1 | Status in settlements and high-risk natural habitats

We find that alien plant species are currently found only in settlements, have not spread to high-risk natural habitats and that they have a strong association to sites of historical animal husbandry, supporting the findings of previous surveys of both non-native plants (e.g. Alsos et al., 2015) and invertebrates (Coulson et al., 2013). Although our field surveys did not reveal alien plant species in the six surveyed bird cliffs, increasing propagule pressure through human activities combined with human disturbance and a warming climate means that alien plants may expand their current distribution ranges in the future, and they will require continued monitoring in order to ensure early detection and enable a rapid response (EDRR) (Lembrechts et al., 2016; Myers-Smith et al., 2020). Figure 3 highlights the association of alien vascular plant species with human activities: Pixels with greater numbers of alien plants are also sites of high human impact, including cells in and around areas of previous animal husbandry, such as in Barentsburg (Figures 3b and 4, and also S2). Typically, sites of disturbance are the prime locations in cold regions for alien plant species to establish in, with ground disturbance being the main predictor of plant invader success over access to higher nutrients, propagule input, temperature, etc. (Lembrechts et al., 2016). Disturbed ground reduces competition with native species that are typically slower growing in polar environments, and often suppressed at seedling stage by disturbance, allowing fast-growing 'weed' species to gain rapid advantage (e.g. Kaarlejärvi & Olofsson, 2014). Furthermore, where there is increased nutrient availability as well as disturbance, invasion success is even greater, such as is found in this study, as well as in alpine regions further south (i.e. Lembrechts et al., 2016).

We find that the systematic eradication efforts from 2013 to 2016 to remove *Anthriscus sylvestris* from Barentsburg have been successful. This species was not re-found in our 2017 survey, nor observed in 2018, 2019 or 2020 (V. Ravolainen, K. Westergaard, I. Paulsen, personal observations). Compared to previous reports, we find a lower occurrence of *Tripleurospermum maritimum* as a result of declines in Pyramiden, and the species was not re-found after a targeted search in 2019 (K. Westergaard, personal observations). *Achillea millefolium* seems to have increased, particularly in Barentsburg where it was found in association with former animal husbandry sites, and frequented paths through the settlement. Whilst *Poa annua* has previously been reported repeatedly from Barentsburg, it was not re-found in our field-survey. Also, in Barentsburg, *P. pratense* was reported instead of *P. annua*, and a report of alien species occurrence in Longyearbyen mentions only *P. trivialis*, and neither *P. pratense* nor *P. annua* (Arnesen et al., 2016). Thus, we question the validity of previous species identifications, and highlight the need for an updated species identification key for future works, and recommend the retention of non-native species materials as herbarium specimens for future reference. The variance in different earlier surveying methodologies means that the data are not entirely comparative. Rather, it is indicative of broad changes and again reinforces the need for repeatable surveys and a standardized methodology that can be statistically evaluated.

Horizon scanning efforts go some way to pre-identify 'door-knocker species' that are at risk of invading (see Peyton et al., 2019; Roy et al., 2014, 2019), but without monitoring data they risk being reduced to thought exercises. Horizon scanning and pathway analysis for invasive species to Svalbard have been undertaken in the past through NOBANIS (NOBANIS, 2009), and more recently by Elven and Westergaard (2018b) who found that of 19 plant species risk assessed, 14 were already reproducing in Svalbard, whilst another five were considered door-knocker species. We have found two such species in this survey: *Tripleurospermum maritimum* and *Ranunculus repens*. All other species found were previously recorded, leaving just three remaining door-knocker species yet to be found in Svalbard (*Capsella bursa-pastoris*, *Lepidotheca suaveolens*, and *Ranunculus subborealis* subsp. *villosus*).

4.2 | Evaluation of previous survey methods

The review of previous works found that prior studies lack 'in-field' assessments, with little or no systematic surveying techniques deployed throughout the 15 studies evaluated. Where a scientific method has been used, the work has tended not to be peer-reviewed (Table 2). Thus, whilst on the surface there appears to be a body of work on alien vascular plant occurrences in Svalbard, it is biased towards literature reviews and database compilations that are based on a handful of studies, all with incomparable results and potentially inaccurate species identification. Efforts to date have largely relied on informal and unstructured surveys that do not record absence, and are broadly unrepeatable. This highlights the need to clearly define the spatiotemporal changes in alien vascular plants in Svalbard, and that a systematic monitoring protocol needs to be established in order to fully grasp the status and ongoing threat to Svalbard's ecosystems. Although there are limited systematically collected data on alien species in Svalbard, it is still considered to be one of the best understood Arctic areas in terms of baseline native biodiversity, and therefore makes an excellent case study for the monitoring of invasions.

4.3 | Supplementary aerial surveying for landscape level spatial–temporal change

We propose future testing of the feasibility of using UAVs with sensors to monitor and identify new potential hotspots of alien plant invasions, as part of future mapping efforts in Svalbard and to supplement ground surveys through, for instance, the following two approaches:

(i) HI mapping using photogrammetry for documentation and visual detection of single alien plants: Our provisional results from field trials find that individual alien plants can be identified and included in a fully georeferenced orthophoto through proximal sensed photogrammetry (3–4 m above ground altitude). Such a dataset could be visually interpreted or automatically classified as demonstrated by Pflanz et al. (2018). Using the belt and telescopic pole system combines a high-resolution orthophoto, with the HI ground-based field survey, which can be repeated each survey season. With a spatial overlap precision of approximately 10 cm, and used in conjunction with the grid system presented in this study to provide comprehensive surveying from both the ground and above, this method shall be of particular use as supporting data that bridge the gap between 20 m^2 HI ground survey and plant-level monitoring.

(ii) Landscape plant activity mapping to detect potential habitats for invasive alien plant species: Multi-spectral sensors can be used to derive straightforward plant information including activity indices (e.g. NDVI). Hence, for lawn-forming alien species, plant productivity UAV surveys can help to identify potential alien plant species habitats in remote, dangerous or hard to access regions. The area covered by the alien lawn-forming plants can correlate well with high plant activity areas (e.g. Figure 5b). It remains to be systematically tested whether abundant/lawn-forming, alien high-productivity species can be readily distinguished from the most productive native vegetation such as that under bird cliffs. The use of parsimonious plant productivity indices or more complex supervized plant classification algorithms (e.g. Alexandridis et al., 2017; Dvořák et al., 2015) might have a great potential to increase the efficiency to monitor alien plant species in polar regions.

5 | SUGGESTED METHODOLOGY FOR LONG-TERM MONITORING

5.1 | Ground surveying for species identification, abundance and distribution

Any alien species monitoring regime must identify both 'hotspots' of alien species' activity as well as early detection of new ones, and in Figure 6 we present the 'gold standard' of such a regime: It must be able to track the (re-)introduction of species through an understanding of pathways, and identify transient or 'door-knocker' species that may be able to establish. The programme should identify alien species with a potentially high ecological impact on the native ecosystem ('risky' species), and include reporting on the reproductive viability of all alien species (after CAFF-PAME, 2017). The goal of such a monitoring programme is to inform environmental management plans, as well as users of the area. Therefore, during surveys, notes should be taken on the site and habitat of species occurrence, species identification reasoning and its reproductive status. Furthermore, in order to establish the impacts of alien plants, time should be given to the assessment of overall native flora cover and diversity (Rooney et al., 2004). The highest standard of alien species monitoring includes EDRR, which would require systematic annual surveys of risk areas, enabling prompt action where necessary (Reaser et al., 2020). An EDRR programme would feed into a formal 5-year monitoring regime for 'general ecological impact assessments of alien species' (GEIAA), which is already established for Norway, and is internationally recognized as the highest replicable method for assessing alien species (see González-Moreno et al., 2019; Sandvik et al., 2019; Figure 6). Our recommendation for a scientific monitoring strategy of alien plant species in Svalbard is to conduct the standard surveys as presented here on alien species occurrence every 3 years, with a more detailed survey of habitat type, native species cover and reproductive viability, conducted every other survey season to feed into the GEIAA. Personnel and resources are typically limited for such monitoring programmes, particularly in remote places, but as raised recently by Reaser et al. (2020), governmental departments and their partners need to overcome 'substantial conceptual, institutional and operational challenges', if they are to sufficiently tackle the issues of alien species. Identifying an appropriate scale of resolution is essential in evaluating the abundance and distribution of alien plant species, and prioritisation of key areas for likely occurrence and/or management intervention (Foxcroft et al., 2009). We found that it is not feasible to conduct uniform HI surveys; the geographic scale of the task would make this extremely resource demanding and would likely not lead to improved results. Therefore, we recommend that the 'HI, LO' method reflects the best option to cover the largest area in an efficient manner and that for tundra environments, the 20 m × 20 m grid used in this study is a workable pixel size and compatible with UAV surveying. As there is a large disparity in the abundance of some species, a dual classification is necessary. We suggest to start off by using an individual plant count for low-density species (<100/pixel), and percentage cover for high-density species (>100/pixel) such as *Festuca rubra* and *Taraxacum* sect. *Ruderalia*, and patch forming species such as *Ranunculus repens*, with new species assigned to an appropriate count method at first sighting. Abundance quantifications in plant surveys pose a particular challenge with plants of varying sizes and growth forms, and we recommend to conduct a test of observer bias and plant detectability during the early years of a monitoring program.

As we have only surveyed the most visited of the bird cliff/landing sites, and an exhaustive survey of all 180 landing sites outside of the settlements would be unfeasible, utilizing citizen-science programmes for the monitoring of plant establishments could be beneficial in future. Guides and the visitors to these places (largely cruise passengers) could be equipped with identification guides and opportunistic surveys conducted upon landing. Citizen-science programmes using cruise passengers have been successful in polar regions already (see www.polar-latitudes.com/citizen-science/), whilst citizen-science for IAS surveying has already contributed to many scientific discoveries and over 30 publications (Johnson et al., 2020). Moreover, the Governor of Svalbard employs summer field inspectors who ensure that environmental legislation is followed, and who could record incidental findings of alien plants. The Governor of Svalbard is currently working on information material for such use.

As part of a long-term ecological study in Wisconsin, USA, a monitoring survey of alien plant invasions was conducted 50 years after the original baseline survey (Rooney et al., 2004). This was possible because of the archiving of original raw data, allowing a repeat of the work which revealed declines in native species richness over the 50-year period and is being developed further to continue tracking invasions (Rooney et al., 2004). Regular monitoring has also proven to be practicable in more remote, polar regions, with a recent annual monitoring programme on the Antarctic South Shetland islands enabling the identification of several new alien invertebrate species (Enríquez et al., 2019) and an increasing trend of alien species introductions. As part of its annual activities, The Norwegian Polar Institute is now including efforts to re-survey the settlements and selected bird cliffs, to provide a basic monitoring to which additional elements can be added.

International initiatives such as the Global Biodiversity Information Facility (www.gbif.org) and the 'DAISIE' inventory of alien invasive species in Europe (www.europe-aliens.org) have proven to be invaluable at providing a platform for information on the temporal-spatial data for IAS, meaning that smaller geographical studies can now fit into a wider pattern of IAS occurrence and their pathways to introduction (e.g. Gallardo et al., 2016; Saul et al., 2016). The work presented here offers an opportunity to initiate a regular systematic regime for monitoring alien species so that such information can be reported for the Arctic, and that early detection of establishing species can be managed in a timely way, thereby minimizing the impacts on these fragile ecosystems.

ACKNOWLEDGEMENTS

This survey was carried out under the project 'Alien plant species – from settlements to nature?' Research in Svalbard ID 10749 (funded by Svalbard Environmental Protection Fund project 17/50, The Governor of Svalbard and The Ministry of Climate and Environment/The Norwegian Polar Institute). Permits to survey and sample were approved by The Governor of Svalbard (Permit Numbers: 17/00784-4 to V.R.). We thank Isabell Eischeid for help in preparing the sampling design and process field data, Torbjørn Alm, from The Arctic University Museum of Norway with assistance in identifying herbarium samples, and field assistants Hanna Boehner, Elke Morgner and Martin Kristiansen. Thank you to the editor and anonymous reviewers who have helped to improve this manuscript.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHORS' CONTRIBUTIONS

V.R. was tasked to conduct the surveys, sourced funding and designed the survey and methodology with R.W. and I.P. V.R., R.W. and I.P. conducted the surveys with field assistants. I.P. compiled the raw data. K.B.W. and F.W. conducted the 2019 UAV field tests. F.W. analyzed and visualized the UAV data. K.B.W. and V.R. conceptualized the manuscript. J.B. analyzed the 2017 survey data, conducted the meta-review and led the writing. J.B., K.B.W. and V.R. interpreted the data and drafted the manuscript. All authors contributed to the draft reviews, and final manuscript preparation.

DATA AVAILABILITY STATEMENT

Data available from the Dryad Digital Repository: https://doi.org/10.5061/dryad.djh9w0vzz (Bartlett, Westergaard, et al., 2021).

PEER REVIEW

The peer review history for this article is available at https://publons.com/publon/10.1002/2688-8319.12056.

ORCID

Jesamine C. Bartlett https://orcid.org/0000-0001-7464-5440

REFERENCES

Alexandridis, T., Tamouridou, A. A., Pantazi, X. E., Lagopodi, A., Kashefi, J., Ovakoglou, G., Polychronos, V., & Moshou, D. (2017). Novelty detection classifiers in weed mapping: *Silybum marianum* detection on UAV multispectral images. *Sensors*, *17*(9), 2007. https://doi.org/10.3390/s17092007

Alsos, I. G., Ehrich, D., Seidenkrantz, M.-S., Bennike, O., Kirchhefer, A. J., & Geirsdottir, A. (2016). The role of sea ice for vascular plant dispersal in the Arctic. *Biology Letters*, *12*, 20160264. https://doi.org/10.1098/rsbl.2016.0264

Alsos, I. G., Ware, C., & Elven, R. (2015). Past Arctic aliens have passed away, current ones may stay. *Biological Invasions*, *17*, 3113–3123. https://doi.org/10.1007/s10530-015-0937-9

Arnesen, G., Johansen, K. S., Haugland, Ø., & Sommersel, G. A. (2016). *Fremmede karplanter i Longyearbyenområdet*. Ecofact rapport 536. 16 s

Artsdatabanken. (2018). *Fremmedeartsliste 2018*. https://www.artsdatabanken.no/fremmedartslista2018

Bartlett, J. C., Westergaard, K. B., Paulsen, I. M. G., Wedegärtner, R. E. M., Wilken, F., & Ravolainen, V. (2021). Data from: Moving out of town? The status of alien plants in high-Arctic Svalbard, and a method for monitoring of alien flora in high-risk, polar environments. *Dryad Digital Repository*. https://doi.org/10.5061/dryad.djh9w0vzz

Bartlett, J. C., Radcliffe, R. J., Convey, P., Hughes, K. A., & Hayward, S. A. L. (2021). The effectiveness of Virkon® S disinfectant against an invasive insect and implications for Antarctic biosecurity practices. *Antarctic Science*, *33*(1), 1–9. https://doi.org/10.1017/S0954102020000413

Bartz, R., & Kowarik, I. (2019). Assessing the environmental impacts of invasive alien plants: a review of assessment approaches. *NeoBiota*, *43*, 69–99. https://doi.org/10.3897/neobiota.43.30122.

Belkina, O., Borovichev, E., Davydov, D., Konoreva, L., Likhachev, A., Petrova, O., & Savchenko, A. (2013). *Study of flora and vegetation in the settlement of Pyramiden and the surroundings*. Research report 30/07-2013. Russian Academy of Sciences N.A. Avrorin Polar-Alpine Botanical Garden Institute.

Benediktsson, K. (2015). Floral hazards: Nootka lupin in iceland and the complex politics of invasive life. *Geografiska Annaler: Series B, Human Geography*, *97*, 139–154. https://doi.org/10.1111/geob.12070

CAFF and PAME. (2017). *Arctic Invasive Alien Species (ARIAS): Strategy and action plan*. Akureyri, Iceland: CAFF. https://www.caff.is/strategies-series/415-arctic-invasive-alien-species-strategy-and-action-plan

Christensen, T., Payne, J., Doyle, M., Ibarguchi, G., Taylor, J., Schmidt, N. M., Gill, M., Svoboda, M., Aronsson, M., Behe, C., Buddle, C., Cuyler, C., Fosaa, A. M., Fox, A. D., Heidmarsson, S., Henning, P. K., Madsen, J., McLennan, D., Nymand, J., … Wedege, M. (2013). *The arctic terrestrial biodiversity monitoring plan*. Akureyri, Iceland: CAFF International Secretariat.

Coulson, S. J., Fjellberg, A., Gwiazdowicz, D. J., Lebedeva, N. V., Melekhina, E. N., Solhøy, T., Erséus, C., Maraldo, K., Miko, L., Schatz, H., Schmelz, R. M., Søli, G., & Stur, E. (2013). Introduction of invertebrates into the High Arctic via imported soils: The case of Barentsburg in the Svalbard. *Biological Invasions*, *15*, 1–5. https://doi.org/10.1007/s10530-012-0277-y

Curran, P. J., Dungan, J. L., & Gholz, H. L. (1990). Exploring the relationship between reflectance red edge and chlorophyll content in slash pine. *Tree Physiology*, *7*, 33–48. https://doi.org/10.1093/treephys/7.1-2-3-4.33

Dash, J. P., Watt, M. S., Paul, T. S. H., Morgenroth, J., & Hartley, R. (2019). Taking a closer look at invasive alien plant research: A review of the current state, opportunities, and future direction for UAVs. *Methods in Ecology and Evolution*, *10*, 2020–2033. https://doi.org/10.1111/2041-210X.13296

Dvořák, P., Müllerová, J., Bartaloš, T., & Brůna, J. (2015). Unmanned aerial vehicles for alien plant species detection and monitoring. *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XL-1/W4*, 83–90. https://doi.org/10.5194/isprsarchives-XL-1-W4-83-2015

Ebbert, S. E., & Byrd, G. V. (2002). Eradications of invasive species to restore natural biological diversity on Alaska Maritime National Wildlife Refuge 8. In C. R. Veitch & M. N. Clout (Eds.), *Turning the tide: The eradication of invasive species* (pp 102–109). Gland, Switzerland: IUCN. https://www.researchgate.net/publication/268415333_Eradications_of_invasive_species_to_restore_natural_biological_diversity_on_Alaska_Maritime_National_Wildlife_Refuge

Eeg-Henriksen, F., & Sjømæling, E. (2016). *This is Svalbard*. Oslo, Norway: Statistics Norway.

Elvebakk, A. (1989). *Biogeographical zones of Svalbard and adjacent areas based on botanical criteria* (PhD thesis). University of Tromsø, Tromsø, Norway.

Elven, R., & Elvebakk, A. (1996). A catalogue of Svalbard plants, fungi, algae, and cyanobacteria. Part 1. Vascular plants. *Norsk Polarinstituttt, Skrifter*, *198*, 9–55

Elven, R., & Westergaard, K. B. (2018a). Anthriscus sylvestris, *assessment of ecological risk*. Alien species list 2018. Artsdatabanken. https://artsdatabanken.no/fremmedarter/2018/S/71

Elven, R., & Westergaard, K. B. (2018b). *Assessment of ecological risk of 19 alien vascular plants in Svalbard*. Alien species list 2018. Artsdatabanken. https://artsdatabanken.no/fremmedartslista2018

Engelskjøn, T. (1986). Eco-geographical relations of the Bjørnøya vascular flora, Svalbard. *Polar Research*, *5*, 79–127

Enríquez, N., Pertierra, L. R., Tejedo, P., Benayas, J., Greenslade, P., & Luciáñez, M. J. (2019). The importance of long-term surveys on species introductions in Maritime Antarctica: First detection of *Ceratophysella succinea* (Collembola: Hypogastruridae). *Polar Biology*, *42*, 1047–1051. https://doi.org/10.1007/s00300-019-02490-8

Foxcroft, L. C., Richardson, D. M., Rouget, M., & MacFadyen, S. (2009). Patterns of alien plant distribution at multiple spatial scales in a large national park: Implications for ecology, management and monitoring. *Diversity and Distributions*, *15*, 367–378. https://doi.org/10.1111/j.1472-4642.2008.00544.x

Frenot, Y., Chown, S. L., Whinam, J., Selkirk, P. M., Convey, P., Skotnicki, M., & Bergstrom, D. M. (2005). Biological invasions in the Antarctic: Extent, impacts and implications. *Biological Reviews*, *80*, 45–72. https://doi.org/10.1017/S1464793104006542

Filella, I., Serrano, I., Serra, J., & Peñuelas, J. (1995). Evaluating wheat nitrogen status with canopy reflectance indices and discriminant analysis. *Crop Science*, *3*, 1400–1405. https://doi.org/10.2135/cropsci1995.0011183X003500050023x

Gallardo, B., Zieritz, A., Adriaens, T., Bellard, C., Boets, P., Britton, J. R., Newman, J. R., van Valkenburg, J. L. C. H., & Aldrifge, D. C. (2016). Transnational horizon scanning for invasive non-native species: A case study in western Europe. *Biological Invasions*, *18*, 17–30. https://doi.org/10.1007/s10530-015-0986-0

Gederaas, L., Moen, T. L., Skjelseth, S., & Larsen, L. K. (Eds.). (2012). *Fremmede arter i Norge – med norsk svarteliste*. Trondheim, Norway: Artsdatabanken. https://www.artsdatabanken.no/Pages/201622/Fremmede_arter_i_Norge_

González-Moreno, P., Lazzaro, L., Vilà, M., Preda, C., Adriaens, T., Bacher, S., Brundu, G., Copp, G. H., Essl, F., García-Berthou, E., Katsanevakis, S., Moen, T. L., Lucy, F. E., Nentwig, W., Roy, H. E., Srėbalienė, G., Talgø, V., Vanderhoeven, S., Andjelković, A., … Arbačiauskas, K. (2019). Consistency of impact assessment protocols for non-native species. *NeoBiota*, *44*, 1–25. https://doi.org/10.3897/neobiota.44.31650

Gyllencreutz, R. (1884). En trädgårdsanlägging på Spetsbergen. *(Horticulture in Spitsvergen) Svenska trädgårdsföreningens tidskrift*, *6*, 8–11

Hadač, E. (1941). The introduced flora of Spitsbergen. *Medd. Norges Svalbard Ishavsunders*, *49*, 13–16.

Hadač, E. (1944). The vascular plants of the "Sassen area" Vestspitsbergen. *Norges Svalbard-Ishavsunders*, *87*, 172.

Hagen, D., & Prestø, T. (2007). *Biologisk mangfold - temarapport som grunnlag for arealplan for longyearbyen planområde*. Trondheim, Norway: Norsk institutt for naturforskning.

Hughes, K. A., Pertierra, L. R., Molina-Montenegro, M. A., & Convey, P. (2015). Biological invasions in terrestrial Antarctica: What is the current status and can we respond? *Biodiversity and Conservation*, *24*, 1031–1055. https://doi.org/10.1007/s10531-015-0896-6

Huiskes, A. H. L., Gremmen, N. J. M., Bergstrom, D. M., Frenot, Y., Hughes, K. A., Imura, S., Kiefer, K., Lebouvier, M., Lee, J. E., Tsujimoto, M., Ware, C., Van de Vijver, B., & Chown, S. L. (2014). Aliens in Antarctica: Assessing transfer of plant propagules by human visitors to reduce invasion risk. *Biological Conservation*, *171*, 278–284. https://doi.org/10.1016/j.biocon.2014.01.038

Meredith, M., Sommerkorn, M., Cassotta, S., Derksen, C., Ekaykin, A., Hollowed, A., Kofinas, G., Mackintosh, A., Melbourne-Thomas, J., Muelbert, M. M. C., Ottersen, G., Pritchard, H., & Schuur, E. A. G. (2019). Polar regions. In H.-O. Pörtner, D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, & N. M. Weyer (Eds.), *IPCC special report on the ocean and cryosphere in a changing climate*. https://www.ipcc.ch/srocc/chapter/chapter-3-2/

IUCN. (2020). *Invasive species | IUCN*. https://www.iucn.org/theme/species/our-work/invasive-species

Johnson, H. B., Polley, H. W., & Mayeux, H. S. (1993). Increasing CO2 and plant-plant interactions: Effects on natural vegetation. *Plant Ecology*, *104*, 157–170.

Johnson, B. A., Mader, A. D., Dasgupta, R., & Kumar, P. (2020). Citizen science and invasive alien species: An analysis of citizen science initiatives using information and communications technology (ICT) to collect invasive alien species observations. *Global Ecology and Conservation*, *21*, e00812. https://doi.org/10.1016/j.gecco.2019.e00812

Kaarlejärvi, E., & Olofsson, J. (2014). Concurrent biotic interactions influence plant performance at their altitudinal distribution margins. *Oikos*, *123*, 943–952. https://doi.org/10.1111/oik.01261

Lassuy, D. R., & Lewis, P. N. (2013). Invasive species: Human-induced. In H. Meltofte (Ed.), *Arctic biodiversity assessment* (pp. 558–565). Akureyri, Iceland: CAFF. https://www.arcticbiodiversity.is/index.php/the-report/chapters/invasive-species-human-induced

Lembrechts, J. J., Pauchard, A., Lenoir, J., Nuñez, M. A., Geron, C., Ven, A., Bravo-Monasterio, P., Teneb, E., Nijs, I., & Milbau, A. (2016). Disturbance is the key to plant invasions in cold environments. *PNAS*, *113*, 14061–14066. https://doi.org/10.1073/pnas.1608980113

Liska, J., & Soldán, Z. (2004). Alien vascular plants recorded from the Barentsburg and Pyramiden settlements, Svalbard. *Preslia*, *76*, 279–290. http://www.preslia.cz/P043CLis.pdf

Lutnæs, P., Movik, E., Stokke, E., & Geving, A. C. (2017). *Action plan against alien species on Svalbard*. Report 1/2017. Sysselmannen på Svalbard.

Meltofte, H., Barry, T., Berteaux, D., Bültmann, H., Christiansen, J. S., Cook, J. A., Dahlberg, A., Daniëls, F. J. A., Ehrich, D., Ehrich, D., Fjeldså, J., Friðriksson, F., Ganter, B., Gaston, A. J., Gillespie, L. J., Grenoble, L., Hoberg, E. P., Hodkinson, I. D., Ims, R. A., … Wrona, F. J. (2013). Synthesis: Implications for conservation. In H. Meltofte (Ed.), *Arctic biodiversity assessment: Status and trends in Arctic biodiversity* (pp. 20–65). Akureyri, Iceland: Conservation of Arctic Flora and Fauna, Arctic Council.

Myers-Smith, I. H., Kerby, J. T., Phoenix, G. K., Bjerke, J. W., Epstein, H. E., Assmann, J. J., John, C., Andreu-Hayles, L., Angers-Blondin, S., Beck, P. S. A., Berner, L. T., Bhatt, U. S., Bjorkman, A. D., Blok, D., Bryn, A., Christiansen, C. T., Cornelissen, J. H. C., Cunliffe, A. M., Elmendorf, S. C., … Wipf, S. (2020). Complexity revealed in the greening of the Arctic. *Nature Climate Change*, *10*, 106–117. https://doi.org/10.1038/s41558-019-0688-1

NOBANIS. (2009). *Invasive alien species pathway analysis and horizon scanning for countries in Northern Europe*. TemaNord 2015517. http://doi.org/10.6027/TN2015-517

Norwegian Ministry for the Environment. (2007). *Strategy on invasive alien species*. https://www.regjeringen.no/globalassets/upload/md/vedlegg/planer/t-1460_eng.pdf

Peyton, J., Martinou, A. F., Pescott, O. L., Demetriou, M., Adriaens, T., Arianoutsou, M., Bazos, I., Bean, C. W., Booy, O., Botham, M., Britton, J. R., Cervia, J. L., Charilaou, P., Chartosia, N., Dean, H. J., Delipetrou, P., Dimitriou, A. C., Dörflinger, G., Fawcett, J., … Roy, H. E. (2019). Horizon scanning for invasive alien species with the potential to threaten biodiversity and human health on a Mediterranean island. *Biological Invasions*, *21*, 2107–2125. https://doi.org/10.1007/s10530-019-01961-7

Pflanz, M., Nordmeyer, H., & Schirrmann, M. (2018). Weed mapping with UAS imagery and a bag of visual words based image classifier. *Remote Sensing*, *10*, 1530. https://doi.org/10.3390/rs10101530

Ravolainen, V., Soininen, E. M., Jónsdóttir, I. S, Eischeid, I., Forchhammer, M., van der Wal, R., & Pedersen, Å. Ø. (2020). High Arctic ecosystem states: Conceptual models of vegetation change to guide long-term monitoring and research. *Ambio*, *49*, 666–667. https://doi.org/10.1007/s13280-019-01310-x

Reaser, J. K., Burgiel, S. W., Kirkey, J., Brantley, K. A., Veatch, S. D., & Burgos-Rodriguez, J. (2020). The early detection of and rapid response (EDRR) to invasive species: A conceptual framework and federal capacities assessment. *Biological Invasions*, *22*, 1–19. https://doi.org/10.1007/s10530-019-02156-w

Roalsø, E. R. (2012). *Alien plant species in Svalbard* (NTNU MSc thesis). https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/245155?locale-attribute=en

Rooney, T. P., Rogers, D. A., Wiegmann, S. M., & Waller, D. M. (2004). Monitoring nonnative plant invasions over fifty years in Wisconsin forests. *Weed Technology*, *18*, 1266–1268. https://doi.org/10.1614/0890-037X(2004)018%5B1266:MNPIOF%5D2.0.CO;2

Rouse, J., Haas, R. H., Schell, J. A., & Deering, D. W. (1974). *Monitoring vegetation systems in the Great Plains with ERTS*. NASA Special Publication 351. https://ntrs.nasa.gov/citations/19740022614

Roy, H., Bacher, S., Essl, F., Adriaens, T., Aldridge, D. C., Bishop, J. D. D., Blackburn, T. M., Branquart, E., Brodie, J., Carboneras, C., Cottier-Cook, E. J., Copp, G. H., Dean, H. J., Eilenberg, J., Gallardo, B., Garcia, M., García-Berthou, E., Genovesi, P., Hulme, P. E., … Kenis, M. (2019). Developing a list of invasive alien species likely to threaten biodiversity and ecosystems in the European Union. *Global Change Biology*, *25*, 1032-1048. https://doi.org/10.1111/gcb.14527

Roy, H., Peyton, J., Aldridge, D. C., Bantock, T., Blackburn, T. M., Britton, R., Clark, P., Cook, E., Dehnen-Schmutz, K., Dines, T., Dobson, M., Edwards, F., Harrower, C., Harvey, M. C., Minchin, D., Noble, D. G., Parrott, D., Pocock, M. J. O., Preston, C. D., … Salisbury, A. (2014). Horizon scanning for invasive alien species with the potential to threaten biodiversity in Great Britain. *Global Change Biology*, *20*, 3859–3871. https://doi.org/10.1111/gcb.12603

Rønning, O. I. (1964). Svalbards flora. Norsk Polarinstitutt.

Rønning, O. I. (1996). *The flora of Svalbard*. Oslo, Norway: Norsk Polarinstitutt.

Rønning, O. I.(1972). *The distribution of the vascular cryptogams and monocotyledons in Svalbard*, Tromsø: Norsk Polar Institutt.

Sala, O. E. (2000). Global biodiversity scenarios for the year 2100. *Science*, *287*, 1770–1774 https://doi.org/10.1126/science.287.5459.1770

Sunding, P. (1961). Noen plantefunn fra Svalbard sommeren 1960. *Blyttia*, *19*, 125–129.

Sandvik, H., Hilmo, O., Finstad, A. G., Hegre, H., Moen, T. L., Rafoss, T., Skarpaas, O., Elven, R., Sandmark, H., & Gederaas, L. (2019). Generic ecological impact assessment of alien species (GEIAA): The third generation of assessments in Norway. *Biological Invasions*, *21*, 2803–2810. https://doi.org/10.1007/s10530-019-02033-6

Saul, W. C., Roy, H. E., Booy, O., Carnevali, L., Chen, H. J., Genovesi, P., Harrower, C. A., Hulme, P. E., Pagad, S., Pergle, J., & Jeschke, J. M. (2016). Assessing patterns in introduction pathways of alien species by linking major invasion data bases. *Journal of Applied Ecology*, *54*, 657–669. https://doi.org/10.1111/1365-2664.12819

Seebens, H., Blackburn, T. M., Dyer, E. E., Genovesi, P., Hulme, P. E., Jeschke, J. M., Pagad, S., Pyšek, P., van Kleunen, M., Winter, M., Ansong, M., Arianoutsou, M., Bacher, S., Blasius, B., Brockerhoff, E. G., Brundu, G., Capinha, C., Causton, C. E., Celesti-Grapow, L., … Essl, F. (2018). Global rise in emerging alien species results from increased accessibility of new source pools. *PNAS*, *115*, E2264–E2273. https://doi.org/10.1073/pnas.1719429115

Simberloff, D., Martin, J.-L., Genovesi, P., Maris, V., Wardle, D. A., Aronson, J., Courchamp, F., Galil, B., García-Berthou, E., Pascal, M., Pyšek, P., Sousa, R., Tabacchi, E., & Vilà, M. (2013). Impacts of biological invasions: What's what and the way forward. *Trends in Ecology & Evolution*, *28*, 58–66. https://doi.org/10.1016/j.tree.2012.07.013

Thomassen, J., Dahle, S., Hagen, D., Hendrichsen, D., Husa, V., Miller, A., Moe, B., Ravolainen, V., Renaud, P. E., & Westergaard, K. B. (2017). *Fremmede arter i Arktis – med fokus på Svalbard og Jan Mayen*. NINA Rapport 1413. Norsk Institutt for Naturforskning. http://hdl.handle.net/11250/2473612

Vilà, M., Espinar, J. L., Hejda, M., Hulme, P. E., Jarošík, V., Maron, J. L., Pergl, J., Schaffner, U., Sun, Y., & Pyšek, P. (2011). Ecological impacts of invasive alien plants: A meta-analysis of their effects on species, communities and ecosystems. *Ecological Letters*, *14*, 702–708. https://doi.org/10.1111/j.1461-0248.2011.01628.x

Ware, C., Bergstrom, D. M., Müller, E., & Alsos, I. G. (2012). Humans introduce viable seeds to the Arctic on footwear. *Biological Invasions*, *14*, 567–577. https://doi.org/10.1007/s10530-011-0098-4

Wasowicz, P., Sennikov, A. N., Westergaard, K. B., Spellman, K., Carlson, M., Gillespie, L. J., Saarela, J. M., Seefeldt, S. S., Bennett, B., Bay, C., Ickert-Bond, S., & Väre, H. (2020). Non-native vascular flora of the Arctic: Taxonomic richness, distribution and pathways. *Ambio*, *49*, 693–703. https://doi.org/10.1007/s13280-019-01296-6

Waugh, J. D. (2009). *Neighborhood watch: Early detection and rapid response to biological invasion along US trade pathways*. Gland, Switzerland: IUCN.

Zhang, H., Aldana-Jague, E., Clapuyt, F., Wilken, F., Vanacker, V., & Van Oost, K. (2019). Evaluating the potential of post-processing kinematic (PPK) georeferencing for UAV-based structure-from-motion (SfM) photogrammetry and surface change detection. *Earth Surface Dynamics*, *7*(3), 807–827. https://doi.org/10.5194/esurf-7-807-2019

Zwolicki, A., Zmudczynska-Skarbek, K. M., Iliszko, L., & Stempniewicz, L. (2013). Guano deposition and nutrient enrichment in the vicinity of planktivorous and piscivorous seabird colonies in Spitsbergen. *Polar Biology*, *36*, 363–372. https://doi.org/10.1007/s00300-012-1265-5

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

How to cite this article: Bartlett JC, Westergaard KB, Paulsen IMG, Wedegärtner REM, Wilken F, Ravolainen V. Moving out of town? The status of alien plants in high-Arctic Svalbard, and a method for monitoring of alien flora in high-risk, polar environments. *Ecol Solut Evidence*. 2021;*2*:e12056. https://doi.org/10.1002/2688-8319.12056