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Short Communication

Human-vectored seed dispersal as a threat to protected areas: Prevention, mitigation and policy

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ABSTRACT

The growing global population size and the increasing mobility of people can make humans as a potentially super-effective dispersal vector of plant propagules. Therefore, human-vectored dispersal (HVD) on clothing and footwear can be an effective way of the dispersal of invasive alien species (IAS). This can be especially problematic in protected areas, which are not exposed to the mass invasions caused by vehicles, construction works, trade or agriculture, but still exposed to HVD by tourists. In this study, we collected those biosecurity measures which currently apply to the control of IAS dispersed on human clothing. We also extracted relevant findings from studies on HVD for giving recommendations in order to improve policy measures aiming the prevention and mitigation of the spread of propagules of IAS on clothing. Even though many peculiarities of HVD are already known, e.g., retention potential of different fabric and cloth types, traits of the species of the most successful IAS dispersed by HVD and potential dispersal efficiency of HVD, we found that current IAS control measures usually do not consider and do not address sufficiently the threats represented by HVD on cloths. We suggest a number of voluntary and institutional measures that could be easily applied to decrease the chance of dispersing IAS by HVD, including information, self-regulation, legislation, quarantine measures, monitoring, interception and visitor management.

1. Introduction

Human-mediated dispersal (HMD) became one of the most important long-distance seed dispersal modes contributing to the spread of invasive alien species (IAS) in modern times (Bullock et al., 2018). HMD includes several indirect mechanisms, through which people contribute to the spread of IAS, including trade, infrastructure development and land use (Nathan 2006). Humans can also act as dispersal vectors during human-vectored seed dispersal (HVD). The growing global population size and the increasing mobility of people can make humans as a potentially super-effective dispersal vector (Ansong and Pickering, 2016). Therefore, HVD (by vehicles and on clothing) of species to extra-range can be considered as a defining force of global biodiversity (Wilson et al., 2009).

Among HVD types, seed dispersal on clothing or footwear can be considered as an alternative form of epizoochory on mammals' fur or hooves (Ansong and Pickering, 2016; Valkó et al., 2020). Healy (1943) was one of the first researchers who identified the important role of HVD on clothing. After a five-day-long field survey in tussock grassland (New Zealand) he found propagules belonging to 33

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plant species on the cuffs of a pair of trousers and more than three hundred nasella tussock (*Nasella trichotoma*) seeds on his socks. Clifford (1956) examined the mud accumulated on footwear in England and identified 43 plant species from the germination experiment. Powell (1968) compiled a list of the harmful plant species which entered New Zealand between 1963 and 1967. He found that there were 45 species not recorded previously in the country which probably entered on clothing or footwear. Vibrans (1999) highlighted the importance of HVD (epiantropochory) in agricultural landscapes, where dispersal by anemochory and zoochory is limited, because the monocultures are much larger than the dispersal range of these vectors. Auffret and Cousins (2013) examined meadow workers' clothing in Sweden. In total, 24,354 seeds of 197 species were counted from 214 samples. 34% of species were elements of the regional species pool, while 36% of species were invasive elsewhere in the world. In their global review Ansong and Pickering (2014a) showed that people mostly disperse weeds by HVD and suggested that this process can cause serious damages in protected areas. A total of 449 species have been documented to be able to disperse on clothing so far. Globally, almost all of them (391 species) are listed as weeds.

The spread of IAS causes serious economic (including direct damages and costs of mitigation and prevention), health (e.g., globally emerging zoonotic diseases) and environmental (e.g., decrease of native biodiversity) issues (Jay et al., 2003; Hall, 2011). The InvaCost Database estimates the mean annual cost associated with IAS could reach 162.7 billion USD globally (Diagne et al., 2021). Tourism plays a major role in this problem. Long-distance transportation networks (air, water, railway and highway) are responsible for the international spread of IAS and the development of tourism-related infrastructure (roads, buildings, hiking trails) increases the local spread of IAS within protected areas (Moodley et al., 2020). HVD on clothing and footwear can also affect those areas of the nature reserves which are not exposed to the mass invasions caused by vehicles, construction works, trade or agriculture (Valkó et al., 2020). The most endangered areas subjected to the spread of IAS are the isolated ones (e.g., Antarctica, Australia, New Zealand, oceanic islands and mountain summits) with special flora and fauna, many of them being globally important biodiversity hotspots (Hughes and Convey, 2010; Hughes et al., 2010; Hall, 2011). Due to the increasing pressure of tourism, we can expect that the importance of HVD as a threat for introducing IAS will increase rapidly; which issue should be properly addressed by biosecurity measures in order to detect, control and manage the spreading of these harmful organisms (Meyerson and Reaser, 2002; McKirdy et al., 2008; Magarey et al., 2009; Sheppard et al., 2014).

In this study, we collected those biosecurity measures which currently apply to the control of IAS dispersed on human clothing. We also extracted relevant findings from studies on HVD for giving recommendations in order to improve policy measures aiming the prevention and mitigation of the spread of propagules of IAS on clothing.

2. Methods

We collected researches on biosecurity measures related to human clothing in Google Scholar to obtain scientific publications in April 2020. We used 'biosecurity seed dispersal' and 'biosecurity seed' combinations of search terms and reviewed potentially relevant references. Initially, we screened the titles and abstracts and then we excluded those that did not mention clothing, biosecurity measures and seed dispersal. We repeated the search in Google to find additional information in the grey literature (e.g., web pages,

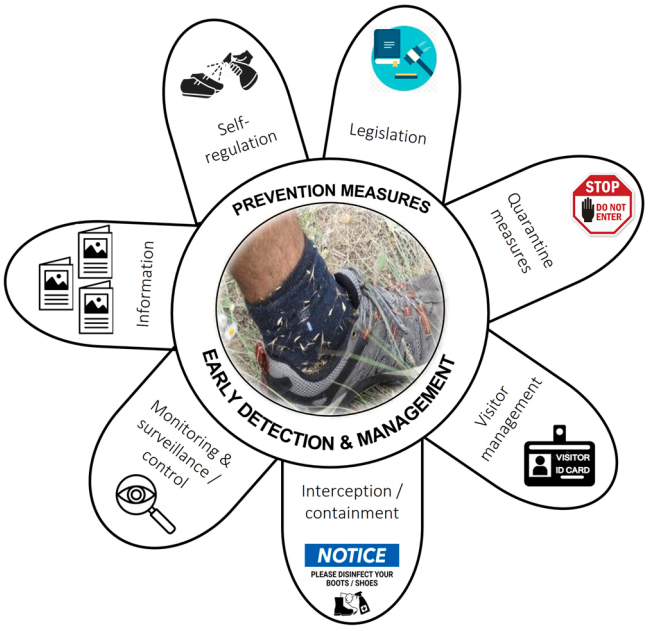

Fig. 1. Conceptual figure showing the most important measures of prevention, early detection and management that can be applied against the spread of invasive alien species by human-vectored seed dispersal on cloths.

reports and guidelines) which considered biosecurity management of human-vectored seed dispersal. Furthermore, we collected relevant studies about tourism, tourism management and tourist codes. The concept of our study was built on the IAS control frameworks that include prevention, early detection and management, based on Meyerson and Reaser (2002) and Simberloff et al. (2013). We grouped and evaluated the studies and items of grey literature based on these frameworks (Fig. 1).

3. Results and discussion

In total, we found eight empirical studies examining the propagules dispersed on clothing and footwear (for the list, please see Table 1), fifteen experimental studies that demonstrate seed dispersal on clothing (Table 2) and only one study that provided information about human behaviour in protected areas (Ansong and Pickering, 2014a). In terms of prevention, we collected the possible biosecurity measures of information, self-regulation, legislation and quarantine measures. Early detection and management are discussed in one chapter which includes monitoring and surveillance/control, interception/containment and visitor management.

3.1. Prevention

Prevention is the most cost-effective form of protection against harmful organisms (Meyerson and Reaser, 2002). It includes informing people about the risks (via brochures, guidebooks, tour guides, maps, notices, signs, posters and web pages), self-regulation (ways of human behaviour that can decrease the chance of seed dispersal on cloths), legislation (binding cleaning of the cloths) and quarantine measures (limiting human contact with seeds to avoid potential risks) (Meyerson and Reaser, 2002; Simberloff et al., 2013). These are presented in detail below.

3.1.1. Information

Providing adequate information to people about seed dispersal by clothing is an essential task to prevent the spread of harmful species. It would be especially important to inform visitors about the dangers related to the spread of IAS by HVD when visiting isolated habitats, islands or nature reserves (Whinam et al., 2005; Mount et al., 2009; Ansong and Pickering, 2014a, 2014b), however in protected areas, this information is seldom provided in most regions. Another option for prevention is the education of the staff working at national parks, farms, or tourism. For instance, the Department of Sustainability and the Environment in Victoria (Australia) organises workshops for contractors and employees where they discuss the biosecurity measures, such as monitoring the weeds, implementing cleaning programmes for machinery, vehicles and equipment and creating washdown facilities (Pickering and Mount, 2010).

3.1.2. Self-regulation

Another cost-effective form of prevention is self-regulation (Ware et al., 2012; Huiskes et al., 2014), which can be especially efficient in those cases, when the rate of seed dispersal depends on the behaviour of the people. Self-regulation is completely voluntary and based on individual decision (e.g., not removing seeds from clothing in natural habitats). Choosing the type of fabric and clothing could also be an important component of self-regulation, as different fabric types have different seed retention potentials (Table 2). Ansong and Pickering (2016) suggest that clothes made of pure cotton, canvas, fine nylon weave, denim and drill cotton can reduce the

Table 1
Empirical studies investigating the plant propagules, bacteria and fungi on clothes, footwear and equipment of tourists in protected areas.

Region	Clothing/Footwear	Samples	Cleaning methods	Registered organisms	Reference
Antarctica	footwear (boots)	72 pairs	stiff-bristle scrub brushes	20 bacterial isolates	Curry et al. (2002)
Antarctica	clothing and equipment	1857 (items)	vacuuming	74 148 seeds, 17 468 bryophyte and lichen fragments	Huiskes et al. (2014)
Antarctica	clothing and equipment	64 samples	vacuuming	981 seeds	Whinam et al. (2005)
Arctic region (Svalbard, Norway)	footwear (hiking/running shoes)	259 samples	stiff-bristled brush and forceps	1 019 seeds	Ware et al. (2012)
Australia (Australian savanna)	backpack, hat, jeans, pockets, shirts, shoes, socks	28 samples	manual removal of seeds	130 seeds of one target species	(Scott, 2009)
Sweden (meadows)	clothes, footwear	214 samples	manual removal of seeds	24 354 seeds	Auffret and Cousins (2013)
New Zealand	footwear (running shoe, tramping boot and gumboot)	4 pairs	dipping (in bleacher) washing with detergent washing with tap water sampling pre and post treatment	bacteria, fungi	Young et al. (2008)
New Zealand	footwear (hiking boots, footwear, sport shoes and golf shoes)	155 samples	sterilised horse-hoof pick	446 seeds	McNeill et al. (2011)

Table 2
Experimental manipulative researches designed to test the human-vectored seed dispersal on clothing types. Clothing types found to have the highest seed retention potential are underlined. The papers published before 2009 are reviewed in detail in the study of Mount and Pickering (2009).

Country and habitat	Used clothing type	No. of species	Reference
Australia	shoes, socks, trousers	24	Wace (1985)
Australia (Kosciuszko National Park)	socks (wool/nylon blend and cotton/nylon blend)	70	Mount and Pickering (2009)
Australia (Kosciuszko National Park)	trousers (drill cotton), socks (cotton/nylon blend)	5	(Pickering et al., 2011)
Australia (Kakadu National Park)	socks (cotton/nylon blend), trousers (drill cotton)	1	Ansong and Pickering (2013)
Australia (Gold Coast campus, Griffith University, Queensland)	trousers (drill cotton), socks (cotton/nylon blend)	8	Ansong et al. (2015)
Australia (Gold Coast campus, Griffith University, Queensland)	trousers (canvas, denim, drill cotton and fine nylon weave), socks (ribbed cotton/nylon blend and double weave wool nylon blend) jumpers/shirts (fleece, knitted wool, pure cotton and polyester mesh fabric)	33	Ansong and Pickering (2016)
Canada (rural habitat)	trousers (drill cotton)	8	Kulbaba et al. (2009)
Costa Rica (deciduous forest and savanna)	trousers (others)	2	Bullock and Primack (1977)
Hawaii	shoes	12	Higashino et al. (1983)
Hungary (University Campus, Debrecen)	cotton socks, fleece sweater, blue jeans	17	Valkó et al. (2020))
New Zealand (tussock grassland)	socks, trousers	1	Healy (1943)
Poland (grassland)	shoes, socks, shoelaces, trousers	30	Fallinski (1972)
United Kingdom (grassland)	shoes (others)	20	Woodruffe-Peacock (1918)
United Kingdom	shoes	39	Clifford (1956)
United Kingdom (England, Dorset coastline)	shoes	2	Wichmann et al. (2009)

attachment of the seeds the most. In contrast, clothes made of fleece, wool, ribbed cotton/nylon blend materials and the garments having Velcro provide good adhesion conditions for seeds (Ansong and Pickering, 2014a; Valkó et al., 2020). We found only one study that provided information on tourist behaviour: Ansong and Pickering (2014b) asked 112 visitors in the D′ Aguilar National Park (Australia) what they do with seeds on their clothes. According to the interview the majority of visitors brushed their clothes in the park or anywhere where they noticed seeds. Other common removing methods were the disposal of the seeds in a bin at home, washing them in laundry or leaving them in the backyard garden or house. Out of these forms of behaviour, brushing clothes outdoor is the most dangerous one, leading to a high probability of seeds reaching suitable germination microsites.

3.1.3. Legislation

Considering the global importance and economic, health and environmental risks associated with the human-vectored dispersal (HVD) of organisms, strict legislation is needed to prevent the spread of harmful species (Hall, 2011). Such legislation measures are the most well established in the case of Antarctica and Oceania, probably because these regions are especially threatened by IAS due to their unique biogeographical position and endemic wildlife. Legislation generally includes cleaning clothes and footwear at the entry point to the country, and in fewer cases at the entry point to the protected areas.

According to biosecurity regulations before arriving in Antarctica and after leaving the continent, all visitors must rigorously clean their footwear, clothes and equipment (Hall, 2010; Hughes and Convey, 2010). The Arctic Expedition Cruise Operators provides useful information for arresting biological invasion risk, while the International Association of Antarctic Tour Operators provides guidelines for tourists and small boat operators in the Antarctica (Curry et al., 2002; Mason, 2005; Hall et al., 2010).

In New Zealand, the Ministry of Agriculture and Fisheries is responsible for enforcing for the biosecurity legislation, which includes cleaning visitor's footwear, clothing and equipment at the entry point to the country, e.g., at the airport or port (Williams and West, 2000; Jay et al., 2003). Furthermore, every visitor must complete a Passenger Arrival Card and declare any biosecurity risk items, including plants or plant products and equipment.

In Australia a number of laws (Regulation of Imports and Exports Act 1982, Biological Control Act 1984, Natural Heritage Trust Act 1997, Environmental Protection & Biodiversity Conservation Act 1999, Biosecurity Act 2015) have been passed over the years to control the spread of IAS (Williams and West, 2000; Ouellet-Plamondon et al., 2009). The Australian Defence Force personnel are required to ensure all items of clothing and equipment is clean when entering and leaving the country. Visiting high-value agricultural sites, tourists must clean their footwear, clothes and equipment at designated wash down locations (see e.g., https://nrmsouth.org.au/biosecurity/farmclean/, https://www.dpi.nsw.gov.au/biosecurity/your-role-in-biosecurity/small-lot-holders).

The abovementioned examples of legislation preventing HVD could be used as model in protected areas in other parts of the world, and the adaptation of such practices would be crucial in the global protected areas as the threats represented by dispersing IAS by HVD are relevant globally.

3.1.4. Quarantine measures

Quarantine measures are a drastic form of prevention (Davies and Sheley, 2007). In endangered habitats, such as national parks, reserves, islands and world heritage areas (e.g., Greater Barrier Reef, the Galapagos or sub-Antarctic islands), which are popular tourist destinations, it is important to provide a single access point to the area and designated walking tracks to effectively control the movement of tourists. During the seed ripening period, which is usually the late dry season (Hill and Pickering, 2006; Scott, 2009; Pickering and Mount, 2010) it is crucial to minimize the contact possibilities between seeds and humans. Restrictions including closing roads or hiking trails, establishing fences might be necessary to reduce seed dispersal on clothing among habitats (Davies and Sheley, 2007).

3.2. Early detection and management

Following the appearance of the harmful species, early detection and management are the next step of invasion control. Regarding HVD on cloths, early detection measures involve the monitoring and interception/containment, while management actions involve visitor management (Meyerson and Reaser, 2002; Mason, 2005; Simberloff et al., 2013).

3.2.1. Monitoring and surveillance/control

Human-vectored seed dispersal is difficult to monitor at the seed level, and it can be better approximated through quantifying human movement and correlating it with the establishment of IAS in protected areas. However, there are only a few cases where information on people's previous routes is available for modelling the spread of IAS. In some islands and isolated countries when entering to the country, visitors need to fill biosecurity declarations, questionnaires and passenger arrival cards which contain questions about their previous travel destinations (Powell, 1968; Young et al., 2008; McNeill et al., 2011 – New Zealand, Hall, 2010, Huiskes et al., 2014 – Antarctica, Ware et al., 2012 – Svalbard Islands). This can be a valuable source of information for tracking the spread of IAS.

3.2.2. Interception/containment

In these actions, the institutionalized regulations prevail, such as interception programs or emergency actions. The most effective way of interception and containment are the obligatory cleaning of clothing and providing cleaning stations for employees and visitors (Meyerson and Reaser, 2002; Simberloff et al., 2013; Hughes and Convey, 2010; Huiskes et al., 2014). At these cleaning stations, it is recommended to first remove the soil from footwear with a brush and then disinfected the organic matter with a solution of 70% ethanol or methylated spirits in 30% water – through a spray bottle or a footbath. It is important to wait until the footwear is completely dry (see e.g., https://www.environment.gov.au/biodiversity/invasive-species/publications/arrive-clean-leave-clean). The public attitudes towards such obligatory measures might be negative, but visitor engagement through dissemination could help to make such measures acceptable for visitors. The results of the questionnaire survey by Ansong and Pickering (2014b) in an Australian protected area show that 49.1% of respondents would support, 30.4% are neutral and 20.5% disagree with the obligatory cleaning of visitors' clothes before entering the protected areas.

3.2.3. Visitor management

Visitor management involves economic (e.g., entrance and car parking fees), physical (e.g., size of car parks, limitation of tourists), educational (e.g., modifying visitor behaviour) and regulatory (e.g., opening times, security staff) forms. In many regions (e.g., Antarctica, Arctic region, Australia, New Zealand and other parts of Oceania, Costa Rica), it has become indispensable to control visitor flows (Mason and Mowforth, 1996; Kuo, 2002; Mason, 2005). Visitor management includes tourism codes, which aim to influence attitudes and modify the behaviour of tourists. Visitor codes are different across regions, but all acknowledge the protection of the protected area being of the highest priority (Mason, 1994, 2005; Mason and Mowforth, 1996). We found only one tourist code, the Ngadha visitor code (Flores, Indonesia, Cole, 2007) which includes recommendations about the type of clothing, but only as a dress code considering cultural and societal requirements (e.g. avoid shorts, tight and dirty clothes).

4. Conclusions

Despite the number of biosecurity measures in effect, the spread of harmful species from one habitat to another is still a major threat for biodiversity worldwide (Jay et al., 2003; Hall et al., 2010; Hall, 2011). Even though many peculiarities of HVD are already known, e.g., retention potential of different fabric and cloth types, traits of the species of the most successful IAS dispersed by HVD and potential dispersal efficiency of HVD (Pickering and Mount, 2009; Mount and Pickering, 2010; Ansong and Pickering, 2014b, 2016), we found that current IAS control measures usually do not consider and do not address sufficiently the threats represented by HVD on cloths. We suggest that there are a number of voluntary and institutional measures that could be easily applied to decrease a chance of dispersing IAS by HVD. Based on our review, we identified the following recommendations for future research and policy.

(1) It is crucial to inform people about the risk of human-vectored seed dispersal. The success of information lies in the combination of the dissemination methods (e.g., provided by brochures, maps, signs, interpretation manuals and tour guides). Also, dissemination of information about the threats of human-vectored seed dispersal to the biodiversity of protected areas should be communicated to a wider public.

(2) It would be important to provide information about those personal decisions that can help people to reduce their potential as vectors of IAS. Information should be made available on those cloth types that can decrease the most the adhesion of seeds, e.g., trousers without pockets and gaiters covering socks and shoelaces (Mount et al., 2009; Scott, 2009; Ansong and Pickering, 2014b). In some cases, such as isolated biodiversity hotspots it would be important to wear new clothing to minimise the introduction of seeds on cloths. Vacuuming or washing can reduce the probability of dispersing viable propagules (Ansong and Pickering, 2014a; Huiskes et al., 2014). In terms of washing temperature, low temperature (30ºC) has negligible effect on seed germination potential, while high temperature (60ºC) can reduce the germination of several species (Lefcort and Lefcort, 2014; Valkó et al., 2020).

(3) The biosecurity legislations related to clothing and footwear usually target the clothing and footwear actually worn, not those inside the luggage. However, seeds can remain germinable attached on clothing after laundry washing (Valkó et al., 2020). Therefore, disinfection of clothing and footwear at the country entry points are necessary, but not sufficient. It would be important to set up cleaning stations at nature reserves, such as in visitor centres at national parks (Valkó et al., 2020). This measure would be the most effective in case of protected areas with one or few entry points.

(4) Quarantine measures would be important in those areas which are particularly sensitive to the spread of IAS. Access to these areas should be restricted and they may be visited only with permission and during certain periods when the probability of seed dispersal is the lowest.

(5) Gathering information on HVD-related habits of visitors would improve the efficiency of biocontrol measures in protected areas. Questionnaires available for tourists on a voluntary basis, about the habitat types and geographical regions previously visited would give important hints about the directions of HVD. In monitoring schemes, not only IAS, but other species recently appearing on protected areas would be important model organisms. On the one hand, those non-harmful species which have not been detected in the area before may cause problems later on and on the other hand, they can model the rate and dynamics of HVD processes.

(6) People should ensure that they do not carry the seeds on their clothing, therefore, cleaning and washing options of clothing, footwear, boots and equipment should be made available at the entry points of protected areas (Sheley et al., 1996; Hughes and Convey, 2010; Huiskes et al., 2014; Valkó et al., 2020). Such practices are established in a few parts of the world and could be easily adapted in a wide range of protected areas. In some cases, washing with water is enough to remove harmful species from footwear or equipment (Young et al., 2008). Nevertheless, the choice of adequate disinfectants is important for mitigating environmental pollution. It is recommended to use authorized disinfectants (e.g., inactivated Virkon S breaks down into harmless salts) to clean the equipment (Curry et al., 2002; Young et al., 2008).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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