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Development of the Alaska agricultural weed flora 1981–2004: a case for prevention

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Summary

Alaska provides a unique laboratory to study the development of agricultural weed floras, since fields were first cleared in 1900–1985. Changes in weed species composition between 1981 and 2004 were studied in 80 agricultural fields near Fairbanks, Nenana, Delta Junction and Palmer, Alaska. Cover and density of all plants were measured in quadrats along a transect in each field. Environmental and management information were collected, including field age, weed control methods, crop, elevation, latitude, longitude, surrounding vegetation type and canopy shading. Detrended correspondence analysis was used to ordinate fields based on weed vegetation. Spearman correlations and graphical overlays were used to examine relationships between environmental and management variables and ordination axes. We found seven weed species that were new to Alaskan agriculture since 1981. Crop, canopy shading, elevation, latitude and longitude were important weed flora determinants. Two distinct weed community/crop associations were identified: (i) vegetables + potatoes and (ii) perennial grass (hay + grass seed). Non-native weed species colonised fields that were largely weed-free in 1981, when a similar weed survey was made. The failure to use weed prevention programmes since 1981, resulted in 40 000 ha of new agricultural land that must be managed for non-native weeds.

Keywords: invasion pathways, weed community development, weed shifts, canopy shading, crop–weed associations, subarctic.

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Introduction

Most studies of weed floras have focused on environmental factors determining the relative abundance of the various weed species present in a region. Environment and crop management are selection factors that influence the species abundance of weed floras (Davis *et al.*, 2005; Murphy & Lemerle, 2006). The importance of crop rotation, tillage, crop residues, herbicides, soil amendments and harvesting methods (Murphy & Lemerle, 2006) to weed floras has been studied directly using experiments and indirectly through use of quantitative surveys, collection of environmental and management data and use of ordinations with correlation analysis (Kenkell *et al.*, 2002).

Regional weed floras can change over time in response to new weed species introductions or changes in management practices. For example, the use of herbicides and reductions in field borders and associated vegetation has led to the decline of weed species on which insects and birds are dependent (Benton *et al.*, 2002; Marshall *et al.*, 2003, 2006). Recently, decreased herbicide use between the early 1980s and late 1990s was thought to increase total dry weight, diversity and

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density of weeds in Finland (Hyvönen *et al.*, 2003, 2005) and frequency of common weed species in Denmark (Andreasen & Stryhn, 2008).

Although much is known about how established weed floras shift with changes in crop management, little is known about the initiation of agricultural weed floras and how associations between weeds and other organisms develop. Alaska offers a unique laboratory for studying the development and changes of weed communities. The agricultural weed flora in Alaska is relatively new, with significant acreage being devoted to agricultural production only beginning in the early 1900s to support early gold mining camps (Thomas & Lewis, 1981). Additional agricultural acreage was added in 1930–1940 and 40 000 ha of land was cleared for farming in 1978–1982 in the vicinities of Delta Junction, Fairbanks, Nenana and Point McKenzie. Since Alaskan botanical inventories began prior to the period of agricultural development, it is possible to determine which weeds are non-native, and which are part of the original non-agricultural native flora. This is unlike the situation in the Middle East, Africa and Europe, where agriculture has been in existence for thousands of years and it is difficult to distinguish between the original flora and non-native species that were introduced before plant distributions were studied (Pysek *et al.*, 2005).

Conn and DeLapp (1983) studied the relationships between Alaskan agricultural weed floras and cropping history and environmental variables using detrended correspondence analysis (DCA) (Hill, 1979). Fields were ordinated based on cover and frequency of weed species and correlation analysis was used to determine which management or environmental variables were related to field location on the ordination axes. Field age (time since forest clearing) explained the most variation in weed floras. Newly cleared fields were dominated by native colonising species, whereas older fields had a greater number of non-native weed species. The weed seedbanks of these fields also shifted along the time gradient from being dominated by seed of native species, to a predominantly non-native seedbank (Conn *et al.*, 1984).

Changes in farming practices may have altered the Alaskan agricultural weed flora since the 1981 survey. Prior to 1986, dinoseb was used almost exclusively for weed control in vegetables grown in Alaska and was also used for weed control in small grain production. After dinoseb was discontinued, other herbicides were used for weed control, including 2,4-D and sulfonylurea herbicides in small grain production, metribuzin and linuron in potatoes and pronamide for lettuce production. During the early 1990s, grain producers adopted reduced tillage systems to minimise damage to the highly erodable silt loam soils. Reducing tillage was shown to increase perennial grass weeds in Alaskan spring barley production (Conn, 1987).

We revisited the agricultural areas sampled in 1981 and conducted a quantitative survey to study the continued development of the Alaskan agricultural weed flora. Our objectives were to determine: (i) if new weed species had been introduced since 1981 and (ii) whether changes in herbicide use or other management factors caused shifts in the weed flora subsequent to the survey in 1981.

Materials and methods

Field sampling

Eighty agricultural fields were sampled in Alaska, USA, during July and August 2004 in the Matanuska/Susitna Valley (80 km east of Anchorage; 32 fields), Delta Junction (160 km southeast of Fairbanks; 27 fields) and Fairbanks-Nenana (within 70 km east or west of Fairbanks; 21 fields) agricultural districts. Crops included 13 potato (*Solanum tuberosum* L.) fields, 23 perennial smooth bromegrass (*Bromus inermis* Leyss.) and timothy (*Phleum pratense* L.) fields, 21 small grain fields with either spring barley (*Hordeum vulgare* L.) or oats (*Avena sativa* L.), four bluegrass (*Poa* L.) seed fields, one field pea (*Pisum sativum* L.) field and 18 vegetable fields with either broccoli (*Brassica oleracea* L. var. *italica* Plenck), carrots (*Daucus carota* L. subsp. *sativa* L.), lettuce (*Lactuca sativa* L.), summer squash (*Cucurbita pepo* L.), or white onions (*Allium cepa* L.). We sampled most of the fields included in our 1981 study of the Alaskan weed flora (Conn & DeLapp, 1983), but we had to include five different fields in 2004 because some fields sampled in 1981 had been abandoned. Consistent with the first survey in 1981, percentage cover of each weed species was recorded in each of ten 1 m^2 quadrats located randomly along a 100 m transect in the middle of each field. Additional environmental and management data collected for each field included: latitude, longitude, elevation, years since forest clearing, weed control methods, surrounding forest type, crop planted and canopy shading [proportion of photosynthetically active radiation (PAR) reaching the ground]. Latitude, longitude and elevation were determined using a Global Positioning System (GPS). Canopy shading was determined using a LICOR Line Quantum Sensor (LI-COR, Lincoln, NE, USA) to measure PAR above the canopy and at ground level in each quadrat.

Data analysis

Cover data for each species were summed over quadrats for each field and expressed as a percent of total weed cover for the field (relative cover). Frequency for each species was determined as the number of quadrats in the field in which the species occurred and were then expressed as a percentage of the total weed frequency in each field (relative frequency). Synthetic importance values were calculated for each species as the average of relative cover and relative frequency.

Ordinations of field weed importance values were made with DCA using PC-ORD Version 4 (McCune & Mefford, 1999). DCA was used for ordination to maintain consistency with the analysis of the 1981 survey data and allow the direct comparison of the relative importance of the ordinal variables. The relationship of field ordinations to the environmental and management categorical variables (crop, weed control method, surrounding vegetation type) was evaluated by graphical overlays using SigmaPlot version 10 (Systat Software, San Jose, CA, USA).

Spearman correlations were used to determine: (i) which of the ordinal variables (field age, latitude, longitude, elevation and canopy shading) were significantly related to the first two ordination axes and (ii) which weed species were significantly correlated to canopy shading. Analysis of variance (ANOVA) was used to determine whether weed species were differentially represented in various crop groupings and Tukey's *post hoc* test was used to separate means. Weed species importance value percentages were arcsine transformed before analysis to meet the assumptions of ANOVA. Importance values presented in tables are the untransformed data. All non-ordination statistical analyses were performed using SAS version 9.2 (SAS Institute, Cary, NC, USA).

Results

A total of 64 weed species were found including 32 non-native and 32 native species. Seven species were found that were not present 23 years earlier: *Cerastium glomeratum* Thuill., *Conyza canadensis* (L.) Cronquist, *Sinapsis arvensis* L., *Silene latifolia* Poir. and *Crepis tectorum* L. In addition, *Hieracium aurantiacum* L. was found in hay fields near Talkeetna, Alaska (although not in fields sampled in this study) and *Sonchus arvensis* L. that was thought to have been eradicated in Alaska (Dearborn, 1959) was found in numerous fields.

In the DCA ordination, 15.7% and 17.8% of the total variation of field weed importance values were explained by axes 1 and 2 respectively. The DCA axis 1 was negatively correlated with time since forest clearing, but positively correlated with canopy shading, elevation, latitude and longitude (Table 1). The DCA axis 2 was positively correlated with time since forest clearing and negatively correlated with elevation and longitude (Table 1).

Table 1 Spearman correlations between field scores for the first two axes of detrended correspondence analysis (DCA) of the 2004 weed community composition in 80 Alaska agricultural fields and measured environmental variables

	Weed community ordination axes	
Environmental variable	1	2
Time since forest clearing	−0.19*	0. 29**
Canopy shading (%)†	0.50**	−0.02
Elevation	0.45**	−0.35**
Latitude	0.38**	0.05
Longitude	0.45**	−0.34**

* and ** denote significant correlations at the $P < 0.1$ and $P < 0.01$ levels respectively.

†% of incident photosynthetically active radiation that reaches the ground.

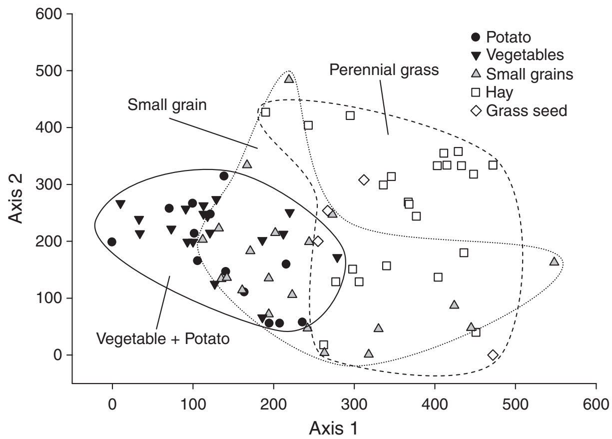

Fig. 1 Graphic overlay of crops on the first two axes of detrended correspondence analysis (DCA) ordination of 80 Alaskan agricultural fields sampled in 2004. Symbols indicate crop grown for each field and three crop groups were discerned: vegetables + potato, perennial grass (hay + grass seed) and small grains.

The importance values of five weed species were weakly correlated with canopy shading. *Trifolium hybridum* L. ($r = -0.27$, $P < 0.02$) and *Plantago major* L. ($r = -0.21$, $P < 0.06$) were negatively correlated, whereas *Equisetum arvense* L. ($r = 0.28$, $P < 0.02$), *Chenopodium album* L. ($r = 0.24$, $P < 0.04$) and *Senecio vulgaris* L. ($r = 0.21$, $P < 0.07$) were positively correlated with canopy shading.

There were no apparent patterns in the graphical overlays of adjacent forest type on field ordinations (data not shown). However, the type of crop grown appeared to influence weed floras. Two distinct crop-related groups of weed floras were found in the graphical overlay of crop type on the DCA ordination (Fig. 1): (i) vegetable + potato and (ii) perennial grass (hay + grass seed). The polygons for these crop groups have less than 6% overlap. The flora of small grain fields overlapped both of the aforementioned groups. Importance values of the annual broad-leaved species *Matricaria discoidea* DC., *Senecio vulgaris*, *C. album* and *Capsella bursa-pastoris* (L.) Medicus were significantly greater in vegetable + potato fields than in perennial grass fields. Conversely, the importance of the perennial weeds *Taraxacum officinale* G. H. Weber ex Wiggers and *Poa pratensis* L. were greater in perennial grass fields than in vegetable + potato fields (Table 2).

A graphical overlay of weed control methods with the DCA ordination (Fig. 2) showed that distinct groupings of fields associated with different weed control methods are difficult to discern, due to a high degree of overlap. The herbicides metribuzin, linuron, metham and the non-chemical means of controlling weeds through the use of soil covered with infrared transmitting plastic (IRT), that precludes wavelengths used in photosynthesis, were all associated with similar weed floras, as observed to be associated with vegetable and potato production (Fig. 1).

Discussion

Seven new weed species have become permanently established in the 23 years since the previous survey of Alaskan agricultural weed flora. Conn and DeLapp (1983) found that only one new weed species, *Galeopis tetrahit* L., had established in Alaska between 1981 and the mid 1950s survey by Dearborn (1959). The rate of new weeds establishing in Alaska agriculture appears to be increasing. This has also been case for all non-native plants in the total flora of Alaska. Carlson and Shephard (2007) determined that the rate of new introductions of exotic taxa in Alaska's flora increased from roughly one species per year from 1941 to 1968 to three species per year from 1968 to 2006, mirroring the threefold increase in human population in Alaska since 1968, as well as the increase of goods shipped to the state.

The presence of two of the new weed species, *C. tectorum* and *H. aurantiacum*, in grass fields, has required a shift from use of low-cost herbicides such as 2,4-D to more expensive herbicides, such as clopyralid or aminopyralid. The addition of these new species has thus caused growers financial loss, due to decreased crop yields or through increased weed control costs (P. Kaspari, pers. comm.).

The total number of weed species found in Alaskan agriculture (64) was much smaller than the 177 species found in a similar study of weeds in Finnish spring cereals near the same latitude (Salonen & Hyvönen, 2010). Weed species richness may be much greater at lower latitudes. For example, Marshall (2009) identified 275 species in fields and field boundaries in southern England and Šilc *et al.* (2009) found 775 species in a study of arable weeds in the north-western Balkans. At high latitudes, weed species richness may increase if temperatures warm, as predicted by climate models (Meehl *et al.*, 2007).

In the 1981 survey, time since forest clearing was the most important factor explaining variability in weed flora, with a 0.91 correlation coefficient with DCA axis 1. Percent cover of non-native species increased from <1% in newly cleared fields to 27% in fields that had been in cultivation for greater than 5 years (Conn & DeLapp, 1983). However, in this study, there was only a 0.19 correlation coefficient between time since forest clearing and DCA axis 1 and 0.29 correlation with DCA axis 2. The decreased importance of time since forest clearing in 2004 may be explained by: (i) the fact that there were no newly cleared fields to sample in 2004; and (ii) the newly cleared fields near Delta Junction and Fairbanks that contained few non-native weeds in 1981 (22 fields) now have non-native dominated floras, similar to the older fields that were sampled in 1981. However, in two of these fields, no non-native weeds were found, suggesting that some growers were able to prevent colonisation by new weed species.

Crop type was an important factor influencing weed flora in the 2004 data. In the graphic overlay of crop type on the DCA ordination (Fig. 1), vegetable + potato and perennial grass groups are discernible. Annual cultivation associated with vegetable and potato production selects for annual weed species that can complete their life cycle between tillage cycles, whereas perennial grass (hay and grass seed) production selects for perennial weeds. Andreasen *et al.* (1991), Fried *et al.* (2008), Marshall (2009) and Šárka and Lososová (2009) also found that crop type was a major determinant of weed flora composition in Danish, French, English and Czech Republic fields.

The positive correlation of DCA axis 1 with canopy shading may be related to crop type and associated canopy architecture and physiology. The weed species *T. hybidum* and *P. major* were associated with low canopy shading and perennial grass production, whereas *E. arvensis*, *C. album* and *S. vulgaris* were associated with high canopy shading vegetable + potato production. Other researchers have shown that canopy shading and wavelength shifts can influence weed seed germination, growth and competition. Light under the canopy has a lower ratio of red light to far-red light, which affects plant phytochrome systems, producing physiological and morphological effects such as rapid stem elongation, retarded leaf development and increased apical dominance (Smith, 1982). Canopy-altered light spectra can also have an effect on reproduction, by decreasing time to flower (reviewed in Brainard *et al.*, 2005) and by increasing seed dormancy (Gorski *et al.*,

Table 2 Mean importance values and ANOVA results for individual weed species grouped into crop categories discernable on detrended correspondence analysis (DCA) ordination of 80 agricultural fields in 2004

Weed species	Common name	ANOVA	Importance value 0–100 Vegetable + potato	Perennial grass	Small grain
Non-native species					
Brassica rapa L.	Birdsrape mustard	NS	0.07	0.00	0.18
Bromus inermis Leyss.	Smooth brome	NS	0.00	0.00	3.58
Capsella bursa-pastoris (L.) Medik.	Shepherd's-purse	**	10.10 a	1.50 b	1.88 b
Cerastium fontanum ssp. *vulgare* (Hartman) Greuter & Burdet	Mouseear chickweed	NS	0.00	0.60	0.00
Chenopodium album L.	Common lambsquarters	***	18.72 a	0.16 b	24.74 a
Conyza canadensis (L.) Cronq.	Horseweed	NS	0.00	0.00	0.30
Crepis tectorum L.	Narrowleaf hawksbeard	NS	0.29	3.45	4.44
Descurainia sophia (L.) Webb. ex Prantl	Flixweed	NS	0.08	0.00	0.00
Elymus repens (L.) Gould	Quackgrass	NS	4.26	1.62	1.95
Galeopsis tetrahit L.	Common hempnettle	NS	2.27	0.20	3.23
Hordeum vulgare L.	Barley	NS	0.49	0.00	0.00
Lepidium densiflorum Schrad.	Greenflower pepperweed	NS	0.00	0.27	0.24
Lolium perenne L.	Perennial ryegrass	NS	0.03	0.00	0.00
Matricaria discoidea DC.	Pineapple-weed	***	16.49 a	1.14 b	1.68 b
Phleum pratense L.	timothy	NS	0.00	0.57	0.00
Plantago major L.	Broadleaf plantain	NS	0.59	1.29	0.00
Poa annua L.	Annual bluegrass	NS	0.12	1.90	0.00
Poa pratensis L.	Kentucky bluegrass	***	0.41 a	21.27 b	1.33 a
Polygonum aviculare L.	Prostrate knotweed	NS	1.27	5.94	7.19
Polygonum convolvulus L.	Wild buckwheat	NS	0.66	0.04	4.18
Polygonum pensylvanicum L.	Pennsylvania smartweed	*	0.00 a	0.00 a	1.57 b
Senecio vulgaris L.	Common groundsel	**	7.78 a	0.33 b	1.63 ab
Silene latifolia Poir.	White campion	NS	0.00	0.00	0.06
Sinapis arvensis L.	Wild mustard	NS	0.00	0.00	0.33
Sonchus arvensis L.	Perennial sowthistle	NS	0.41	0.00	0.00
Spergula arvensis L.	Corn spurry	NS	1.51	1.90	0.07
Stellaria media (L.) Vill.	Common chickweed	***	12.34 a	0.63 b	5.38 a
Taraxacum officinale G.H. Weber ex Wiggers	Dandelion	***	1.52 a	21.15 b	1.69 a
Thlaspi arvense L.	Field pennycress	NS	2.09	0.00	0.00
Trifolium hybridum L.	Alsike clover	*	0.00 a	0.34 b	0.00 ab
Trifolium repens L.	White clover	NS	1.64	0.00	0.00
Vicia cracca L.	Bird vetch	NS	0.31	0.49	0.00
Native species					
Achillea millefolium L.	Common yarrow	*	0.00 a	1.76 b	0.12 ab
Agrostis clavata Trin.	Clavate bentgrass	NS	0.00	0.59	0.00
Agrostis scabra Willd.	Rough bentgrass	NS	0.06	1.59	0.05
Alopecurus aequalis Sobol.	Shortawn foxtail	NS	0.00	0.43	0.00
Beckmannia syzigachne (Steud.) Fern.	American sloughgrass	NS	0.00	0.03	0.00
Calamagrostis canadensis (Michx.) Beauv.	Bluejoint	NS	0.00	0.44	0.40
Chamerion angustifolium (L.) Holub	Fireweed	NS	1.95	2.29	3.80
Chenopodium capitatum (L.) Ambrosi.	Blite goosefoot	NS	0.04	0.17	0.00
Cornus canadensis L.	Bunchberry	NS	0.00	0.14	0.00
Corydalis sempervirens (L.) Pers.	Pale corydalis	NS	0.00	0.00	0.35
Dasiphora floribunda (Pursh) Kartesz, comb. nov. ined.	Bush cinquefoil	NS	0.00	0.00	0.18
Dracocephalum parviflorum Nutt.	American dragonhead	NS	0.00	0.16	0.16
Elymus trachycaulus (Link) Gould ex Shinners	Slender wheatgrass	NS	0.00	0.00	1.95
Epilobium hornemannii Reichenb.	Hornemann's willowherb	NS	0.00	0.14	0.00
Epilobium palustre L.	Marsh willowherb	NS	0.00	0.38	0.00
Equisetum arvense L.	Field horsetail	NS	5.29	6.25	16.22
Festuca rubra L.	Red fescue	NS	0.00	2.15	0.43
Galium boreale L.	Northern bedstraw	NS	0.00	0.00	0.16
Geum macrophyllum Willd.	Largeleaf avens	NS	0.00	0.09	0.00

Table 2 (*Continued*)

Weed species	Common name	ANOVA	Importance value 0–100 Vegetable + potato	Perennial grass	Small grain
Hordeum jubatum L.	Foxtail barley	*	0.67	9.38	7.11
Mertensia paniculata (Ait.) G. Don	Northern bluebells	NS	0.00	0.07	0.11
Picea glauca (Moench) Voss	White spruce	NS	0.00	0.16	0.00
Populus balsamifera L.	Balsam poplar	NS	0.17	0.85	0.00
Populus tremuloides Michx.	Quaking aspen	NS	0.77	0.85	0.00
Potentilla norvegica L.	Rough cinquefoil	NS	0.77	3.09	1.89
Rorippa palustris (L.) Bess.	Marsh yellowcress	NS	4.81	1.10	1.12
Rosa acicularis Lindl.	Prickly rose	NS	0.00	0.24	0.17
Rubus idaeus L.	European red raspberry	NS	0.00	1.62	0.00
Salix arbusculoides Anderss.	Littletree willow	NS	0.00	0.06	0.00
Salix bebbiana Sarg.	Bebb willow	NS	0.00	0.50	0.00
Salix spp.	Willow species	NS	2.04	0.00	0.12
Stellaria longipes Goldie	Alaska chickweed	NS	0.00	0.66	0.00

Species that were significantly different between crop categories ($P < 0.05$ Tukey's *post hoc* test) are distinguished by different lowercase letters. Categorisation of species as to native or non-native status follows Hultén's (1968) designations.
ANOVA significance levels: NS, not significant; *significant at $P < 0.05$; **significant $P < 0.01$; ***significant at $P < 0.001$.

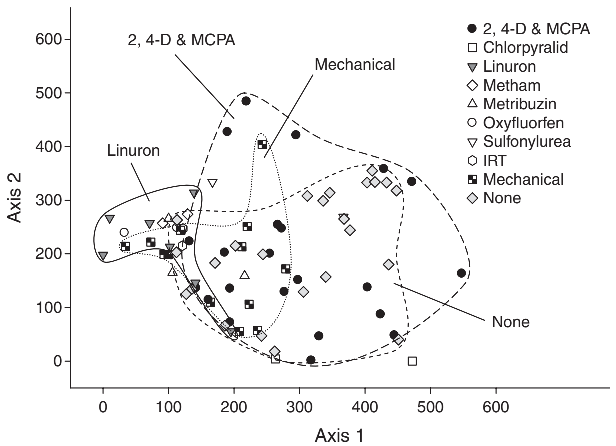

Fig. 2 Graphic overlay of weed control method on the first two axes of DCA ordination of 80 Alaskan agricultural fields sampled in 2004. Symbols indicate weed control method for each field.

1978). Liu *et al.* (2009) reported that plant competition is triggered initially by the red to far-red ratio from neighbouring plants. Canopy cover also reduces the intensity of light, thereby reducing photosynthesis, and weed species adapted for growing under crop canopies have low respiration rates (Patterson, 1985).

The broad-scale environmental gradients of altitude and latitude were significantly correlated with the weed flora of Alaskan agricultural fields. Similar results have been documented in Canada (Dale *et al.*, 1992), Europe (Anderrsson & Milberg, 1998); Sweden (Hallgren *et al.*, 1999) and the Czech Republic and Slovakia (Lososova *et al.*, 2004). More spring cereals, perennial hay and grass seed are grown in the agricultural areas around Delta Junction and Fairbanks, Alaska that are located at higher elevation, higher latitude and lower longitude than in the Matanuska and Susitna Valleys, where potatoes and vegetables are the primary crops. Thus the influence of latitude, longitude and altitude may be more associated with the crops grown, canopy shading and related crop management in specific locations than a direct effect of these environmental gradients on the weed flora.

Conclusions

The agricultural weed flora of Alaska in 1981 was characterised by native colonisers on newly cleared fields and by non-native weed species on older fields. In 2004, the weed flora of all fields except two were characterised by non-native weed species and floristic variability was mainly influenced by crop type. Seven additional weed species became established in Alaskan agriculture during the 23 years between the two studies. The much smaller weed flora in Alaska than Finland (64 species versus 177) shows that many more weed species could invade Alaskan fields if preventative measures are not taken.

After establishing the newly cleared fields, farmers failed to prevent weed introductions and the opportunity was lost to farm 40 000 ha of new agricultural fields without the economic and environmental costs of mechanical or chemical weed control. The fact that several fields were found where non-native weed species had not colonised in 23 years since forest clearing shows that it is possible to prevent weed introductions. The same pathways for invasion that have operated for millennia were likely responsible for the invasion of non-native weeds onto this new farmland: use of weed-contaminated farm implements and planting weed-contaminated crop seed. Weed research has made great advances in developing control methods, but much less progress has been made in designing comprehensive prevention programmes (Davies & Sheley, 2007). Pathways for weed movement are generally known, but little studied (Conn *et al.*, 2008). Weed management has much in common with communicable disease, oil spill and forest fire management, in that costs of controlling an outbreak are much higher than preventing one. Research into prevention strategies and implementation of prevention programmes have been key to the success of communicable disease, oil spill and forest fire programmes, but should be used more in weed management.

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