Effects of human-mediated processes on weed species composition in internationally traded grain commodities

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Summary

International trade is a major route by which non-indigenous organisms are introduced into new habitats. Various kinds of weed seeds have been introduced through grain trade. The objectives of this study were to understand the factors that affect the initial assemblage of plant species introduced by the international grain trade and to extract their general attributes. We surveyed weed seed contamination of spring wheat imported from Canada to Japan and analysed the effects of the field abundance of each weed and of harvesting and cleaning on the quantity of weed seed included in the imported wheat. The field abundance was positively correlated with the weed seed quantity. Seeds of short weeds and seeds with a pappus were eliminated from the wheat by the harvesting or cleaning process. Many other crop plants contaminated the wheat. Because various transportation vehicles, temporary storage sites and port elevators are used commonly with all exported crops and it is difficult to remove all residues from them, other crops might be carried over into the wheat commodity. These relationships also apply to other grains.

Keywords: cleaning, harvesting, contamination, field abundance, weed seeds, wheat.

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Introduction

The transportation of invasive alien species among continents, regions and nations has often had significant impacts on the recipient ecosystems (Williamson, 1996; Mack *et al*., 2000; Sala *et al*., 2000) and has caused major economic losses in agriculture, forestry and other industries ([OTA] U.S. Congress, Office of Technology Assessment, 1993; Pimentel *et al*., 2000). Disease-causing invaders (McCormick & Platt, 1980; Van Riper *et al*., 1986), predation and grazing by invaders (King, 1984; Dickman, 1996; Goldschmidt, 1996; Naylor, 1996) and superior competitiveness of invaders (D'Antonio & Mahall, 1991) can devastate native species and reduce crop production.

Successful invasion comprises three stages: introduction of a species to a new habitat outside its native range, establishment of self-sustaining populations within the habitat and spread of the organism to nearby habitats (Williamson, 1996). The establishment and spread stages have received the greatest attention. On the other hand, very limited study has focused on understanding how species are introduced (Puth & Post, 2005, but see Green, 1997; Tilman, 1997; Lonsdale, 1999), although several authors have pointed out that variations in the level of invasions among recipient communities could be simply the consequence of differences in the numbers of exotics introduced (Williamson, 1996; Mack *et al*., 2000).

Identifying general attributes of introduced species can help prevent their establishment and spread. Many attempts have been made to construct lists of common traits shared by successful invaders (Heywood, 1989). Although some invaders may have traits in common, such

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lists are applicable only for a small group of species and exceptions abound (Rejmanek & Richardson, 1996). These discrepancies could simply reflect a lack of consideration of the mechanisms of introduction, rather than a lack of attributes that favour establishment and spread (Simberloff, 1989). Thus, information on how many propagules of each species were introduced and which of them succeeded in establishment and spread is required.

To understand opportunities for alien species introduction, we need to take into account human-mediated processes. International trade has long been recognised as a major route by which non-indigenous organisms are introduced to new habitats (Lonsdale, 1999; Mack *et al.*, 2000; Levine *et al.*, 2003). Many worldwide invasive plants were introduced accidentally or intentionally through global commerce (Mack *et al.*, 2000). Exotic weeds in agricultural fields are typical cases of unintended introduction. Some studies reported that various kinds of weed seeds were contained in imported grain seeds (Fay, 1990; Huelma *et al.*, 1996; Shimizu, 1998). Because the volume of global trade of cereals is more than 100 million tonnes every year (USDA, 2004), a very large amount of weed seeds is introduced into grain-importing countries, even if the commodity contamination levels are very low. Human-driven movements of organisms now have more impact on species distribution than the movements of organisms by natural forces (Carlton & Geller, 1993).

The objectives of this study were to understand the factors that affect the assemblage of plant species introduced as contaminants through the international grain trade and to extract their general attributes. We surveyed weed seed contamination of spring wheat imported from Canada to Japan for the following reasons: (i) Canada is one of the world's principal exporters and Japan is a major importer of cereal grains (FAO, 2004); (ii) the grain cleaning process in Canada is well documented (CGC, 2006b); and (iii) the species composition and density of the weed flora have been well surveyed periodically in agricultural ecosystems in Canada (Thomas, 1985; Leeson *et al.*, 2005). In this study, we analysed the effects of the field abundance of weeds and of grain harvesting and cleaning on the quantity of weed seed included in the wheat.

Materials and methods

Prairie weed survey

The cereal and oilseed grains exported from Canada are produced mostly in the central provinces of Alberta, Saskatchewan and Manitoba (i.e. the Canadian Prairies). Researchers have periodically surveyed the species composition and density of the weed flora in agricultural ecosystems there since the 1970s (Thomas, 1985; Leeson *et al.*, 2005). Field selection was based on a stratified, random-sampling methodology using ecodistricts, which are areas of similar landform, soil, vegetation and land use, as the units for stratification. The surveys were conducted in the summer before harvest. We used the data from 1593 spring wheat fields in the 2000s, the most recent data available. We calculated the abundance of each species (number of plants per m^2) from the frequency (number of fields in which a target species occurred as a percentage of the total number of fields), field uniformity (number of quadrats per field in which a target species occurred as a percentage of the number of quadrats) and density (number of individuals of a target species per m^2, expressed as an average over the fields in which the target species occurred) of each target species: 1593 fields $\times$ frequency/100 $\times$ 20 quadrats $\times$ field uniformity/100 $\times$ field density. The abundance of each species fluctuated across the years, but the general trend of major weeds was almost similar over several years. Therefore, we assumed that the records of the 2000s would be appropriate for our analysis of wheat samples obtained in 2006.

Grain cleaning in Canada

More than 20 million tonnes of grain is exported from Canada every year (CGC, 2006a). Port elevators are used to receive, clean, dry, store and ship grain before export (CFIA, 2006). Grain is cleaned to remove the 'dockage' to meet the export standards as established by the Canadian Grain Commission (CGC, 2006b). Dockage is waste material in grain, which must be removed for assignment of a grade. Any material left in grain after the cleaning is called 'foreign material'. The foreign material usually includes weed seeds, roughage, stones, ergot, *Sclerotinia* sclerotes and so on, even after cleaning. The maximum total foreign material allowed in highest-quality export wheat is 0.4% by weight. During cleaning, light waste material is removed by aspiration, waste material larger than threshed wheat is removed by 'riddle' (sieve) and then waste material smaller than threshed wheat is removed by 'buckwheat sieves' (CGC, 2006b).

The ports of Vancouver and Prince Rupert are the major ports in Canada (CGC, 2006a). Wheat exported to Japan is treated at both ports. All exported grains are processed through shared elevators at each port.

Identification of weed seeds detected from spring wheat imported into Japan

In 2006, we investigated two 20-kg and one 10-kg samples of spring wheat imported from Canada to

Japan to determine contaminant seed composition. The wheat is destined for milling for human food trade. Each sample came from a different shipment. The samples had not gone through any cleaning or processing in Japan. First, we sieved each sample in a No. 7 hand sieve (opening of 2.83 mm; Bunsekifurui Co., Tokyo, Japan) to separate out the material smaller than the wheat. The grain remaining on the sieve was a mixture of large seeds and wheat seeds; we picked out the large seeds by hand. The material that passed through was then placed in a No. 48 sieve (opening of 0.297 mm) to separate out the fine dust. No seed was present in the dust. Seeds other than wheat were picked out of the material remaining on the No. 48 sieve. These processes were conducted carefully so as not to miss any weed seeds. The hand-sorted seed samples were then weighed and the percentage was calculated. The seeds were identified on the basis of the shape, size, colour and texture of the surface (Martin & Barkley, 1961; Davis, 1993; Ishikawa, 1994; Guo, 1998; Guan *et al*., 2000) and the number of each type was counted. To verify the seed identification, some of the seeds were germinated and grown in an isolated garden to maturity and then the plants were identified (Osada, 1989; Flora of North America Editorial Committee, 1993 +; Flora-Kanagawa Association, 2001).

Statistical model

As suggested in Asai *et al*. (2007), several factors might affect contamination: field abundance at harvest, life cycle (annual or perennial), plant height, seed size, presence or absence of a pappus and status as weed or crop. We took these factors into account for several reasons:

1. Generally, a positive correlation is expected between the field abundance of a weed and its total seed production. Therefore, seeds of abundant weeds are more likely to contaminate wheat.
2. Most annuals reproduce only by seeds, but perennials often regenerate from vegetative organs. Because perennials sometimes allocate resources for reproduction into vegetative propagation instead of into seeds (Silvertown, 1987), field abundance and seed production of perennials do not necessarily correlate positively. Therefore, fewer seeds of perennials than of annuals were expected.
3. Wheat grows *c*. 100–120 cm tall. Seeds of shorter weeds than this are likely to be eliminated during harvesting. Therefore, seeds of taller weeds are more likely to contaminate wheat.
4. Seeds larger or smaller than wheat can be eliminated by the cleaning processes. Therefore, similar size seeds to wheat are more likely to contaminate wheat.
5. Seeds with a pappus are likely to disperse and be eliminated by the harvesting or cleaning processes. Therefore, seeds without a pappus are more likely to contaminate wheat.
6. Various transportation vehicles, temporary storage sites and port elevators are used between the farm fields and the commodity sampling in Japan, all of which usually handle various crops and are subject to incomplete cleaning, resulting in carry-over of non-commodity crops into wheat. Therefore, seeds of other crops are more likely to contaminate wheat.

We compared species contaminating the wheat with those ranked in the top 100 by field abundance in spring wheat fields (Leeson *et al*., 2005), but pteridophyte species were excluded from the analysis. Seed size was defined as the longest dimension of the seed. Information about typical seed size was obtained from seed identification books (Davis, 1993; Guan *et al*., 2000) and the Seed ID Workshop (McDonald *et al*., 2006). Information about plant height and life cycle was obtained from the PLANTS Database (USDA, 2006) and *Flora of North America* (Flora of North America Editorial Committee, 1993 +). If ranges of seed size and plant height were presented, median values were used. Biennial herbs were categorised as annuals. The nomenclature followed Darbyshire (2003).

We used a general linear mixed-effects model fitted by maximising the restricted log- likelihood to analyse the effects of field abundance, life cycle, plant height, seed size, pappus presence and status as crop or weed on the number of weed seeds in the wheat. The wheat samples were included as a random variable. We added 0.5 to the seed number and field abundance and then log-transformed the seed number, field abundance, seed size and plant height. Statistical analyses were performed using R v. 2.3.1 (R Development Core Team, 2006).

Results

Contaminant seed composition

Forty-two types of weed seeds from 13 families were found in the wheat samples (Table 1). Thirty-five were identified to species level, three to genus level and four to family level only. Poaceae was the most dominant family, with 11 types, followed by Brassicaceae (5), Asteraceae (5) and Chenopodiaceae, Fabaceae and Polygonaceae (4 each). The mean percentage of contaminant seeds in wheat samples was 0.23% by weight. The total number of contaminant seeds was about 1700 per 10 kg of wheat (Table 1). The species composition of each sample was similar. Seed of *Brassica* spp. (oilseed

Table 1 Numbers of each seed type detected in spring wheat imported from Canada into Japan. Weights of wheat samples 1, 2 and 3 were 20 , 20, and 10 kg respectively

Family	Scientific name	English name	Seed number/10 kg wheat			
			Sample 1	Sample 2	Sample 3	Mean
Alismataceae	*Alisma plantago-aquatica* L.	European water plantain	0.0	0.5	0.0	0.2
Amaranthaceae	*Amaranthus retroflexus* L.	Redroot pigweed	4.5	1.5	5.0	3.7
Asteraceae	*Anthemis cotula* L.	Stinking mayweed	1.0	0.0	0.0	0.3
	Cirsiinn arvense (L.) Scop.	Canada thistle	0.5	0.0	0.0	0.2
	Helianthus annuus L.	Sunflower	0.5	2.0	1.0	1.2
	Sonchus asper (L.) Hill	Spiny annual sow-thistle	0.0	1.0	0.0	0.3
	Asteraceae sp.	–	1.0	0.0	0.0	0.3
Boraginaceae	*Buglossoides arvensis* (L.) I.M. Johnston	Corn gromwell	0.0	0.5	0.0	0.2
Brassicaceae	*Brassica* spp.	Canola/rapeseed	204.0	584.0	896.0	561.3
	Camelina microcarpa Andrz. *ex* DC.	Small-seeded false flax	2.0	0.0	0.0	0.7
	Sinapis alba L.	White mustard	32.0	5.5	173.0	70.2
	Thlaspi arvense L.	Stinkweed	4.0	1.5	17.0	7.5
	Brassicaceae spp.	–	3.0	0.0	9.0	4.0
Caryophyllaceae	*Silene noctiflora* L.	Night-flowering catchfly	2.5	2.5	0.0	1.7
	Stellaria media (L.) Vill.	Chickweed	2.5	0.0	1.0	1.2
	Vaccaria hispanica (Mill.) Rauschert	Cow cockle	42.5	5.0	22.0	23.2
Chenopodiaceae	*Chenopodium album* L.	Lamb's-quarters	8.5	2.0	14.0	8.2
	Kochia scoparia (L.) Schrad.	Kochia	35.0	18.5	72.0	41.8
	Salsolakali L. subsp. *ruthenica* (Iljin) So —	Russian thistle	1.0	0.5	6.0	2.5
	Chenopodiaceae sp.	–	2.5	0.0	2.0	1.5
Fabaceae	*Glycine max* (L.) Merr.	Soya bean	4.0	3.0	5.0	4.0
	Lens culinaris Medic.	Lentils	1.5	2.5	4.0	2.7
	Medicago saliva L.	Alfalfa	3.0	0.5	0.0	1.2
	Trifolium spp.	Clover species	0.0	0.0	1.0	0.3
Linaceae	*Linum usitatissimum* L.	Flax	44.5	47.5	50.0	47.3
Malvaceae	*Malvapusilla* Sm.	Round-leaved mallow	3.5	1.5	5.0	3.3
Poaceae	*Avena fatua* L.	Wild oats	231.0	178.5	374.0	261.2
	Avena saliva L.	Oats	4.0	44.0	7.0	18.3
	Bromus leclorum L.	Downy brome	51.5	15.5	18.0	28.3
	Echinochloa crusgalli (L.) P. Beauv.	Barnyard grass	22.5	19.0	21.0	20.8
	Hordeum vulgar e L.	Barley	136.5	207.5	727.0	357.0
	Lolium persicum Boiss. & Hohen. ex Boiss.	Persian darnel	139.0	68.5	48.0	85.2
	Phalaris canariensis L.	Canary grass	3.0	3.5	8.0	4.8
	Phleum pralense L.	Timothy	0.5	0.0	2.0	0.8
	Selaria pumila (Poir.) Roem. & Schult.	Yellow foxtail	11.5	13.5	0.0	8.3
	Selaria viridis (L.) P. Beauv.	Green foxtail	22.0	27.0	37.0	28.7
	Poaceae sp.	–	1.0	1.5	1.0	1.2
Polygonaceae	*Fallopia convolvulus* (L.) Á. Löve	Wild buckwheat	114.0	108.5	108.0	110.2
	Polygonum lapalhifolium L.	Pale smartweed	2.5	3.0	6.0	3.8
	Polygonum persicaria L.	Lady's- thumb	0.0	0.0	1.0	0.3
	Rumex spp.	Dock species	2.0	2.5	5.0	3.2
Rubiaceae	*Galium spurium* L.	False cleavers	1.0	3.5	3.0	2.5
		Total	1145.5	1376.0	2649.0	1723.5

rape) was the most abundant (Table 1, Fig. 1). A large number of seeds of *Hordeum vulgare* L. (barley), *Avena fatua* L. (wild oats) and *Fallopia (Polygonum) convolvulus* (L.) Á. Löve (wild buckwheat) were also present. Oilseed rape and barley are major export crops in Canada (CGC, 2006a). Among the four seed types that were identified only to family level, one type of Brassicaceae was either or both of *Capsella bursa-pastoris* (L.) Medik. and *Descurania sophia* (L.) Webb *ex* Prantl. One type of Asteraceae was tentatively identified as *Senecio vulgaris* L. We had absolutely no idea about one type of Chenopodiaceae and one type of Poaceae. Therefore, we excluded these four species and their data from the following analysis.

In the species (types) ranked in the top 100 by field abundance in spring wheat fields (Leeson *et al.*, 2005), Asteraceae was the most dominant family, with 20 types, followed by Poaceae (15), Fabaceae (11), Brassicaceae (9), Caryophyllaceae (8) and Polygonaceae (8). Thirty-two of these were common to the three wheat samples. Thirteen were excluded from the following comparison because the seed sizes were unknown.

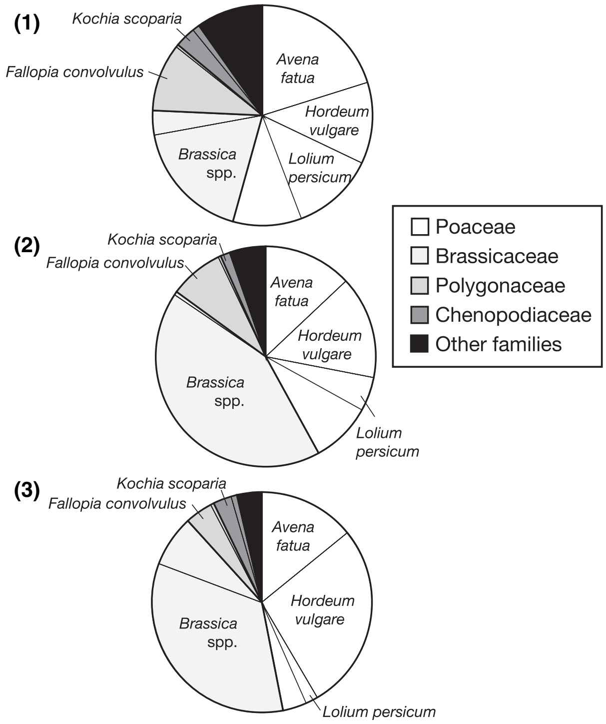

Fig. 1 Percentage distribution of the number of weed seeds in each wheat sample. The seeds are grouped by family. Names of species or genera with especially large numbers of seeds are shown. The total numbers of seeds in each sample are shown in Table 1.

Table 2 Effects of factors on the number of seeds contaminating the wheat analysed as a general linear mixed-effects model. The wheat samples were treated as a random effect

Fixed effects	d.f.	Coefficient	SE	*t*	*P*
Field abundance	1	0.28	0.03	8.52	<0.0001
Life cycle (perennial)	1	−0.37	0.22	−1.71	0.0886
Plant height	1	0.44	0.16	2.79	0.0058
Seed size	1	0.23	0.12	1.92	0.0564
Pappus (presence)	1	−1.07	0.29	−3.72	0.0002
Status (weed)	1	−0.97	0.30	−3.25	0.0013

Factors affecting contaminant seed composition

There was a significant positive relationship between field abundance and the number of contaminant seeds in the wheat samples (Table 2, Fig. 2). Plant height was also positively correlated with the number of contaminant seeds. Seeds with a pappus were proportionally less common than seeds without pappus. Seeds of other crops were more abundant than those of weeds. On the other hand, life cycle and seed size did not show a significant correlation with the number of contaminant seeds. The adjusted R^2 of this model was 0.387. So, 38.7% of the variability in the number of contaminant seeds was explained by fitting the model.

Discussion

As would be expected, field abundance was the most significant factor affecting the number of seeds contaminating the wheat samples (Table 2). Plant height, presence or absence of a pappus and status as weed or crop also had significant effects. Seeds of short weeds and seeds with a pappus were likely eliminated from the wheat by the harvesting and cleaning processes. Common use of various transportation vehicles, temporary storage sites and port elevators would explain carry-over of other crops into wheat.

Globally, nearly 40% of troublesome weeds occur in two families: Poaceae and Asteraceae (Radosevich & Holt, 1984). These families were also dominant in spring wheat fields in the Canadian Prairies, with 14% and 20% of types respectively (Leeson *et al.*, 2005). However, we found only a small number of Asteraceae seeds in the wheat. This is because many species of Asteraceae produce seeds with a pappus, which, under natural conditions, assists in long-distance dispersal by wind (Tackenberg *et al.*, 2003). Adaptation to anemochory results in seeds that are easily dislodged and dispersed at harvest time (rather than being captured) and are more readily eliminated by cleaning processes. In spite of their prevalence as weeds, the dispersal mechanisms of the Asteraceae result in proportionally lower commodity contamination levels. This may suggest a distinct difference between the population dynamics, distribution and dispersal of common troublesome weed species of Poaceae and Asteraceae on a worldwide basis. Most populations of Asteraceae weeds may be typically self-sustaining within local areas, whereas some populations of Poaceae weeds may often be augmented by repeated introductions from other sources. Such a difference may be revealed by analysis of genetic differentiation among populations around the world.

Life cycle did not affect the number of contaminant seeds in wheat, contrary to our expectation (Table 2). We expected that because perennials can allocate more resources into vegetative propagation than into seeds, we would find fewer seeds of perennials than of annuals. Troublesome perennial weeds are characterised by vigorous vegetative reproduction or regeneration from cut pieces (Radosevich & Holt, 1984). As vegetative reproducers develop faster and become reproductive more quickly than germinated seedlings (Benson & Hartnett, 2006), they can grow large enough to produce many seeds within a year. Therefore, perennial weeds can match the seed production of annual weeds by having a head start.

We also expected that seeds whose size is different from that of wheat would be eliminated; however, we did not find such a relationship. Seeds of various sizes

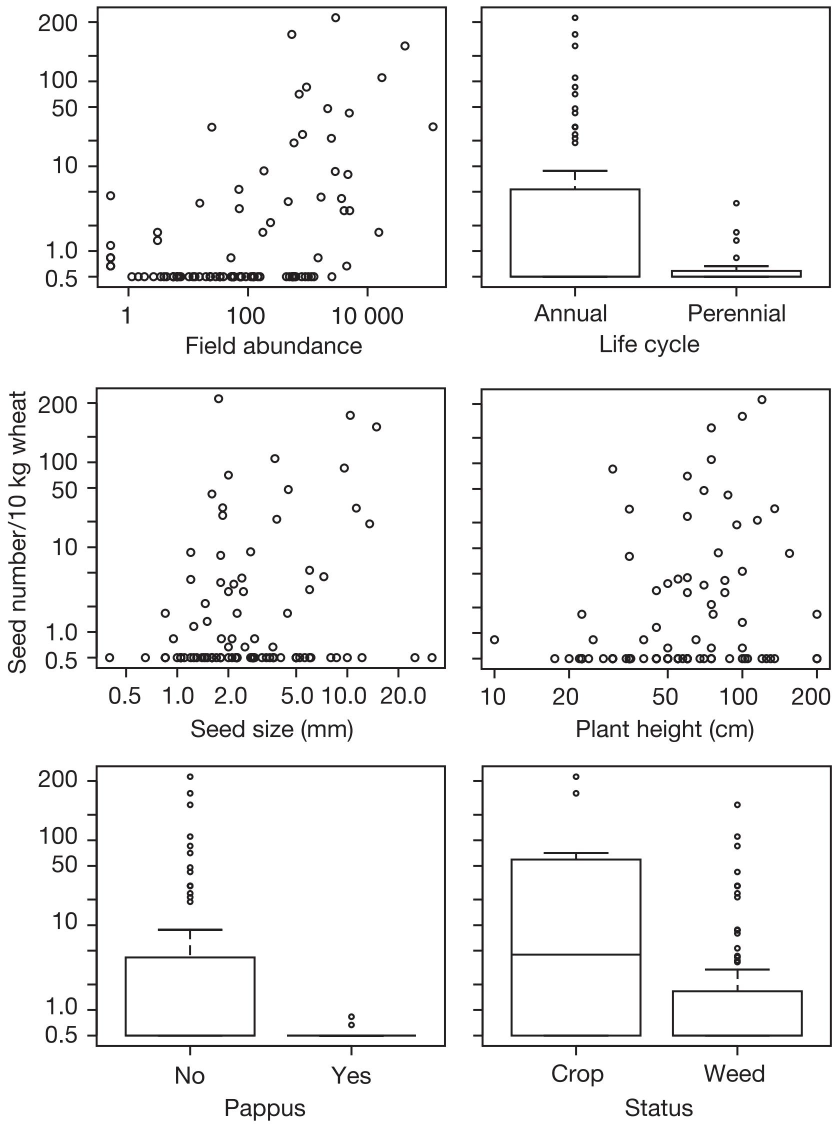

Fig. 2 Relationship between each factor and mean number of seeds in wheat. The field abundance and the seed number had 0.5 added. Box plot represents 75th (top), 50th (middle) and 25th percentile (bottom). Top whisker extends to the most extreme data point which is no more than 1.5 times the interquartile range from the box. The values which lie beyond the extremes of the whiskers are shown by circle points. Sample unit is each weed species.

seem to have the same potential for elimination by cleaning processes or not, except for extremely big seeds.

The general linear mixed-effects model explained only 38.9% of the variability in the number of contaminant seeds, suggesting that other factors contribute. One important factor might be seed dispersal timing. If the seed dispersal timing of a weed corresponds with the harvest time of a crop, serious contamination is likely. In fact, the seed dispersal timing of four weed species [*A. fatua*, *F. convolvulus*, *Kochia scoparia* (L.) Schrad. and *Lolium persicum* Boiss. & Hohen.], which were serious contaminants (average of more than 40 seeds per 10 kg of wheat), corresponds with the harvest time of spring wheat (Sharma & Vandenborn, 1978; Hume *et al.*, 1983; Holman *et al.*, 2004; NWCB, 2006). Crops and associated weeds have evolved together under similar cultural practices or environments, so the growth and reproduction of the most successful weeds tend to match those of the crops (Radosevich & Holt, 1984). Furthermore, a non-seed-shattering habit is likely to be related to contamination. Two non-seed-shattering crops, oilseed rape and barley, were serious contaminants. Because easy shattering reduces yield due to grain loss during harvest, these seed crops have been selected to retain the seeds on their heads (Konishi *et al.*, 2006). As a result, seeds of volunteer crops are harvested with the crop, resulting in serious contamination. In addition, oilseed rape and barley are major export crops in Canada (CGC, 2006a). Therefore, many of these seeds may be left in various vehicles, temporary storage sites and port elevators as residues.

Some weed seeds might contaminate wheat via other commodities. We found seeds of *Alisma plantago-aquatica* L., *Buglossoides arvensis* (L.) I.M.Johnst., *Anthemis cotula* L., *Camelina microcarpa* Andrz. ex DC, and *Polygonum persicaria* L. Gray in the wheat, yet these species were not found in wheat fields. Furthermore, we found a couple of dozen seeds of *Bromus* *tectorum* L., a winter annual on the Canadian Prairies, whose seeds are shed long before wheat is harvested. Therefore, contamination of these seeds may occur at sites such as vehicles, containers and port elevators. The seed productivity of each weed might also improve the predictability of weed seed quantity in wheat, but we could not find reliable data for analysis.

Identifying the predominant attributes of introduced weed species can help identify critical species, evaluate their invasiveness and prevent their spread. For example, seeds of *A. fatua* and *F. convolvulus*, which are noxious aliens in Japan (Osada, 1976; [NARO] National Agriculture and Food Research Organization, 2006), were abundant in the imported wheat. On the other hand, although a large number of seeds of *K. scoparia* and *L. persicum* were also present, neither species is recognised as a weed in Japan. These four species have been introduced into Japan through the grain trade over at least 10 years (Asai *et al.*, 2004). The difference in their invasiveness may be related to seed viability: that of the latter two species is rapidly lost in soil (Holman *et al.*, 2004; NWCB, 2006), but that of the former can remain high for several years (Sharma & Vandenborn, 1978; Zollinger *et al.*, 2006). Seed viability is thus a likely key factor in invasion via the grain trade. Further studies are needed to assess the percentage of viable seeds of each species in wheat, because they would identify the species most likely to represent a potential invasion risk. Importing 1700 seeds 10 kg^{-1} of wheat is not a threat if all the seeds are non-viable.

To our knowledge, this is the first study to analyse the effects of field abundance and human-mediated processes (harvesting and cleaning) on contaminant seed quantity in imported grain. These relationships can also apply to other grains, which are handled similar to wheat. New noxious weeds are now expected because the adoption of genetically modified crops, changes in herbicides and tillage systems and crop diversification have brought about changes in weed communities (Derksen *et al.*, 2002; Culpepper, 2006). Therefore, new weed species might be introduced into grain importing-countries. Although grain-cleaning techniques are improving, it will remain impossible to remove all weed seeds completely, because of the enormous cost. Therefore, predictions of potential alien weeds based on the flora and weed control systems of trading partner countries will become increasingly important.

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References

ASAI M, KUROKAWA S, SHIMIZU N & ENOMOTO T (2004) Identification of weed seeds contaminated in imported winter cereal grains and rapeseeds. *Grassland Science* **50**(Suppl.), 466–467.

ASAI M, KUROKAWA S, SHIMIZU N & ENOMOTO T (2007) Exotic weed seeds detected from imported small cereal grains into Japan during 1990s'. *Journal of Weed Science and Technology* **52,** 1–10.

BENSON EJ & HARTNETT DC (2006) The role of seed and vegetative reproduction in plant recruitment and demography in tallgrass prairie. *Plant Ecology* **187,** 163–177.

CARLTON JT & GELLER JB (1993) Ecological roulette – the global transport of nonindigenous marine organisms. *Science* **261,** 78–82.

CFIA (2006) *Grains, field crops and their exporting facilities* [WWW document]. Canadian Food Inspection Agency. URL http://www.inspection.gc.ca/english/plaveg/grains/r001/r-001e.shtml [accessed on 20 December 2006].

CGC (2006a) *Canadian grain exports, crop year 2004–05* [WWW document]. Canadian Grain Commission. URL http://www.grainscanada.gc.ca/pubs/exportsyearly/exports-year-e.htm [accessed on 20 December 2006].

CGC (2006b) *Official Grain Grading Guide* [WWW document]. Canadian Grain Commission. URL http://www.grainscanada.gc.ca/Pubs/GGG/ggg-e.htm [accessed on 20 December 2006].

CULPEPPER AS. (2006) Glyphosate-induced weed shifts. *Weed Technology* **20,** 277–281.

D'ANTONIO CM & MAHALL BE (1991) Root profiles and competition between the invasive, exotic perennial, *Carpobrotus edulis*, and two native shrub species in California coastal scrub. *American Journal of Botany* **78,** 885–894.

DARBYSHIRE SJ (2003) *Inventory of Canadian agricultural weeds* [WWW document]. Agriculture and Agri-Food Canada. URL http://res2.agr.ca/ecorc/weeds_herbes/title-titre_e.htm [accessed on 20 December 2006].

DAVIS LW (1993) *Weed Seeds of the Great Plains: A Handbook for Identification*. University Press of Kansas, Lawrence, KS, USA.

DERKSEN DA, ANDERSON RL, BLACKSHAW RE & MAXWELL B (2002) Weed dynamics and management strategies for cropping systems in the northern Great Plains. *Agronomy Journal* **94,** 174–185.

DICKMAN CR (1996) *Overview of the Impacts of Feral Cats on Australian Native Fauna*. Australian Nature Conservation Agency, Canberra ACT, Australia.

FAO (2004) *FAO statistical yearbook, 2004. C.16. Imports and exports of selected agricultural commodities, Group I* [WWW document]. URL http://www.fao.org/docrep/009/a0490m/a0490m00.htm [accessed on 20 December 2006].

Fay PK (1990) A brief overview of the biology and distribution of weeds of wheat. In: *Systems of Weed Control in Wheat in North America* (ed. WW Donald), 35–50. Weed Science Society of America, Champaign, IL, USA.

Flora of North America Editorial Committee (1993+) *Flora of North America North of Mexico. 12+ vols*. New York and Oxford, USA. Vol. 1, 1993; vol. 2, 1993; vol. 3, 1997; vol. 4, 2003; vol. 5, 2005; vol. 19, 2006; vol. 20, 2006; vol. 21, 2006; vol. 22, 2000; vol. 23, 2002; vol. 25, 2003; vol. 26, 2002.

Flora-Kanagawa Association (2001) *Flora of Kanagawa 2001*. Kanagawa Prefectural Museum of Natural History, Kanagawa, Japan.

Goldschmidt T (1996) *Darwin*'s Dreampond: Drama in Lake Victoria. Massachusetts Institute of Technology Press, Cambridge, MA, USA.

Green RE (1997) The influence of numbers released on the outcome of attempts to introduce exotic bird species to New Zealand. *Journal of Animal Ecology* **66,** 25–35.

Guan GQ, Zhang YR, Sun GY, Ding SX & Wang YB (2000) *Atlas of Weeds*. Science Press, Beijing, China.

Guo QX (1998) *Identification of Weed Seeds with Colored Pictures*. China Agricultural Press, Beijing, China.

Heywood VH (1989) Patterns, extents and modes of invasions by terrestrial plants. In: *Biological Invasions : A Global Perspective, SCOPE37* (eds JA Drake, HA Mooney, F di Castri, RH Groves, FJ Kruger, M Rejmánek, M Williamson), 31–60. John Wiley & Sons Ltd, Chichester, UK.

Holman JD, Menalled FD & Bussan AJ (2004) *Persian darnel: identification, biology and ecology* [WWW document]. Montana Sate University Extension Service. URL http://www.montana.edu/wwwpb/pubs/mt200411.html [accessed on 20 December 2006].

Huelma CC, Moody K & Mew TW (1996) Weed seeds in rice seed shipments: a case study. *International Journal of Pest Management* **42,** 147–150.

Hume L, Martinez J & Best K (1983) The biology of Canadian weeds. 60. *Polygonum convolvulus* L. *Canadian Journal of Plant Science* **63,** 959–971.

Ishikawa S (1994) *Seeds/*Fruits of Japan. Ishikawa Shigeo Zukan Kanko Iinkai, Tokyo, Japan.

King C (1984) *Immigrant Killers, Introduced Predators and the Conservation of Birds in New Zealand*. Oxford University Press, Auckland, New Zealand.

Konishi S, Izawa T, Lin SY *et al.* (2006) An SNP caused loss of seed shattering during rice domestication. *Science* **312,** 1392–1396.

Leeson JY, Thomas AG, Hall LM *et al.* (2005) *Prairie Weed Surveys of Cereal, Oilseed and Pulse Crops from the 1970s to the 2000s*. Agriculture and Agri-Food Canada, Saskatoon Research Centre, Saskatchewan, Canada.

Levine JM, Vila M, D'antonio CM, Dukes JS, Grigulis K & Lavorel S (2003) Mechanisms underlying the impacts of exotic plant invasions. *Proceedings of the Royal Society of London Series B, Biological Sciences* **270,** 775–781.

Lonsdale WM (1999) Global patterns of plant invasions and the concept of invasibility. *Ecology* **80,** 1522–1536.

Mack RN, Simberloff D, Lonsdale WM, Evans H, Clout M & Bazzaz FA (2000) Biotic invasions: causes, epidemiology, global consequences, and control. *Ecological Applications* **10,** 689–710.

Martin AC & Barkley WD (1961) *Seed Identification Manual*. Blackburn Press, NJ, USA.

McCormick JF & Platt RB (1980) Recovery of an Appalachian forest following the chestnut blight or Catherine Keever – you were right. *The American Midland Naturalist* **104,** 264–273.

McDonald M, Bennet M, Evans A & Sites A (2006) *Seed ID Workshop* [WWW document]. Ohio State University. URL http://www.oardc.ohio-state.edu/seedid/ [accessed on 20 December 2006].

[NARO] National Agriculture and Food Research Organization (2006) *Naropedia*. Ruralnet, Tokyo, Japan.

Naylor R (1996) Invasions in agriculture: assessing the cost of the golden apple snail in Asia. *Ambio* **25,** 443–448.

NWCB (2006) *About the Washington State Noxious Weed List, Class B Noxious Weeds – Kochia* [WWW document]. Washington State Noxious Weed Control Board. URL http://www.nwcb.wa.gov/weed_list/weed_list.htm [accessed on 20 December 2006].

Osada T (1976) *Colored Illustrations of Naturalized Plants of Japan*. Hoikusya Publishing Co., Osaka, Japan.

Osada T (1989) *Illustrated Grasses of Japan*, enlarged edition. Heibonsha Ltd, Tokyo, Japan.

[OTA] U.S. Congress, Office of Technology Assessment (1993) *Harmful Non-Indigenous Species in the United States*. Government Printing Office, Washington, DC, USA.

Pimentel D, Lach L, Zuniga R & Morrison D (2000) Environmental and economic costs of nonindigenous species in the United States. *Bioscience* **50,** 53–65.

Puth LM & Post DM (2005) Studying invasion: have we missed the boat? *Ecology Letters* **8,** 715–721.

R Development Core Team (2006) *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0. http://www.R-project.org.

Radosevich SR & Holt JS (1984) *Weed Ecology: Implications for Vegetation Management*. John Wiley & Sons, Inc., New York, USA.

Rejmanek M & Richardson DM (1996) What attributes make some plant species more invasive? *Ecology* **77,** 1655–1661.

Sala OE, Chapin FS, Armesto JJ *et al.* (2000) Biodiversity - global biodiversity scenarios for the year 2100. *Science* **287,** 1770–1774.

Sharma MP & Vandenborn WH (1978) Biology of Canadian weeds. 27. *Avena fatua* L. *Canadian Journal of Plant Science* **58,** 141–157.

Shimizu N (1998) Recent situation of invasion and diffusion of alien weeds and its control. *Japanese Journal of Ecology* **48,** 79–85.

Silvertown JW (1987) *Introduction of Plant Population Ecology*, 2nd edn. Longman Group UK Ltd, London, UK.

Simberloff D (1989) Which insect introductions succeed and which fail? In: *Biological Invasions : A Global Perspective, SCOPE37* (eds JA Drake, HA Mooney, F di Castri, RH Groves, FJ Kruger, M Rejmánek, M Williamson), 61–75. John Wiley & Sons Ltd, Chichester, UK.

Tackenberg O, Poschlod P & Bonn S (2003) Assessment of wind dispersal potential in plant species. *Ecological Monographs* **73,** 191–205.

Thomas AG (1985) Weed survey system used in Saskatchewan for cereal and oilseed crops. *Weed Science* **33,** 34–43.

Tilman D (1997) Community invasibility, recruitment limitation, and grassland biodiversity. *Ecology* **78,** 81–92.

USDA (2004) *Grain: world markets and trade, 2004 circulars* [WWW document]. United States Department of Agriculture. URL http://usda.mannlib.cornell.edu/fas/grain-market/2004/ [20 December 2006].

USDA (2006) *PLANTS database* [WWW document]. United States Department of Agriculture, Natural Resources Conservation Service. URL http://plants.usda.gov/index.html [accessed on 20 December 2006].

Van Riper C, Van Riper SG, Goff ML & Laird M (1986) The epizootiology and ecological significance of malaria in Hawaiian land birds. *Ecological Monographs* **56,** 327–344.

Williamson M (1996) *Biological Invasions*. Chapman & Hall, London, UK.

Zollinger R, Peterson D & Moechnig M (2006) *Glyphosate, weeds, and crops: biology and management of wild buckwheat* [WWW document]. Purdue University. URL http://www.ces.purdue.edu/extmedia/GWC/GWC-10-W.pdf [accessed on 20 December 2006].

