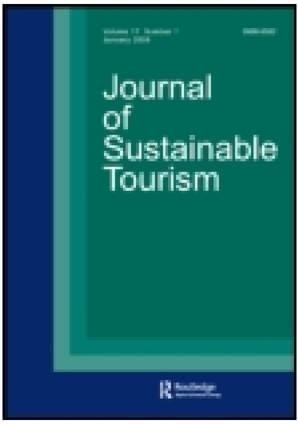

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Do tourists disperse weed seed? A global review of unintentional human-mediated terrestrial seed dispersal on clothing, vehicles and horses

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Do tourists disperse weed seed? A global review of unintentional human-mediated terrestrial seed dispersal on clothing, vehicles and horses

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Human-mediated seed dispersal is recognised as an important, but under-researched, issue. To assess the potential for tourists to act as unintentional seed dispersal agents, we reviewed published and unpublished data on seed dispersal via clothing, vehicles (cars) and in/on horses and donkeys, all of which can be used by tourists. Seeds from 754 species of terrestrial plants have been collected from these vectors, 15% of which are internationally recognised environmental weeds. Seeds were collected from personal clothing and equipment (228 species), the fur of donkeys and horses (42 species), horse dung (216 species) and vehicles (505 species). Most were herbs (429 species) or graminoids (237 species) and native to Europe. Annual Poa, White Clover, Kentucky Bluegrass and Yorkshire Fog were the most frequent species. There have been eight studies specifically on tourists, which identified 12 species on clothing, 26 on vehicles and 133 from horse dung. Methods that minimise the risk of tourists as human-mediated dispersal agents may therefore be appropriate for some tourism activities/destinations: suggestions are made. Further sampling using standardised experimental techniques is required to assess the relative risk associated with specific tourist activities and locations and determine which, and how much, seed is transported.

Keywords: human-mediated seed dispersal; plant invasions; vehicle; protected areas; quarantine risk

Introduction

Tourism by its very nature involves humans travelling. This includes among continents, between countries and within countries as well as to and within destinations. Tourists travelling to, from and within destinations can inadvertently carry seed on clothing, equipment, vehicles and/or even animals (horses, donkeys, lamas, dogs, etc.). Human-mediated dispersal can occur over longer distances than many natural mechanisms that often involve seed dispersal within a few metres of the parental plant (Fenner & Thompson, 2005; Nathan, 2008; Wichmann et al., 2009). Such long-distance dispersal, even if it is rare, has major implications for conservation (Nathan, 2008; Wichmann et al., 2009). Of particular concern for sustainable tourism, especially in protected areas, is the risk that tourists may act as unintentional dispersal agents of weed seeds, particularly environmental weeds (Pickering & Hill, 2007).

Weeds are plants that grow where humans do not want them to (Benvenuti, 2007; Richardson et al., 2001; Webber, 2003). The status of a plant as a weed is dependant on

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where it is growing, as a species can be native in one region, can be considered a major weed in another region and may be introduced into but not be a problem in a third region. For example Kentucky Bluegrass, *Poa pratensis*, is native in Europe, North Africa and Asia (Weber, 2003). In the United States and in Australia it is used as a turf species, but it can also be a problem, out-competing native species (United States Department of Agriculture [USDA], 2002; Weber, 2003). Plants can be agricultural weeds, which are plants that colonise agricultural lands where they may have adverse impacts including these on food production (Benvenuti, 2007; Richardson et al., 2001; Webber, 2003). They can also be environmental weeds, which are plants that invade natural vegetation and usually adversely effect native biodiversity and/or ecosystems (Benvenuti, 2007; Richardson et al., 2001; Webber, 2003). An example of a species that is both an agricultural and an environmental weed is Chilean needle grass (*Nassella neesiana*). This native of South America is a major weed in Australia and New Zealand where it out-competes pasture and native grasses, causing agricultural losses and declines in native plant diversity (Cooperative Research Centre for Australian Weed Management [CRC Weeds], 2003; Global Invasive Species Database [GISD], 2005). Weeds can be non-native species (i.e. alien, introduced, exotic) or native: it depends on their impact. For example, *Pittosporum undulatum* is a native of the subtropics of Australia and is sold in nurseries as an attractive tree species in many parts of the world. It has become a native environmental weed in the temperate regions of Australia as well as a non-native environmental weed in New Zealand, Cuba, Jamaica, Mauritius, Portugal, Hawaii and South Africa (GISD, 2005; Gleadow & Ashton, 1981).

Weeds have massive economic effects. The total economic losses due to weeds were US $37.7 billion dollars per year (2001 values) for pasture and crop weeds in Australia, the United States and the United Kingdom (Pimentel et al., 2001). Environmental loss from weeds was US $148 million per year in the United States (Pimentel et al., 2001). The accelerated rate of introduction of invasive species is considered to be the second most important cause of biodiversity loss internationally (World Conservation Union [IUCN], 2000).

In both urban and rural ecosystems many species including ornamental, forestry and agricultural species are deliberately introduced for commercial and related reasons. There is also unintentional human-mediated seed dispersal via farm equipment and the movement of soil, fertilizer, grain, hay and mulch (Benvenuti, 2007; Hodkinson & Thompson, 1997). In natural ecosystems, however, tourists could be the main dispersal mechanism for new species, as few other types of human activities are permitted. Also the deliberate introduction of new species (pasture, crop or ornamental) is usually restricted, particularly in protected areas.

For many protected areas, more tourism is associated with the presence of more non-native plant species (Lonsdale, 1999; McKinney, 2002; Usher, 1988). Non-native plants including environmental weeds are often found growing around tourism infrastructure including roads, tracks and trails in protected areas (Pauchard & Alaback, 2004; Pickering, Hill, & Bear, 2007; Potito & Beatty, 2005). Disturbance during the construction and use of tourism facilities can benefit the establishment and growth of weeds at the expense of natives. But do tourists act as human-mediated dispersal agents for non-native species, or are they only dispersed by other means, such as wind, native animals and water?

Activities commonly undertaken by visitors within protected areas include sightseeing, hiking/walking, camping, horse or mountain bike riding, rock climbing, fishing and water sports such as canoeing and four-wheel driving (Newsome, Moore, & Dowling, 2002; Worboys, Lockwood, & De Lacy, 2005). There is limited research on the potential for human-mediated dispersal of terrestrial seed by tourists undertaking these activities, despite it commonly being cited as an impact of tourism (Buckley, 2003; Landsberg, Logan,

& Shorthouse, 2001; Newsome et al., 2002; Pickering & Hill, 2007). Within terrestrial protected areas seed samples have been collected from tourist clothing (boots – Higashino, Guyer, & Stone, 1983), from tourist's cars (Lonsdale & Lane, 1994) and from the dung of horses ridden by tourists (Campbell & Gibson, 2001; Gower, 2008; Quinn et al., 2008; Torn, 2007; Weaver & Adams, 1996; Wells & Lauenroth, 2007).

Other studies conducted in protected areas have simulated tourist activities to quantify which seeds may be transported on clothing (socks, trousers and shoes – Mount & Pickering, 2009) or on horse dung (Whinam, Cannell, Kirkpatrick, & Comfort, 1994). In addition there are more general studies of human-mediated seed dispersal studies via clothing (Bullock & Primack, 1977; Clifford, 1956; Falinski, 1972; Healy, 1943; Wace, 1985; Whinam, Chilcott, & Bergstrom, 2005; Wichmann et al., 2009), cars (Clifford, 1959; Hodkinson & Thompson, 1997; Moerkerk, 2006; Schmidt, 1989; Von der Lippe & Kowarik, 2007, 2008; Wace, 1977; Zwaenepoel, Roovers, & Hermy, 2006) and horses (coats – Couveur, Christiaen, Verheyen, & Hermy, 2004; Couveur, Cosyns, Hermy, & Hoffmann, 2005; dung – Cosyns & Hoffmann, 2005; Mouissie, Vos, Verhagen, & Bakker, 2005; St John-Sweeting & Morris, 1991) that have identified seeds that could be transported by tourists.

To determine which species of plants have been or could be unintentionally dispersed by tourists, a global database was established of records of terrestrial seeds carried on equipment, animals or clothing of types that are used for tourism and recreational activities. It includes data from studies on tourists and studies simulating tourism activities in protected areas as well as other studies of the same vectors. The database was analysed to determine the following: (1) what methods have been used to collect and identify species; (2) which species of plants could be dispersed on clothing, vehicles and animals that are used for tourism; (3) if there are species in common among the vectors; (4) the characteristics (origin, growth form, life form and seed structures) of the species that could be dispersed by tourists; and (5) if they may be a threat (non-native, a recognised weed species, an international environmental weed).

Methods

An extensive search of scientific publication electronic databases (Google Scholar, Scopus, Science Direct, etc.) was conducted between February and May 2008 using different combinations of search terms such as vectors, visitors, man, human, clothing, horse, mountain bike, bike, boots, weeds, alien plants, cars, seeds and vehicles. Personal communication from other researchers and the authors' own work provided additional published and unpublished datasets (Table 1). Authors of two published studies (Moerkerk, 2006; Von der Lippe & Kowarik, 2007, 2008) kindly provided more complete species lists than were included in the original papers.

Two datasets from the authors of this paper were included in the global database (Table 1). Both are from manipulative experiments that quantified the amount and type of seeds collected and dispersal distances on human clothing. The first dataset is from seed collected on socks, shoes and trousers when walking in roadside and natural vegetation in Kosciuszko National Park in temperate south-eastern Australia (Mount & Pickering, 2009; Pickering & Mount, unpublished data – Kosciuszko National Park). The second is for seeds from socks and shoes worn on a walking track linking two national parks on the east coast of Australia in the subtropics (Pickering & Mount, 2008, 2009 unpublished data – Gold Coast). Two papers identified in the electronic searches (Von der Lippe & Kowrik 2007, 2008) represented different aspects of the result from the same experiment and therefore were treated as one dataset.

Table 1. Characteristics of 32 datasets/studies examining seeds collected on clothing, animals (horses and donkeys) and vehicles that can be used when engaging in recreational activities in protected areas.

Source	Vector	Continent	Zone	Sampled tourists	In protected area	Study type	Limited diversity	Method of Id	*Taxa in source	*Species listed	*Not native to continent of study	*Somewhere weed	Environmental weed
Clifford, 1956	H	Eu	Temperate	N	N	O	N	GG	42	39	3	35	13
Falinski, 1972	H	Eu	Temperate	N	N	NE	N	DI	32	30	3	26	3
Bullock & Primack, 1977	H	CA	Tropical	N	N	ME	Y	DI	3	2	1	2	0
Wace, 1985	H	Aus	Various	N	N	O	N	?	38	24	21	21	13
Whinam et al., 2005	H	Aus	Various	N	N	NE	N	GG	81	32	25	28	20
Mount, 2008	H	Aus	Temperate	N	Y	ME	N	DI	70	50	19	21	10
Mount & Pickering, 2009 + up. data KNP	H	Aus	Temperate	N	Y	ME	N	DI	—	59	21	30	12
Pickering & Mount, up. data GC	H	Aus	Subtropical	N	N	ME	N	DI	—	46	30	44	6
Wichmann et al., 2009	H	Eu	Temperate	N	N	ME	Y	DI	2	2	0	2	0
Higashino et al., 1983	H	Haw	Tropical	Y	Y	NE	N	DI, GG	16	12	12	11	3
Healy, 1943	H	NZ	Temperate	N	N	O	N	DI	33	1	1	1	1
Clifford, 1959	V	Afr	Tropical	N	N	O	N	GG	40	39	19	35	2
Wace, 1977	V	Aus	Temperate	N	N	NE	N	GG	259	96	74	93	30
Schmidt, 1989	V	Eu	Temperate	N	N	O	N	GG	124	34	6	33	9
Lonsdale & Lane, 1994	V	Aus	Tropical	Y	Y	NE	N	DI	88	26	12	17	3
Hodkinson & Thompson, 1997	V	Eu	Temperate	N	N	NE	N	GG	37	36	9	36	9
Zwaenepoel et al., 2006	V	Eu	Temperate	N	N	NE	N	GG	33	28	4	28	5

(Continued)

Von der Lippe & Kowarik, 2007, 2008	V	Eu	Temperate	N	N	NE	N	GG	20	200	40	194	39
Moerkerk, 2006, 2008	V	Aus	Temperate	N	~N	NE	N	GG, DI	20	222	181	211	59
Couveur et al., 2004	C	Eu	Temperate	N	Y	NE	N	Glab	75	38	4	38	13
Couveur et al., 2005	C	Eu	Temperate	N	Y	NE	N	Glab	29	29	4	29	9
Whinam et al., 1994	D	Aus	Temperate	N	Y	ME	N	GF	10	10	10	10	8
Weaver & Adams, 1996	D	Aus	Temperate	Y	Y	NE	N	GG	29	24	23	24	11
Campbell & Gibson, 2001	D	NA	Subtropical	Y	Y	ME	N	GG, GF	77	66	28	61	7
Cosyns & Hoffmann, 2005	D	Eu	Temperate	N	Y	NE	N	GG	106	70	5	68	19
Couveur et al., 2005	D	Eu	Temperate	N	Y	NE	N	Glab	53	53	5	51	17
Wells & Lauenroth, 2007	D	NA	Temperate	Y	N	NE	N	GG	20	17	9	16	4
Gower, 2008	D	NA	Temperate	Y	Y	ME	N	GF	3	3	3	3	2
Torn, 2007	D	Eu	Temperate	Y	Y	ME	N	GF	12	8	1	7	3
Quinn et al., 2008	D	NA	Subtropical	Y	~N	NE	N	GG, GF	32	31	25	28	8
St John-Sweeting & Morris, 1991	D	Aus	Temperate	N	N	ME	Y	DI, GG	6	6	6	5	3
Mouissie et al., 2005	D	Eu	Temperate	N	N	NE	N	GG	35	35	3	35	11

Key: Pickering & Mount 2009 + up. data KNP = Published and unpublished data of the authors collected in Kosciuszko National Park in 2009. Pickering & Mount, up. data GC = Unpublished data of the authors collected in on the Gold Coast in 2008 and 2009. Origin: Aus = Australia, Eu = Europe, NA = North America, CN = Central America, Afr = Africa, Haw = Hawaii; Vector: H = Human, V = Vehicles, C = Coats (Horse and Donkey), D = Dung (Horse); Study Type: O = Opportunistic sampling, NE = Natural experiment, ME = Manipulative experiment; Protected areas: N = study not conducted in a protected area, Y = study conducted in a protected area; Species identified from: GG = seed germinated in glasshouse, GF = seed germinated in the field, Glab = seed germinated in the lab, DI = direct identification of seed. *Taxa in source = number of species, genera and morphotaxa listed in source. *Species listed = total number of species identified. Some where a weed if listed in Global Compendium of Weeds (Randall, 2007), Environmental weed if listed by Weber (2003) in "Invasive Plant Species of the World".

Three datasets that examined dispersal time/viability/distances of a few selected species were included, as they still demonstrate that the vector can collect and transport seed from these species. Bullock and Primack (1977) examined the potential for clothing to act as a dispersal agent for three species (*Achyranthes aspera, Bidens* sp. and *Petiveria alliacea*) in Costa Rica. They quantified retention rates and mean dispersal distances, as well as examining the height at which seeds attached to different materials. St John-Sweeting and Morris (1991) fed six penned horses a mixture of seeds from six species of plants in south-eastern Australia and then examined seed viability from the dung over time. Wichmann et al. (2009) assessed human-mediated seed dispersal for *Brassica oleracea* spp. *oleracea* and *Brassica nigra* by exposing the soles of shoes to a fixed number of seeds of a given species and then assessed the number of seeds remaining on shoes after walking fixed distances. They modelled dispersal kernels for these two species that are found on walking tracks in Dorset, England. This study provides a method for assessing the potential for long-distance dispersal by humans.

The global database only recorded presence/absence of all species listed in each of the datasets, as there were differences in the methods used, in the duration and location of studies and in the measurements used (presence/absence, percentage of seeds, number of seeds, frequency of seed) to quantify seed among the studies. Data were recorded at the level of species, and hence taxa recorded only at the level of genera, or where the alternative species were listed or only as morphotaxa were not included. Details about the methods used to collect the datasets were entered, including the type of seed vector (human, vehicle, coat or dung), geographical location of study (actual location and continent or island on which the study took place – Africa, Europe, North and Central America, Hawaii and Australia), general climatic zone of the study (tropical, temperate, mountain, subtropical or unspecified), detail of sampling method (including if it was a manipulative or natural experiment or incidental observations, if it used seed germination or directly recorded seed collected and the like), if tourists were sampled and if the study was conducted in a protected area.

For each species recorded in one or more studies the following information was included in the global database: synonyms, origin, life form and seed appendages to aid dispersal for each species. Data on these species characteristics were obtained from published reference books (Harden, 1993; Weber, 2003) and reputable databases including PlantNET (2006), United States Department of Agriculture (USDA, 2008) and RBG Kew: GrassBase – The Online World Grass Flora (Clayton, Harman, & Williamson, 2008). Seed appendages to aid dispersal included wings, awns, hairs, spines, burs, ridges, pappus or bristles.

As the weed status of a species is location-dependent, we used three criteria to highlight the potential impact of a species. First we determined if a species was non-native to the continent in which the study was undertaken. For protected areas the presence of non-native plants is of concern even if they are not environmental weeds, as they alter the naturalness and conservation value of the area. Second, we listed a species as potentially a weed if it was included in a large comprehensive web-accessible database of over 28,000 species listed as weeds based on data from over 1000 sources (A Global Compendium of Weeds, Randall, 2007, 2009). This does not mean the plant was a weed in the location where the study was undertaken; it does mean that it has satisfied the criteria of being a weed in one or more published sources/locations. Therefore, in locations where it is a weed, it has the potential to be dispersed by the vector. Finally plants were identified as a global environmental weed if they were among the 400 species identified as major invasive plants species internationally by Weber (2003).

Data analysis

The total number of species, the number of species that were non-native to the study continent, that are weeds and serious environmental weeds was calculated from the global database for each study. For each vector type, the total number of species, number of species native to Australia, North American and Europe, the number of non-native species, somewhere weed species and environmental weeds were also calculated. Details on the most common species among studies were obtained from the database. For the studies conducted just in Australia, North America or Europe, the total number of species, number of species non-native to that continent, number of species somewhere a weed and number of environmental weeds were calculated overall and for each vector type.

Results

Research into tourism and recreational activities as seed vectors

Over the past 70 years only 32 scientific publications were identified from database searches and personal communication from other researchers in the field. Of the four vector types assessed, 11 studies looked directly at human clothing items; 8 were studies on cars and on animals used for tourism; 2 studies considered fur; and 11 examined dung (Table 1). Overall 8 datasets sampled tourists directly, and 13 datasets were obtained in protected areas. Eleven datasets were from Australia, 13 from Europe, 4 from North America, with 1 each from Hawaii, Africa, New Zealand and Central America (Table 1).

Currently there appears to be little consistency in the methods used to examine seed on clothing, on vehicles, on fur or in dung. The studies used a range of methods to collect seed, including picking, brushing and vacuuming seed off clothing and equipment, brushing seed from the fur of horses and donkeys, collecting dung in pastures and from trails, vacuuming seed or scraping mud off vehicles and even setting up seed traps in vehicle tunnels. Species in 11 datasets were directly identified using taxonomic guides and seed reference collections, while the other studies identified plants from material germinated in laboratories, glasshouses and/or the field (Table 1). Most datasets were from natural experiments (17 datasets) where samples were taken from people's clothing, vehicles or horse dung and quantified exposure and/or number of seeds per item/area/volume. Ten were from manipulative experiments where exposure was standardised for multiple replicates, and data were statistically analysed. Five datasets were opportunistic, with observations made of seeds collected on a few samples obtained as part of other activities.

Diversity of seeds collected

Seeds from 754 species representing 86 plant families were collected from people's clothing and equipment, fur and dung of horses and donkeys and vehicles that can be used when engaging in tourism and recreational activities including in protected areas (Table 2; in addition a full species list of seeds collected from clothing, horses and donkeys – fur or dung – and/or vehicles is available on request from the authors). Of these, 650 have been identified as weeds somewhere in the world, 372 were not native to the continent where the research was undertaken; and 114 were considered global environmental weeds (Table 2). Grasses (*Poaceae*) were the most common family accounting for 26% (195 species) of the total species, with the next most diverse family being the daises (*Asteraceae*, 120 species). Species of seed were predominantly from herbs (57%) and graminoids (31%; grasses, rushes, sedges, etc.), with seed from few species of shrubs or trees

Table 2. Number of species recorded in 32 studies that examined seed collected on humans (clothing and equipment), animals (horses and donkeys) and vehicles that can be used when engaging in recreational activities in protected areas.

Vector	Total	Humans	Vehicles	Animals	Fur	Dung
Number studies	32	11	8	13	2	11
Total species	754	228	505	234	42	216
Origin						
Australian species	155	80	78	16	4	15
European species	386	107	289	164	36	150
North American species	117	19	59	66	5	64
Problem status						
Not native to study continent	372	94	288	95	6	91
Somewhere a weed	650	167	472	220	42	202
Environmental weeds	114	44	98	48	13	45
Growth form						
Tree	32	1	29	2	0	2
Shrub	40	17	22	3	1	3
Graminoid	237	93	157	67	13	65
Herb	429	113	290	160	27	145
Life form						
Perennial	386	152	227	111	22	106
Annual/biennial	284	53	224	95	18	84
Attachment type	416	139	272	124	27	113

collected (Table 2). More perennial than annual species were collected. Attachment structures occurred in just over half of the species (Table 2).

A total of 169 species of these seeds were collected directly from tourists, from their shoes (one study, 16 taxa, 12 species identified), cars (one study, 88 taxa, 26 species identified) or the dung of horses they have ridden (six studies, 133 species). Thirty-five of all the species collected from tourists, their cars and horses were environmental weeds.

Three vehicle datasets had the highest diversity of species collected (Table 1). The studies conducted by Moerkerk (2006), composed of 222 species, were identified from samples taken from 154 sedans and utilities. The vehicles were owned by the government and contractors, with samples taken as part of a training programme in minimising weed spread conducted by the, Victorian Department of Sustainability and the Environment in Australia (Moerkerk, 2006, personal communication, 2009). A total of 200 species were identified from seed traps from three motorway tunnels in Europe that collected samples for a year (Von der Lippe & Kowarik, 2007, 2008). The third study with high diversity was of 96 species germinated from sludge collected over a year from a car wash in Canberra, the capital city of Australia (Wace, 1977) (Table 1).

Common species

There were few species in common among the studies, with 521 species unique to a specific study. The most commonly recorded species was the annual grass *Poa annua* (Winter Grass) which was collected from the bottom of shoes in Europe and Hawaii and clothing of tourists returning to Australia from Kashmir, on clothing of expeditioners to a sub-Antarctic island, on shoes and socks of expeditioners in the alpine and subtropics of Australia, on vehicles in Australia, England, Germany and France and in dung from horses in Australia, United States and Europe (20 studies in total; Table 3). Although not considered a serious environmental

Table 3. Characteristics of species recorded in 10 or more of 32 studies that examined seeds collected on humans (clothing and equipment), animals (horses and donkeys) and vehicles that can be used when engaging in recreational activities in protected areas. Gram. = Graminoid.

Species	Family	Common name	Geographic origin	Growth form	Life form	Environmental weed	Weed some where	Total studies	Humans	Vehicles	Animals	Fur	Dung
Poa annua	Poaceae	Winter Grass, Annual Poa	Europe	Gram.	Annual		Y	20	7	5	8	2	6
Trifolium repens	Fabaceae	White Clover	Europe, N Africa, Asia	Herb.	Perennial	Y	Y	17	3	5	9	1	8
Poa pratensis	Poaceae	Kentucky Bluegrass	Europe, N Africa, Asia	Gram.	Perennial	Y	Y	15	3	5	7	2	5
Holcus lanatus	Poaceae	Yorkshire Fog	Europe, N Africa, Asia	Gram.	Perennial	Y	Y	14	3	4	7	2	5
Plantago lanceolata	Plantaginaceae	Lamb's Tongues, Plantain	Europe, N Africa, Asia	Herb	Perennial	Y	Y	13	4	3	6		6
Agrostis capillaris	Poaceae	Browntop Bent	Europe, Africa, Asia	Gram.	Perennial	Y	Y	12	4	2	6	2	4
Plantago major	Plantaginaceae	Large Plantain	Europe, Asia	Herb	Perennial		Y	12	1	5	6	2	4
Stellaria media	Caryophyllaceae	Common Chickweed	Europe	Herb	Annual		Y	12	1	5	6		6
Juncus bufonius	Juncaceae	Toad Rush	Australia	Gram.	Annual		Y	12	1	5	6	1	5
Lolium perenne	Poaceae	Perennial Ryegrass	Europe, N Africa, Asia	Gram.	Perennial	Y	Y	11	3	4	4	1	3
Dactylis glomerata	Poaceae	Cocksfoot	Europe, N Africa, Asia	Gram.	Perennial	Y	Y	10	2	4	4	2	2
Acetosella vulgaris	Polygonaceae	Sheep Sorrel	Europe, N Africa, Asia	Herb	Perennial	Y	Y	10	3	3	4		4

weed (Weber, 2003), this native of Europe is an invasive weed in parts of North America (USDA, 2008) and of disturbed sites in Australia (PlantNET, 2006).

The next most common species was the perennial herb *Trifolium repens* (White Clover), which is used as a forage species (Table 3). This native of Europe is an invasive weed in natural areas in Australia and occurs in a range of habitats in New Zealand, southern Africa, tropical Asia and South and North America (Weber, 2003). *Trifolium repens* seeds were collected from clothing in Australia, from vehicles in Australia, Germany and England, from the fur of horses and donkeys in Belgium and in horse dung in the United States, Europe and Australia (17 studies; Table 3).

Poa pratensis (Kentucky Bluegrass) is a perennial grass native to Europe, North Africa and Asia. It is a serious environmental weed in Australia, Canada, the United States and Mexico. It has been introduced in Hawaii, New Zealand, Africa and Asia (Weber, 2003). It is competitive, spreads rapidly and often out-competes native grasses and forbs (Weber, 2003). It was collected on clothing in Australia, on vehicles in Australia and Europe, on the coats of horses in Belgium and in dung in Australia, North America and Europe (15 studies; Table 3).

The perennial grass *Holcus lanatus* (synony mous with *H. argenteus*, Yorkshire Fog) is a serious environmental weed in Australia, Hawaii and the western part of the United States (Weber, 2003). It has been introduced to southern Africa, tropical Asia, New Zealand, Mexico and South America (Weber, 2003). It can out-compete natives and produces large amounts of wind-dispersed seed (Weber, 2003). It was collected on clothing in Australia, vehicles in Australia, Germany and England and the fur of horses and in donkeys in Belgium and horse dung in Australia and Europe (14 studies; Table 3).

Of the other eight species common to 10 or more studies, all are annual or perennial graminoids or herbs, and all but one is native to Europe, with all regarded as weeds somewhere in the world, five of which are considered serious environmental weeds (Table 3).

People's clothing as a seed vectors

Clothing and equipment can transport seeds including weed seeds. Seeds from 228 species have been obtained from clothing and equipment; 94 were not native to the study continent, of which 44 species were environmental weeds (Table 2). Seeds have been obtained from a variety of clothing including shoes (Clifford, 1956; Falinski, 1972; Higashino et al., 1983; Mount & Pickering, 2009; Pickering & Mount, unpublished data; Wace, 1985; Wichmann et al., 2009), socks (Falinski, 1972; Mount & Pickering, 2009; Wace, 1985), trousers (Falinski, 1972; Healy, 1943; Mount & Pickering, 2009; Wace, 1985), shirts (Bullock & Primack, 1977) and backpacks and jacket pockets and seams (Whinam et al., 2005). Nearly all of the species collected from clothing were herbs (113 species) or graminoids (93 species), with a few shrubs (17 species) and only one tree species (Table 2). The most common species among the clothing datasets were *Poa annua* (seven datasets), *Hypochaeris radicata* (six datasets), *Agrostis capillaris* (four datasets), *Plantago lanceolata* (four datasets), *Taraxacum officinale* (four datasets), *Anthoxanthum odoratum* (four datasets) and *Bidens pilosa* (four datasets).

In the study that directly sampled tourists' clothing, 12 species were identified from the running shoes of ~720–810 people in the Hawaii Volcanoes National Park (Higashino et al., 1983). All of these were not native to the continent of study, and 11 were weeds somewhere in the world, of which 3 species were serious environmental weeds (Table 1). One of the species, *Melinis minutiflora*, was considered to be of particular concern, as it was already invasive in the park (Higashino et al., 1983).

Manipulative experiments simulating tourist behaviour were undertaken by the authors in Kosciuszko National Park in south-eastern Australia in 2009 (Mount & Pickering 2009; Pickering & Mount, unpublished 2009 data – Kosciuszko National Park) and on a roadside walk that connects two national parks in the Gold Coast in the subtropics of eastern Australia (Pickering & Mount, 2008, unpublished 2009 data – Gold Coast). These studies identified seeds from 105 species that could be transport on clothing, 59 in Kosciuszko National Park and 46 on the Gold Coast. Statistically significant differences in the number and diversity of seeds were found among shoes, socks and trouser legs but not among different types of shoes (Mount & Pickering, 2009; Pickering & Mount, 2008, unpublished 2009 data – Gold Coast).

Vehicles as seed vectors

Over two-thirds of all the species in the global dataset were collected from vehicles (Table 2). This may reflect the greater capacity of cars to act as dispersal agents or greater sampling intensity. Three vehicle datasets are from studies conducted over a long period (a year or more) and/or sampled a large number of sources (Moerkerk, 2006, 2008; Von der Lippe & Kowarik, 2007, 2008; Wace, 1977). Nearly all of the species collected from vehicles (94%) are weeds somewhere, and 288 species were not native to the study continent. However, only 12% of the species were internationally environmental weeds. There were some differences in the growth forms of species collected on vehicles, with more seed from a greater range of tree species found on vehicles than from clothing or horses (Table 2). The most frequent species on vehicles in the global database were the graminoids *Poa annua*, *Poa pratensis and Juncus bufonius* and the herbs *Plantago major*, *Chenopodium album*, *Polygonum aviculare*, *Sonchus asper*, *Stellaria media* and *Trifolium repens*, which occurred in five datasets. As there were no studies on vehicle-mediated dispersal from North America, there were relatively few North American species collected.

Horses as seed vectors

Just over a third of all the species were collected from horses (and donkeys coats), with 42 found on the coats of horses and donkeys transferred between nature reserves and 216 species collected from the dung of horses (Table 2). Although three of the datasets came from Australian studies, there were only 16 species native to Australia collected, with many European (164) and some North American species (66) germinating from dung. Nearly all the species in dung were weeds somewhere (94%) with just over 20% environmental weeds (Table 2). The most common species on horses were *Trifolium repens* (nine studies), *Poa annua* (eight studies), *Poa pratensis* and *Holcus lanatus* (seven studies each), and *Juncus bufonius*, *Plantago major*, *Stellaria media*, *Plantago lanceolata* and *Agrostis capillaries* (six studies each).

Tourists as seed vectors in Europe

A total of 315 species were recorded from the 13 European datasets (Table 4). Across the four studies that examined seed from horse dung, 101 species were identified, 9 of which were not native to Europe. The two studies examining seeds on the fur of horses and donkeys identified 42 species, all but 6 of which native to Europe (Table 4). From clothing 70 species were identified, only 6 of which were not native to Europe. Well over two-thirds of the species identified in European studies came from vehicles, although none directly sampled tourists' vehicles or were conducted in protected areas. Although they sampled roadsides linking urban areas or in car parks in urban areas their results highlight the diversity of seed that can be carried on vehicles in Europe.

Table 4. Summary of the total weeds and environmental weed species in European, North American and Australian studies that looked at seeds collected by humans, animals and vehicles that can be used in recreational activities in protected areas.

Vector	Studies	Total species	Not native to the continent	Somewhere a weed	Environmental weed
European					
All	13	315	59	298	54
Human	3	70	6	62	15
Vehicle	4	228	49	221	42
Coats of horses	2	42	6	42	13
Dung	4	101	9	96	24
North America					
Dung	4	110	60	102	18
Australia					
All	11	410	271	335	87
Human	5	155	78	103	31
Vehicle	3	296	228	274	76
Dung	3	33	32	32	17

Tourists as seed vectors in North America

No studies of seeds on humans or vehicles conducted in North America were found in the database searches, despite there being a large body of research available for North America on weeds (USDA, 2008) and recreational ecology (Buckley, 2005). The four North American studies examining species that germinated from horse dung identified 110 species, of which 55% were not native to continental North America (Table 4). Nearly all of the species collected are a weed somewhere (102 species), and 18 are environmental weeds (Table 4).

Tourists as seed vectors in Australia

Eleven datasets came from Australia: five on human clothing and equipment, three on vehicles and three on horse dung (Table 4). These studies accounted for just over half of all the species recorded (410 species). The three vehicle studies collected the greatest diversity of seed (296 species). Most of these were not native to Australia (77%); nearly all are weeds somewhere (93%); and many are international environmental weeds (26%).

In the Australian studies, 155 species were identified as adhering to and being transported by people's clothing and equipment (Table 4). Just over half of these species were not native to Australia, even though three of the five studies were conducted in protected areas where weeds should be less common. A total of 31 of the species were international environmental weeds (Table 4).

The studies looking at seed germinating from horse dung in Australia collected the lowest number of species (33 species) of which all but one were not native to Australia, and 17 of which were international environmental weeds (Table 4).

Discussion

People's clothing and equipment and their vehicles and animals (horses and donkeys) used for tourism and recreation have the potential to carry seeds from a wide range of species.

Over a quarter of species considered to be important environmental weeds internationally have been found to be transported by these vectors (114 of 400 species listed in Weber, 2003). The dispersal distances associated with these vectors are likely to be larger than many natural dispersal mechanisms, as seeds were transported at landscape (10^2–10^3 m, Mount & Pickering, 2009) and regional (10^3–10^5 m) scales (Wichmann et al., 2009), and some at the biogographical scale (10^5–10^7 m; Whinam et al., 2005; Nathan, 2008). Therefore, people moving among tourism destinations may introduce new species into continents (Wace, 1985), countries (Wace, 1985), islands (Whinam et al., 2005) and protected areas (Campbell & Gibson, 2001; Lonsdale & Lane, 1994; Weaver & Adams, 1996). They may also contribute to seeds movement within tourism destinations through transporting weed seeds from road and track verges further into the natural environment (Bullock & Primack, 1977; Mount & Pickering, 2009; Wichmann et al., 2009). As weeds are major threats to biodiversity internationally (WCU-IUCN, 2000; Weber, 2003; Williams & West, 2000) and are expensive to control (Pimentel et al., 2001), the results highlight the significant threat to sustainability that tourists may pose when they act as accidental weed seed vectors.

There is very little standardisation in the methods used to obtain the different datasets, limiting the capacity to test for differences in the diversity or number of seeds among vectors and locations. Some studies have estimated the number and diversity of seeds carried by a particular vector in a given location and even for a given duration/distance of exposure. Estimates for clothing indicate that a large amount of seed from a wide range of species can be transported, often over long distances. The cuffs (also called turn-ups) of a single pair of trousers were found to carry 17 g of seeds representing 33 species of plants (Healy, 1943). An average of 15 propagules per person was obtained for expeditioners travelling from Tasmania, Australia, to a sub-Antarctic island (Whinam et al., 2005). The amount and diversity of seeds they carried was highly variable, with 20 of the 64 people sampled having no seed and 1 person having 309 seeds (9 species; Whinam et al., 2005). Socks worn for a five-minute walk along roadsides in Kosciuszko National Park in Australia collected an average of 648 seeds, representing six species ($n = 9$; Mount & Pickering, 2009).

Once attached to clothing seeds can be dispersed over long distances. The mean dispersal distances of the herb *Achyranthes aspera* ranged from 5 m to 2.4 km when attached to cloth in manipulative experiments conducted in Costa Rica (Bullock & Primack, 1977). Some seeds from two small herbs remained attached to shoes after 5 km of walking in experiments modelling human and natural dispersal kernels in England (Wichmann et al., 2009).

Studies of vehicles have also found that large numbers of seed can be carried per car, with high variability within and among studies. An average of 6.4 seeds was collected per car (maximum 789 for a single car) in Kakadu National Park in the tropics of Australia ($n = 304$ cars; Lonsdale & Lane, 1994). For cars in south-eastern Australia, the number of taxa of seeds carried varied between none and 69 per car, with an average of 20 taxa per car (Moerkerk, 2006, 2008). A total of 3926 seedlings (124 species) were collected from a single car in Germany after it was driven 15,000 km (Schmidt, 1989). In contrast, cars in Belgium only carried an average of three seeds per car ($n = 240$; Zwaenepoel et al., 2006).

Many seeds can germinate from horse dung collected from tourist horses ridden in protected areas. For example, 382 seedlings per litre of dung were obtained from 56 samples collected from four dune reserves in Belgium, although one or no seedling germinated from many samples (Cosyns & Hoffmann, 2005). The dispersal distances for seed in horse dung can be large, as seed eaten by horses on one day may not be deposited for several days, during which time the horses may have moved or may have been transported far away from the source. When the time it takes for seed to pass through the digestive tract of horses was assessed, peak transmission was found at three to five days after the seeds were eaten, and viable seeds were still present in dung produced 10 days after the seeds were eaten (St John-Sweeting & Morris, 1991). Due to this long transmission time of viable seed, what the animal is fed prior to entry to protected areas is important in reducing the accidental introduction of non-native seeds (Pickering, 2008).

Comparative experimental research using standardised techniques can be used to test for differences in the amount and diversity of seed transported by tourists clothing, vehicles and animals. Research by the authors on clothing has quantified the amount and type of seed that can be collected per item and per period/distance of exposure on different types of clothing worn in the same location (Mount & Pickering, 2009; Mount & Pickering, 2008, unpublished 2009 data – Gold Coast). For example, we are using the amount of seed collected on sports socks after replicating five-minute walks as a standard for comparing seed dispersal by tourists in different locations and at different times of the year. We are replicating 100-m walks to compare the seeds collected on horses, hikers' socks and boots and mountain bikes. We have already used 100-m walks on roadsides in a manipulative experimental design (split plot) to compare among items of clothing (Mount & Pickering, 2009). Boots, uncovered socks and laces were found to collect significantly more seeds than covered socks and laces. This resulted in 17% fewer seeds collected by someone walking in trousers compared with shorts. The average number of seeds collected after a 100-m walk along a roadside was 66 per boot, 157 per uncovered sock, 10 per covered sock, 66 per uncovered lace, 30 per lace partly coved by trouser leg and 145 per trouser leg.

In addition to knowing what seed is carried and how much of it is carried, it is important to determine how far it is carried. Recent research that modelled the dispersal kernel for human-mediated seed dispersal indicates that an exponential power model best matched the way in which seed from two species of wild cabbage dispersed from the soles of shoes (Wichmann et al., 2009). Testing this model on a greater range of species and for attachment to different items of clothing, as well as other vectors, will help elucidate the contribution that tourists might unintentionally be making to long-distance dispersal of weeds. Sampling a greater range of activities/equipment/animals is also likely to identify new species. For example, seeds are likely to be carried on the wheels of other types of recreational vehicles including mountain bikes, quad bikes and motorbikes.

Managing the risk

Tourists have the potential to transport seeds over long distances, including seeds from many environmental weeds. Awareness of these risks and methods to minimise them are, therefore, important. This is true for tourists, tourism operators and those responsible for the management of where tourists go (protected-area managers, national quarantine organisations, etc.). This is particularly important for isolated reserves such as islands in world heritage areas, for example the Greater Barrier Reef and the Galapagos or sub-Antarctic islands – all destinations with high conservation values, with ecosystems that are at particular risk from new environmental weeds and where tourism is popular.

Simple measures such as cleaning cars, boots and other equipment prior to travelling and before leaving a destination are likely to reduce risks. Some government agencies responsible for managing natural areas have already implemented educational programmes emphasising these approaches to minimise the risk of weed spread. The Department of Sustainability and the Environment in Victoria, Australia, runs weed movement and machinery inspection and clearing workshops (WeedStop) to educate contractors and those employed by government agencies. They discuss strategies to minimise the spread of weeds including identifying species that are a problem locally, selecting fodder and grain that is likely to be free of weed seeds, checking stock for seeds and implementing cleaning programmes for machinery and vehicles including establishing washdown facilities (Moerkerk, 2006, personal communication, 2009). Codes of conduct are another way protected-area managers can reduce the risk of weed introduction particularly by horses. They can include recommendations on cleaning vehicles, gear and horses prior to transport to protected areas, providing weed-free processed feed to horses including prior to arrival in the protected area and only using tethering areas within parks (Wells & Lauenroth, 2007; Australian Alps Liaison Committee [AALC], 2009; Environment Protection Agency [EPA], Queensland Government, 2009). Methods used to restrict the spread of pathogens such as the root rot fungus *Phytophthora* are likely to have the incidental effect of reducing the risk of weed spread. They include recommendations for staff and tourists to wash down vehicles and boots, the closure of walking tracks and, in some cases, the closure of parks at certain times of the year (Boon, Fluker, & Wilson, 2008; Buckley, King, & Zubrinick, 2004). Educational programmes including interpretive signage, flyers and web pages about minimal impact behaviour by tourists including for *Phytophthora,* however, do not always result in recognition of the issue and the desired changes in tourists' behaviour (Boon et al., 2008; Littlefair & Buckley, 2008). Providing better information for visitors about why such programmes are important may change behaviour (Boon et al., 2008).

Finally, some organisations have changed the type of equipment, or the material it is made of, or the way it is fastened to those that are less likely to collect and transport seed. For example, as result of the Whinam et al. (2005) study, there have been changes in the storage and cleaning of equipment, in what it is made of and in how clothing is fastened for people travelling with the Australian Antarctic Division to sub-Antarctic islands and Antarctic bases. This includes minimising the use of Velcro to fasten gaiters, jackets and other equipment, as many of the seeds collected from expeditioners were found attached to Velcro fastenings.

Conclusions

A wide range of weed species have the potential to be transported by tourists into and within tourism destinations including protected areas. Further research to obtain better estimates of this dispersal mechanism is required. This includes the following: (1) research on tourists themselves, (2) more experimental manipulative research that can quantify and test for differences among vector types, (3) research into the distances seed is dispersed and (4) research into the potential effectiveness of control measures. Application of the precautionary principle would suggest that until such data are collected, methods to minimise potential impacts should still be considered by people managing tourism and protected areas.

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