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Critical Literature Review

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Title: **Alien Invasions of the Antarctic Mainland: current knowledge and lessons from the wider Antarctic region and beyond**

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Abstract (ca. 200 words): Two species of invasive alien grass species have established themselves on the Antarctic Peninsular. The Antarctic mainland is expected to undergo further spread of these species and introductions of new species as a result of warming caused by climate change and by increased human activity in the area.

This report considers the properties and behaviours of invasive species, together with the means by which they reach and establish themselves in new and vulnerable areas, such as ice-free areas of the Antarctic mainland. Specific pathways relating to human activity in the Antarctic are reviewed, alongside some effective controls for reducing the introduction of new plant material into the region by these routes. Consideration is given to control, containment and eradication strategies, including suitable methods of plant removal within the Antarctic context. The existence of seed banks and the likelihood of reinvasion due to local changes which persist after alien populations have been eradicated are discussed. These, together with climate change and increased propagule pressure, point to the importance of ongoing monitoring programmes. Finally, suggestions are made for allocating responsibility for monitoring and responding to current and future non-native plant populations and their timely removal.

Alien Invasions of the Antarctic Mainland: current knowledge and lessons from the wider Antarctic region and beyond

Introduction

Two non-native species are known to have established themselves on the Antarctic mainland. Both are grasses and are found only on the Peninsula. This grass family, *Poaceae,* has been described as one of the globally most invasive[1]. The species *Poa Annua* is already known to be invasive and has been found in multiple locations[2]. *Poa Pratensis* has historically been confined to a single location, but has recently shown signs of spreading[3]. As well as directly competing for sites[4], the presence of aliens can affect the biological performance of nearby native species[4].

Extreme cold and remoteness are two reasons why Antarctica was previously isolated from the rest of the world. However, these barriers are being eroded by climate change and human activity[2]. If Antarctic biodiversity is to be protected from encroachment by alien species, as is required by the Antarctic Treaty, action must be taken to preserve it. Lessons learned from plant invasions on the Maritime Antarctic and Sub-Antarctic Islands are especially relevant to the Antarctic mainland, because of the similar period of human activity[5], the similar nature of the invading species[6], and because these islands constitute a bank of potential plant invaders close to the Antarctic mainland.

The low biodiversity[7] and lack of competition within ecological niches[7], together with the simple structures and slow life cycles of Antarctic ecosystems[8], permit easy encroachment by alien species[8]. Antarctic islands vary in the diversity of their ecosystems[9], but all have gaps within their ecosystems that make them also vulnerable to introduced species[10]. Islands are also considered to be more vulnerable to alien introductions than continents because their ecosystems are less able to survive the changes that occur alongside introduced species[1]. Larger and warmer islands are especially vulnerable to alien introductions than colder islands, apparently due to their more favourable conditions for human activity and plant establishment[9], which has implications for the warming Peninsula region.

The diversity of Antarctica's ecosystem decreases as latitude increases[11], and the mainland has been considered to be as vulnerable as the Antarctic islands to invasion, given that its ice-free areas closely resemble ice-bound islands[1].

Characteristics of Invasive Plants and their Introductions

Invasive plants usually grow well and in large numbers within the invaded environment[12]. Typically, they can grow in a wide range of climatic conditions, and so can spread over wide areas[12]. They are often perennials[1], have light and easily transported seeds[12], and reach maturity quickly[12]. Influential factors in the establishment of an invasive species, and relevant to Antarctica, are the size of the initial introduction and the number of subsequent introductions ("propagule pressure"), their distribution area, and the elapsed time since their first introduction[13]. Propagule pressure has increased significantly due to humans bringing large numbers of seeds and propagules to the continent[14]. Multiple introductions are indicated by high genetic variation of *Poa Annua* on King George Island[15], as substantiated by similar evidence among its lichen population[16]. And, after 60

years showing no signs of invasive behaviour[3], *Poa Pratensis* now appears to be spreading from its Peninsula location[3].

Whether a given plant will become invasive when introduced into a new environment can depend on the species's tolerance for the new conditions and/or its ability to genetically adapt[13], the potential for hybridisation[13], and the properties of the ecosystem that it is introduced into[13]. Although some species appear to be innately invasive[13], others may not be invasive prior to introduction, but subsequently evolve invasive traits due to genetic modification or hybridisation[13], the lack of natural predators[13], or exploitation of unfilled biological niches within the new environment[5]. Therefore it is not easy to predict which species will behave invasively[13]. Species filling unoccupied biological niches often have a greater impact on the native ecosystem than other invasive species[13].

Not all introduced species are invasive, but may instead be either transient or persistant[17]. In the Antarctic Islands, by far the majority of introduced species have been classified as persistant[1,17]. Similarly, transient species have been recorded on the Antarctic mainland, with five such species establishing themselves around a station in the Larsemann Hills of East Antarctica[18].

An available transport vector is the first requirement in order for a species to become established[18]. Alien species can reach the Antarctic by natural methods of transportation, such as wind, sea, animals and debris[8, 11]. This involves travelling long distances against the prevailing winds, and crossing the Antarctic circumpolar ocean current[18]. Far fewer materials - by several magnitudes - are transported by natural transport than by human activities[6].

The second requirement is that these seeds or propagules must be able to survive the journey and journey time[8, 18]. Human activities can introduce viable plant matter more quickly and under less onerous conditions compared to natural transport[8]. *Poaceae* has shown great resilience to time and cold, with *Poa Trivialis* seeds remaining viable after 284 days of transport at sea at temperatures reaching -1.5C[8].

Thirdly the propagule must reach a site suitable for it to become established[18]. Disturbed ground such as that caused by glacier retreat or growth in animal colonies is thought to provide favourable conditions for establishment[19]. Disturbed soils appear to contain higher levels of nutrients including nitrogen than surrounding soils[19], making these sites particularly favourable to *Poa Annua*[19]. *Poa Annua* has recently spread from the Arctowski station to land exposed by the retreat of the Ecology Glacier[20], and the significant spread of *Poa Annua* at Cave Bay on Prince Edward Island is believed to be partly due to an increase in numbers of seals nearby[21]. Several examples from the Antarctic show that the disturbed ground associated with the movement of people and vehicles around bases[18, 19], and also the construction of bases themselves, creates artificially favourable sites[22]. Bases also create locally sheltered regions which favour the establishment of alien species such as *Poa Annua*, both on the mainland and in the broader Antarctic[15, 19]. While plant material transported to the continent by natural methods must reach the 0.32% of the Antarctic mainland that is free from ice in order to establish themselves[18], human activities introduce propagules and seeds preferentially into ice-free areas, where they have a greater chance to establish[8, 11].

Finally, the resulting plant must be able to reproduce and establish a colony[18], an act which involves overcoming competition from local species[11], and environmental transformation such as nitrogen enrichment of the soil to facilitate population growth[11]. Several alien species in the region have failed to reach this step, including one species on Discovery Island[7], several on South Georgia, Marion Island and the Kerguelen and Crozet Islands where pollinating insects have not yet become

established[17], and the colony of *Poa Pratensis* on the Peninsula, which does not currently produce seed[23], but spreads only due to vegetative growth[3].

Chance plays a non-trivial role in both the introduction and establishment of new species[13]. This has been observed in a number of instances within the wider Antarctica. An established *Poa Annua* colony was destroyed by a lahar at Whaler's Bay on Deception Island[7], and three introduced species of vascular plant from Marion Island which are belived to have since died out[21].

While it is not known how many species are capable of establishing themselves within Antarctica[8], especially those already pre-adapted to cold conditions[18], it has been speculated that the combination of these four barriers make natural colonisation very unlikely for the majority of species that reach Antarctica[18, 24].

Human Activities and Introduction Pathways

Many activities in Antarctica have been found to be potential vectors for the introduction of new species. Six main drivers of alien introductions have been identified; in increasing order of risk these are scientists, tourists, human residence, imported fresh foodstuffs, agriculture, and aircraft runways[6]. Every large bio-regions of the broader Antarctica has been found to have at least one specific risk associated with it[6]. Managing these risk pathways is believed to be essential for reducing introductions of alien species[13].

Categories and subcategories which have been investigated in detail include tourists, scientists, and cargo; land vehicles (including both importation and subsequent use within Antarctica), ships and air travel; and the impact of constructing and occupying bases.

Tourists have attracted much attention, due to their large numbers[15, 19], the ongoing increase in scale[25] and nature of their activities on the mainland[9], and their intensive use of ice-free areas[25], including preferential attraction to vulnerable, higher diversity sites[1]. However, studies have shown the number of seeds carried by tourists is significantly lower than most other categories of visitor[14]. Further research has yielded helpful insights such as that tourists on small ships have both more interactions and more active interactions with Antarctica than travellers on larger ships[14]; that tourists who travel during spring and autumn months are more likely to transport propagules and seeds than those who travel in the summer[14]; and that tourists tend to reuse their cold weather gear from one cold holiday to another[14]. From this data, some useful suggestions have been made regarding the provision of new clothing[14], the issuing of over-clothing on reaching Antarctica rather than before[3], and the effectiveness (or otherwise) of washing and vacuuming clothing[14]. However, the finding of seeds within a new rubber raft is cited as a warning that even new equipment cannot be assumed to be free from contaminants[5].

Scientists are prolific seed importers[14]. One study of 44 scientists found a total of 981 propagules on clothing and equipment, with 20 people carrying none and one person accounting for 309 of these[5]. Education, the appointment of biosecurity officers on ships and the cleaning of equipment by staff trained to recognise potential contamination pathways have all been effective in reducing seed transport[5].

There have been two major incidents involving the import of uncleaned vehicles to sites within the Antarctic region. One involved the Australian Casey Station[11] in which large amounts of soil and plant

material were deposited on a nearby road[11], and the other occurred at the British Rothera station[11] where approximately 40,000 seeds were imported within soil on four vehicles[11]. The British incident led to a tightening of import controls[18]. Seeds from vehicles which become buried in the vehicle's tracks may germinate many years later when another vehicle disturbs the soil[11]. Meanwhile, vehicle use within Antarctica causes ground disturbance, which has been suggested as a vector for the spread of species on Deception Island[7].

Cargo transported by ship is thought by some to be the most significant route by which seeds reach the mainland[8]. Shipping routes have been found to correlate with bluegrass contamination across the Antarctic Islands and peninsula[4]. One ship destined for a UK research station on the Brunt Ice Shelf carried cargo contaminated with 176 seeds, 30.4% of which belonged to the *Poaceae* family, and a further 32.1% of seeds from *Asteraceae*[8], another globally invasive family[1] which is flourishing on Deception Island[7]. However, cargo has been identified as the pathway where the greatest action can be taken to prevent species's introductions[5], and the Australians have demonstrated this with measures including fumigation, cleaning and sterilisation and changing the purchasing and packing of fresh produce[5]. Eliminating pallet designs associated with high contamination rates has also helped[5]. A useful technique for forming policy in this area has been to consider the technical feasibility and cultural acceptibility of suggested improvements to quarantine procedures[5].

There seem to be no confirmed reports of contamination due to aircraft within the Antarctic. However, helicopters have been suggested as a possible vector for spread of species on both Deception[7] and Marion[21] Islands, and contamination by helicopter is identified as a major risk of ship-to-shore resupply missions[5]. Cleaning of all aircraft is now recommended[18].

Station building is thought to account for the introduction of 2000-3000 seeds for each station per year[14], and there is a clear association between recorded species introductions and nearby research stations[18]. In addition, a correlation has been found between *Poa Annua* and the length of time since base construction and renovation, a relationship which has not been found for either tourists or scientists and which is believed to be due to soil modification[19].

Responses to Alien Invaders

One strategy that has been suggested is to allow the invasions to continue unchecked, and to use the islands as case studies both for species encroachment due to human activity and as part of natural processes[26,27]. This argument makes the case that eradication of alien species constitutes a moral choice which scientists are not equipped to make[27], and suggests that the establishment of aliens enhances species diversity at a local level[26], and maximises the use of local resources[26]. However, this implies replacing rare native species with species that are ubiquitous, and it is hard to agree that the loss of rare natives is adequately compensated for by the spread of mice, feral horses and black and Norwegian rats[26]. The opposing case, for action against alien species, has been convincingly argued[28].

Preventing alien introductions is preferable to their later eradication[4] and is, at least in principle, cheaper where invasive species are concerned[13]. Existing quarantine measures have been found to reduce alien introductions[21] and should both be continued and improved upon. However, given the failure to prevent species' introductions[18], both on the mainland and in particularly within the broader Antarctic, methods of dealing with established aliens must be considered.

Control and containment are two possible strategies involving, respectively, the reduction of the species in question, and restricting its spread[29]. These require less investment in time and money up front than eradication[29], but require indefinite commitment of resources, and allow at best only slow recovery of the native biota[29]. Nevertheless, control is regarded as a practical and sustainable method, particularly for dealing with invasive plants[13].

Eradication is the generally preferred strategy for dealing with established invasive populations[29], but with the proviso that larger alien populations require proportionally more effort to eradicate. Invasive populations spread over areas bigger than 1000 hectares are regarded as very unlikely to be eradicated[13]. Even for areas of 1-100 hectares, the probability of success is thought to be only 30%[13]. Plants are particularly difficult to eradicate than other introductions[13], and of 23 plant eradication attempts on the Galapagos Islands, only four were successful[13]. The spread of *Poa Annua* on the Arctowski station is now thought to be impossible to eradicate[7].

Properties of successful eradication programmes include very careful targeting[29], removing all aliens[29], and careful monitoring afterwards[29], education of inhabitants[13], obtaining community co-operation[13], adequate mapping[13], and resource planning[13]. Early detection[13] and rapid response to invaders[13,3] is vital.

Eradication programmes carry with them the risk of negative and unexpected effects on the affected ecosystem. Sometimes these relate to the methods used for eradication, such as weedkiller poisons being transferred within the food chain[29]. In other cases, species' imbalances may be created within ecosystems, often involving other aliens[13], but also including scarce resources for native species which may thus face a reduction of food or habitat[29].

Moreover, areas which have been invaded previously remain at higher risk of invasion[13], since aliens can effect local changes to soil nutrients and microbes which persist long after removal of the plants[13]. As well as new introductions, seeds can persist in the local area for considerable time[23]. Most *Poa Annua* seeds in Antarctica appear to be stored locally within the tussocks that this grass forms in polar regions[23], rather than being spread over long distances[23], however the number of stored seeds can be considerable, being estimated at around 3000 seeds per square metre[23].

Conclusion

There are probably only a few species capable of establishing themselves on the Antarctic mainland, even with the warming due to climate change. However, these species are likely to belong to highly invasive and widespread families such as *Poaceae*. Existing quarantine procedures must be improved but, given the number of routes by which seeds and propagules can reach the Antarctic, attention must be given to methods of dealing with aliens when they arrive, including ongoing response and monitoring systems.

The Peninsula is clearly the location most at risk due its warming conditions, its heavy traffic and the existence of *Poaceae* populations already established. However, the rate of *Poaceae* spread here has been slow, and has been relatively easy to identify given the strong human presence. Coordination and clear guidance are, however, required for prompt and unified action. As action by the relevant committees has so far been slow[6,18], this is unlikely to be driven by top-down policy, and is probably most practically handled by bases near to alien specimens. At tourist landing sites, tourists themselves might be encouraged to photograph and report suspected alien species, with the

nearest base investigating the report. The strongest encouragement should be given for follow-ups in areas where previous invasions have taken place. As well as ongoing action against *Poa Annua*, the population of *Poa Pratensis* should be removed as a priority before conditions permit this species to produce viable seed.

A huge concern is remote areas, particularly those with disturbed ground being contaminated by scientists, as invasions could potentially spread over wide areas before being discovered. Bases should be encouraged to take responsibility for monitoring and removing specimens found at areas near to their base and/or where their members have a research interest. If biosecurity officers are not already appointed at bases, consideration should be given to doing so. More research, and in particular scientist-specific guidance on improved working practices, is urgently required.

It appears that where aliens have been removed on the mainland the removal has been done by manual pulling rather than by using chemicals. This appears to be adequate in terms of removing the plants and avoids the introduction of poisons, albeit perhaps at the cost of greater ground disturbance. At this stage, it would be unwarranted – and highly controversial - to use weed killer to treat soils contaminated with large numbers of *Poa Annua* seeds. However, since invasions are expected to continue, it would be prudent for research to be carried out elsewhere in the broader Antarctic region regarding the effectiveness and consequences of using chemical eradication methods against *Poa Annua*.

Ongoing lessons from the continued eradication of invasive species on the Sub-Antarctic islands are relevant to continuing efforts of quarantine and eradication across the region. In particular, attention should be given to islands close to the mainland, as temperatures and conditions here may most closely mimic those on the mainland, and the removal of these alien populations may remove a significant source of propagule pressure on the mainland. It is, however, very unlikely that the ecosystems of heavily invaded islands such as Marion Island, can be repaired in the foreseeable future[21, 29].

While there may be grounds for believing that the mainland remains reasonably well protected against invasive species[19], complacency would clearly be extremely unwise and potentially extremely costly. There appears to be little scientific value in allowing invaders to become established in Antarctica given the large number of other sites globally where such research can be conducted. Moreover Antarctica will continue to experience ongoing invasions due to increasing human activity and warming temperatures, at sites of previous invasions, and from existing seeds preserved in the soil, and thus Antarctica will continue to make valuable contributions to invasive species research.

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