

# Supporting Information

Driscoll et al. 10.1073/pnas.1409347111

## SI Text

### FFICRC

The FFICRC pioneered integration of environmental weed risk assessment with agricultural plant development and promotion (1). In one case when the system was applied, perennial veldt grass (*Ehrharta calycina*) was rated as a very high risk of becoming an environmental weed. The rating discouraged further promotion of this species within the organization. In a second case, tall wheatgrass (*Thinopyrum ponticum*) was rated as a very high risk in one Australian state (Victoria), but as high risk in three other southern states. If the benefits are considered to outweigh the risks, high-risk species may continue to be developed and promoted by the FFICRC. Management guidelines to minimize risk of escape were provided for this species. However, the weed risk assessment differentiates among states only by the extent of the area of native vegetation that the taxon could invade. The risk of environmental impacts in suitable environments is the same. Thus, release of tall wheatgrass in the high-risk states of New South Wales and South Australia could facilitate invasion of the adjacent state of Victoria where the weed risk is very high. Although integrating weed risk assessment with pasture development is an important advance, the detail of how weed risk is assessed (2), the scale to which it is applied, and the industry and government\* response to those assessments, strongly influences whether environmental impacts are likely to be prevented. The FFICRC ceased operations in June 2014.

### Does Government Guard Against Environmental Weed Risk?

All countries surveyed have lists of excluded species and in most cases include a small number of pasture species (South Africa, 22; Australia, 19; New Zealand, 13; United States, 12; India, 6; Chile, 3; Canada 1; Czech Republic, 0). Below we provide details of the legal frameworks that contribute to regulating pasture plants in each country.

#### Australia.

**Law/regulation.** Quarantine Act, 1908 (Cth)

Environment Protection and Biodiversity Conservation (EPBC) Act 1999 (Cth)

Australian Weeds Strategy

Australia's Biodiversity Conservation Strategy 2010–2030

Weeds of National Significance

Standards Australia HB 294:2006 National Post-Border Weed Risk Management Protocol, CRC Australian Weed Management, Adelaide, and Standards Australia International Ltd., Sydney (a nonbinding guideline)

**Department responsible.** Department of Agriculture, Forestry and Fisheries

Department of the Environment

Individual State Agencies

**Extent to which new taxa are regulated.** Quarantine Act 1908 (Cth), Proclamation 1998 (as amended), Schedule 5 lists permitted species (which includes all subspecific taxa of each species). The Quarantine Act 1908 (Cth), Proclamation 1998 (as amended), Schedule 6 lists species that cannot be imported, including two

pasture species and six pasture genera.<sup>†</sup> Species within three of these genera are also listed on Schedule 5, limiting exclusions to subsets of the genera. Considering the range of potential pasture species,<sup>†</sup> the number of excluded pasture species is 19. Species that are not on the permitted or excluded list are subject to a weed risk assessment.

Federal, state, and territory policies are reactive and not preventative; they can require eradication once a species is listed as a threatening process, under the EPBC Act for example; or impose obligations on land-mangers to eradicate and control weeds, as occurs under weed legislation such as the Noxious Weeds Act 1993 (NSW). Notably, once the impacts of a species are listed as a threatening process, no further action is taken unless the relevant minister thinks that adopting a threat abatement plan is a feasible and cost-effective means of abating the threat; see for example, sections 74 and 83 of the Threatened Species Conservation Act 1995, (NSW) and section 270A of the EPBC Act 1999 (Cth). The absence of remedial action despite listing is exemplified by the recent listing in Victoria of invasion by tall wheatgrass (*Thinopyrum ponticum*) as a potentially threatening process. This species continues to be promoted by the Victorian government for use in agriculture.

#### Canada.

**Law/regulation.** International Plant Protection Convention

Office International des Epizooties

International Maritime Organization

Convention on Biological Diversity

World Trade Organization Agreement on Sanitary and Phytosanitary Measures

Health of Animals Act

Canadian Environmental Protection Act

Environmental Assessment Act

Seeds Act

Pest Control Products Act

Forestry Act

Natural Resources Act

Transportation of Dangerous Goods Act

Oceans Act

Fisheries Act

Canada Wildlife Act

Wild Animal and Plant Protection

Regulations of International and Interprovincial Trade Act

Canada National Parks Act

Plant Protection Act

**Department responsible.** Ministry of Agriculture and Agri-Food

Ministry of Fisheries and Oceans

Ministry of Natural Resources

Ministry of the Environment

**Extent to which new taxa are regulated.** A permit from the Canadian Food Inspection Agency is required to import plant material into Canada, and this includes a weed risk assessment that considers weed risk alongside agricultural pest risks.

New taxa, imported or developed within Canada, must be referred to the Safety Assessment Process if they meet the definition of plants with novel traits (these must be declared by the importer/developer). This assessment includes consideration of

\*Unrelated to the FFICRC, the Victorian Government continues to promote the use of tall wheatgrass, despite the species being listed as a potentially threatening process in that state. Although the weed risk is legally recognized, the feed paradigm dominates regulation.

<sup>†</sup>To ensure a consistent method for identifying pasture species on lists of prohibited species, we used the [www.feedipedia.org](http://www.feedipedia.org) database, accessed 22 January 2014. At that time, 599 feed species were listed. We included all species that are used as fodder for livestock, including fodder trees and fodder crops in that database.

invasion risk. To date, approved plants with novel traits were genetically modified and no conventionally bred pasture taxa have been nominated.

Canada maintains a list of species that are not permitted (pests), which includes one pasture species.<sup>†</sup> There is also a list of Prohibited Noxious Weed Seeds in Canada under the Weed Seeds Order (2005), with no pasture species listed. Plants may be imported from the United States without a permit, provided they are not on the excluded lists and are not plants with novel traits.

#### Chile.

**Law/regulation.** Application of Sanitary and Phytosanitary (ASPS) regulations, as dictated by the World Trade Organization (WTO)

The ASPS refers to the International Plant Protection Convention (IPPC)

**Department responsible.** Service of Agriculture and Livestock (SAG), Ministry of Agriculture

**Extent to which new taxa are regulated.** The main aim of IPPC is to protect wild and cultivated plants by preventing the introduction and spread of pests and to minimize interference with the international movement of goods and people. Chile follows IPPC International Standards for Phytosanitary Measures (ISPM), among which the ISPM No. 11 stands out because it provides for “Pest Risk Analysis (PRA) for quarantine pests, environmental risks, and living modified organisms” and ISPM No. 5, which includes a glossary of phytosanitary terms and terminology of the Convention on Biological Diversity (CBD).

New species introduced to Chile need to undergo a modified version of the Australian weed risk assessment. However, most effort is directed to detect agricultural weeds. Environmental concerns are just recently being considered. New taxa need to be declared and registered, but no risk assessment is required.

Chile has a list of quarantine pests, which includes 3 pasture species<sup>†</sup> of 22 excluded plant species. New regulations are being discussed for environmental weeds under the new Ministry of the Environment.

#### Czech Republic.

**Law/regulation.** EU: CBD Article 8h, Bern Convention

Bird Directive 79/409/EHS

Habitat Directive Směrnice 92/43/EEC

Act no. 114/1992 Sb. On protection of nature and landscape

Act no. 326/2004 Sb. on plant protection

Act no. 289/1995 Sb. § 32 odst. 1 on forest protection

Act no. 334/1992 Sb. on protection of agricultural land

Act no. 99/2004 Sb. on fisheries

**Department responsible.** Ministry of Environment

Ministry of Agriculture

State Phytosanitary Administration Agency

**Extent to which new taxa are regulated.** The Czech Republic has a list of environmental weeds that are classified based on scientific criteria. A “black list” for state authorities has been prepared and may be adopted by the government soon. The black list does not include any pasture species, whereas a gray list (permitted but warrants close monitoring) includes three pasture species.<sup>†</sup> Species that are not on this list will not be subject to biosecurity consideration.

#### India.

**Law/regulation.** Destructive Insects and Pest Act 1914 and amendments

The Plant Quarantine (Regulation of Import into India) Order 2013

International Plant Protection Convention

WTO-SPS Agreement

Indian Forest Act 1927

Biological Diversity Act 2002

**Department responsible.** National Biodiversity Authority, Chennai, India

Plant Quarantine Organization of India

State Biodiversity Board

Biodiversity Management Committees

**Extent to which new taxa are regulated.** The Indian institute must sign a material transfer agreement with the institution from where seeds or plants were sourced, and then an import permit is obtained from the National Bureau of Plant Genetic Resources (NBPGR). Imported/introduced plant material passes through a quarantine process.

Lists of excluded and permitted species are maintained under the Plant Quarantine Order 2013; these focus on excluding diseases and weeds of crops. Schedule IV lists 13 excluded species, none of which are typical pasture plants (grasses or legumes), although 6 are sometimes regarded as forage species<sup>†</sup> (banana, cassava, taro, oak, sugarcane, and the tuberous liana *Dioscoria*). Although new subspecific taxa of pasture plants pass through a quarantine process, regulation does not consider environmental risks of the new taxa.

#### New Zealand.

**Law/regulation.** The Biosecurity Act 1993

Hazardous Substances and New Organisms Act 1996

**Department responsible.** Ministry for Primary Industries (MPI)

**Extent to which new taxa are regulated.** The Biosecurity Act 1993 reformed the laws relating to pests and other unwanted organisms. It was a world first. In the act, an unwanted organism is defined as one that “is capable or potentially capable of causing unwanted harm to any natural and physical resources or human health” and a restricted organism means “any organism for which a containment approval has been granted in accordance with the Hazardous Substances and New Organisms Act 1996.” Part 5 of the act provides for a National Pest Management Strategy and Regional Pest Management Strategy.

MPI's Plants Biosecurity Index identifies approved species for importation by their scientific name. Only species listed in the Plants Biosecurity Index with a valid seed for sowing import specification can be imported. The Plants Biosecurity Index also lists 414 species that are prohibited from entry into New Zealand including 13 pasture species.<sup>†</sup> Importation of species not on the Plant Biosecurity Index requires full risk assessment for potential weed risk.

#### South Africa.

**Law/regulation.** National Environmental Management: Biodiversity Act, 2004 (Act No. 10 of 2004) (NEMBA)

Conservation of Agricultural Resources Act, 1983 (Act No. 43 of 1983) (CARA)

Genetically Modified Organisms Act, 1997 (Act No. 15 of 1997) (GMOA)

Plant Breeders' Rights Act, 1976 (Act No. 15 of 1976) (PBRA)

Plant Improvement Act (Act No. 53 of 1976) (PIA)

**Department responsible.** Department of Environmental Affairs

Department of Agriculture, Forestry, and Fisheries

**Extent to which new taxa are regulated.** NEMBA provides for the placement of species under two categories: 1a species must be controlled/removed, and 1b species require a management program to be drawn up. NEMBA provides for the placement of species under four categories, all of which may not be imported into the country, sold, spread, grown or released in the country (unless with a permit). Category 1a species must be controlled/eradicated and control must be maintained, and 1b species must be contained. Management programs must be developed for these species, and landowners must implement the plan. Category 2 species require a permit to be on a landowner's property and must be contained within the boundaries of the property. Category 3 species may not be imported into the country.

CARA species are also categorized (1–3) and may only occur within biological control reserves and/or demarcated areas.

NEMBA and CARA both prohibit the import of listed species, and NEMBA requires a risk assessment for the import of any alien species. In terms of both of these laws, it is possible that if a pasture species was to become problematic, it could be motivated to be added to the NEMBA list. However, there is no provision in these laws for new cultivars of species already in the country to have to undergo any sort of risk assessment.

The three other acts deal with the importation of new species or taxa into the country: The GMOA requires permits for genetically modified species and risk assessments for these species. Taxa with Plant Breeders' Rights may not be imported into the country without permission from the PBR owner (PBRA), but there is no need for risk assessment. The PLA exempts a number of agricultural species from the need for import permits. All other species require permits in terms of this law, but these merely require e.g., minimum germination standards.

One pasture species is excluded by CARA, and 21 pasture species<sup>†</sup> are excluded by NEMBA.

**United States.**

**Law/regulation.** Plant Quarantine Act of 1912

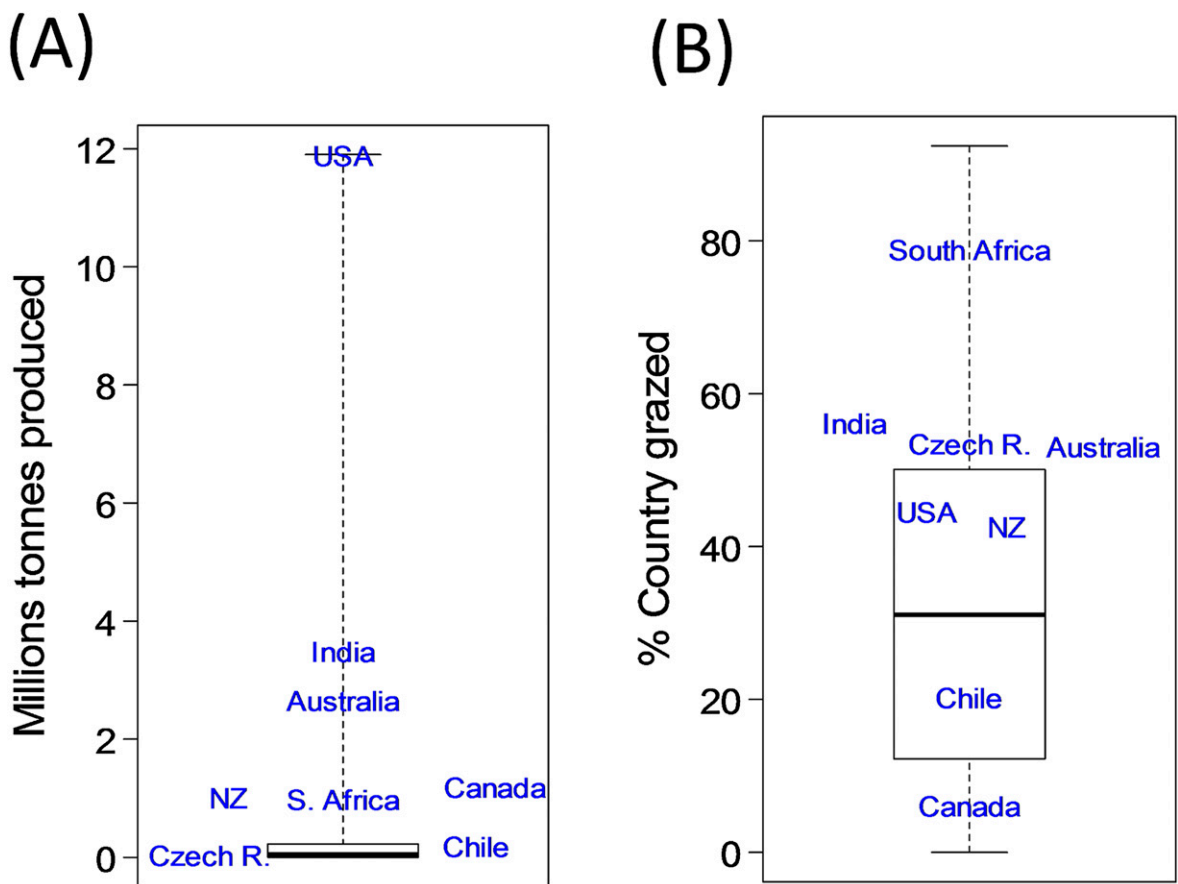
Federal Plant Pest Act of 1957  
 Federal Noxious Weed Act of 1974  
 Plant Protection Act of 2000

**Department responsible.** US Department of Agriculture, Animal and Plant Health Inspection Service (USDA APHIS)

**Extent to which new taxa are regulated.** Only species on state or federal noxious weed lists are regulated in the United States. USDA APHIS, and more specifically the Plant Protection and Quarantine program, is responsible for determining which species are added to the federal list, which follows a weed risk assessment. At the federal level, species for planting can be added to the Not Authorized Pending Pest Risk Analysis list, followed by a weed risk assessment and final judgment for listing by APHIS officials. Individual states vary greatly in their process: some have formal risk assessment systems, but most do not. Regulatory authority at the state level is not consistent among the 50 states (for a detailed description of noxious weed lists, see ref. 3). The federal noxious weeds list includes 12 pasture species,<sup>†</sup> which cannot be imported.

1. Stone LM, Byrne M, Virtue JG (2008) An environmental weed risk assessment model for Australian forage improvement programs. *Aust J Exp Agric* 48(4):568–574.
2. Hulme PE (2012) Weed risk assessment: A way forward or a waste of time? *J Appl Ecol* 49(1):10–19.

3. Quinn LD, Barney JN, McCubbins JSN, Endres AB (2013) Navigating the “noxious” and “invasive” regulatory landscape: Suggestions for improved regulation. *Bioscience* 63(2):124–131.



**Fig. S1.** Meat production (A) and area subject to livestock grazing (B) for target countries compared with the rest of the world. To describe how livestock production in our surveyed countries compares with global production, we accessed the Food and Agriculture Organization of the United Nations tool, FAOSTAT ([faostat3.fao.org/faostat-gateway/go/to/home/E](http://faostat3.fao.org/faostat-gateway/go/to/home/E)) in July 2014. We summed production of beef, buffalo, sheep, and goats as an estimate of meat production. To estimate the percentage of land area subject to grazing by livestock, we subtracted the percentage of land permanently under crops from the total percentage under agriculture. The remaining agricultural land is therefore used for grazing or both grazing and cropping. Box plots show the median, interquartile range, and maximum and minimum values. Country names are positioned by their y axis value and offset horizontally to avoid text overlap.

**Table S1. Description of taxa developed and biosecurity measures undertaken by agribusinesses that develop and/or sell pasture taxa**

Country	Organization	Description of taxa being developed	Description of biosecurity assessments
Australia	Agribusiness 1. Future Farm Industries Cooperative Research Centre (FFCRC), Government and industry funded research and product delivery collaboration, closed in June 2014. Its products were marketed through a commercial agribusiness which exports to over 50 countries and is itself a subsidiary of one of the world's leading grass seed organizations which markets into almost 100 countries and has subsidiaries in The Netherlands, France, United Kingdom, Belgium, Luxembourg, Poland, Denmark, Italy, Russia, USA, Argentina, Brazil, Chile, New Zealand, Australia, China and South Africa. Agribusiness 2. Government and industry funded research organization. Pasture taxa promoted in the Pacific including: New Zealand and Fiji; SE Asia including: Philippines, Malaysia, Thailand, Indonesia; Africa including: South Africa, Kenya, Tanzania, Zimbabwe, Zambia, Malawi, Botswana, Mozambique. Agribusiness 3. Federal government organization. Agribusiness 4. Association funded by industry. Agribusiness 5. Government funded agency.	The FFCRC developed perennial shrubs to improve animal productivity in low and high rainfall areas, also developing tropical and subtropical forages. Taxa developed included cocksfoot ( <i>Dactylis glomerata</i> *), tall fescue ( <i>Schedonorus arundinaceus</i> *), phalaris ( <i>Phalaris aquatica</i> *), panic grass ( <i>Urochloa maxima</i> *), a salt-tolerant grass ( <i>Distichlis spicata</i> *) and the legumes <i>Lotus corniculatus</i> *, tедера ( <i>Bituminaria bituminosa</i> *), messina ( <i>Melilotus siculus</i> *), including a new salt-tolerant Rhizobium strain), <i>Cullen australasicum</i> <sup>1</sup> and <i>Cullen pallidum</i> <sup>1</sup> . They also promoted use of the salt-tolerant taxa old man saltbush ( <i>Atriplex nummularia</i> *) <sup>1</sup> and tall wheatgrass ( <i>Thinopyrum ponticum</i> *).	Protocols were established to rank weed risk. Pamphlets were produced describing weed risk for some species. For very high risk species, FFCRC policy was to cease promotion. For high risk species, management information was provided to help land-holders and others to assess and manage the risk.
Australia	Agribusiness 2. Government and industry funded research organization. Pasture taxa promoted in the Pacific including: New Zealand and Fiji; SE Asia including: Philippines, Malaysia, Thailand, Indonesia; Africa including: South Africa, Kenya, Tanzania, Zimbabwe, Zambia, Malawi, Botswana, Mozambique. Agribusiness 3. Federal government organization. Agribusiness 4. Association funded by industry. Agribusiness 5. Government funded agency.	Developed nearly all Australian <i>Phalaris</i> * varieties. <i>Phalaris aquatica</i> *, <i>Phalaris arundinacea</i> *, <i>Trifolium subterraneum</i> *	Programs that tackle invasive species issues are not linked to pasture development within the organization.
Canada	Agribusiness 3. Federal government organization.	New cultivars of alfalfa ( <i>Medicago sativa</i> *), cicer milkvetch ( <i>Astragalus cicer</i> *), orchardgrass ( <i>Dactylis glomerata</i> *), sainfoin ( <i>Onobrychis vicifolia</i> *)	No evidence found
Canada	Agribusiness 4. Association funded by industry.	Surinam grass ( <i>Urochloa</i> (formerly <i>Brachiaria</i> ) <i>decumbens</i> *) introduced from Africa; new commercial varieties of alfalfa ( <i>Medicago sativa</i> *)	No evidence found
Chile	Agribusiness 5. Government funded agency.	Pasture grasses and legumes. One native species ( <i>Bromus valdivianus</i> *) <sup>1</sup> , one exotic species ( <i>Trifolium pratense</i> *) have already been patented as Chilean varieties. Also, recent work on <i>Trifolium repens</i> * and <i>Lotus uliginosus</i> *.	No evidence found
Chile	Agribusiness 6. Private company. Sells to Argentina, Bolivia, Brazil, Ecuador, Peru.	Previously worked on <i>Lotus tenuis</i> * and <i>Lotus uliginosus</i> *. Specialising in Lucern ( <i>Medicago sativa</i> *). A range of varieties available, imported largely from the USA. New varieties are produced from hybrids of imported taxa with "local" taxa.	No evidence found
Chile	Agribusiness 7. Private company.	Sells grasses and grass hybrids ( <i>Lolium perenne</i> *, <i>Schedonorus arundinaceus</i> *, <i>Bromus valdivianus</i> *, <i>Lolium multiflorum</i> *, <i>Festuca pratensis</i> * X <i>Lolium multiflorum</i> *, <i>Festuca arundinacea</i> * X <i>Lolium multiflorum</i> *, <i>Festuca perennis</i> ), Legumes ( <i>Pisum sativum</i> , <i>Vicia atropurpurea</i> , <i>Trifolium pratense</i> *, <i>Trifolium repens</i> *, <i>Trifolium subterraneum</i> *, <i>Trifolium incarnatum</i> *), and Brassica ( <i>B. oleracea</i> *, <i>B. napus</i> * X <i>B. oleracea</i> *). All seeds are brought directly from Denmark and New Zealand. Seed mixes are made in Chile. No seed multiplication or development in Chile.	No evidence found



Table S1. Cont.

Country	Organization	Description of taxa being developed	Description of biosecurity assessments
Czech Republic	Agribusiness 8. Private company. Develops cultivars for grass and fodder mixtures. Exports to Germany.	They offer 15 grass and fodder species (of which 12 are cultivars of native species). Exotics include clover ( <i>Trifolium hybridum</i> *), Italian ryegrass ( <i>Lolium multiflorum</i> *), and brome grasses ( <i>Bromus sitchensis</i> *, <i>B. marginatus</i> ). <i>Trifolium</i> and <i>Lolium</i> originate from Europe. Native species include the grasses <i>Lolium perenne</i> * <sup>†</sup> , <i>Dactylis glomerata</i> * <sup>†</sup> , <i>Festuca rubra</i> * <sup>†</sup> , <i>Cynosurus cristatus</i> * <sup>†</sup> , <i>Agrostis stolonifera</i> <sup>†</sup> , <i>Poa nemoralis</i> <sup>†</sup> , <i>Alopecurus pratensis</i> * <sup>†</sup> , <i>Bromus inermis</i> * <sup>†</sup> , and the legumes <i>Trifolium pratense</i> * <sup>†</sup> , <i>Trifolium repens</i> * <sup>†</sup> , <i>Lotus corniculatus</i> * <sup>†</sup> .	No evidence found
Czech Republic	Agribusiness 9. Private company. Exports to Germany, Switzerland, Austria and Slovakia, Ukraine and France.	The company promotes four exotic species and six cultivars of native grasses and legumes. Exotics are redtop bentgrass ( <i>Agrostis gigantea</i> *), Italian ryegrass ( <i>Lolium multiflorum</i> *), sainfoin ( <i>Onobrychis viciifolia</i> *) and alfalfa ( <i>Medicago sativa</i> *). All exotics except alfalfa originate from Europe. Native species include the grasses <i>Anthoxanthum odoratum</i> * <sup>†</sup> , <i>Lolium perenne</i> * <sup>†</sup> , and the legumes <i>Anthyllis vulneraria</i> <sup>†</sup> , <i>Melilotus alba</i> * <sup>†</sup> , <i>Trifolium repens</i> * <sup>†</sup> and <i>Trifolium pratense</i> * <sup>†</sup> .	No evidence found
India	Agribusiness 10. Government organization.	Research focused on improving seed yield in a range of legumes and grasses. Grasses ( <i>Axonopus compressus</i> *, <i>Bothriochloa intermedia</i> <sup>†</sup> , <i>Bothriochloa pertusa</i> <sup>†</sup> , <i>Brachiaria brizantha</i> *, <i>Brachiaria mutica</i> *, <i>Cenchrus ciliaris</i> *, <i>Cenchrus setigerus</i> * <sup>†</sup> , <i>Chloris gayana</i> *, <i>Chrysopogon fulvus</i> <sup>†</sup> , <i>Coix lacryma</i> * <sup>†</sup> , <i>Cynodon dactylon</i> * <sup>†</sup> , <i>Dichanthum annulatum</i> * <sup>†</sup> , <i>Digitaria decumbens</i> * <sup>†</sup> , <i>Diplachne fusca</i> * <sup>†</sup> , <i>Eragrostis curvula</i> * <sup>†</sup> , <i>Eulaliopsis binata</i> <sup>†</sup> , <i>Heteropogon contortus</i> , <i>Isellema laxum</i> <sup>†</sup> , <i>Lasiurus indicus</i> <sup>†</sup> , <i>Melinis minutiflora</i> *, <i>Panicum antidotale</i> *, <i>Panicum maximum</i> *, <i>Panicum turgidum</i> , <i>Paspalum dilatatum</i> *, <i>Paspalum notatum</i> *, <i>Pennisetum claudenstinum</i> *, <i>Pennisetum pedicellatum</i> *, <i>Setaria neurosum</i> , <i>Setaria sphacelata</i> *, <i>Tripsacum dactyloides</i> , <i>Urochloa mosambicensis</i> *, <i>Vetiveria zizanioides</i> *. Legumes ( <i>Atylosia scarabaeoides</i> * <sup>†</sup> , <i>Calopogonium mucunoides</i> *, <i>Centrosema pubescens</i> *, <i>Clitoria ternatea</i> *, <i>Desmanthus virgatus</i> *, <i>Desmodium intortum</i> *, <i>Indigofera hirsuta</i> , <i>Lablab purpureus</i> *, <i>Lotononis bainesii</i> <sup>†</sup> , <i>Macroptilium atropurpureum</i> * <sup>†</sup> , <i>Macroptilium lathyoides</i> *, <i>Macrotyloma axillares</i> *, <i>Neontonia wightii</i> *, <i>Pueraria phaseoloides</i> *, <i>Stizolobium deeringianum</i> *, <i>Mucuna pruriens</i> ), <i>Stylosanthes guianensis</i> *, <i>Stylosanthes hamata</i> *, <i>Stylosanthes humilis</i> *, <i>Stylosanthes scabra</i> *, <i>Vigna luteola</i> ). In addition, 204 accessions of 10 species of the legume <i>Leucaena</i> (136 accessions belonged to <i>L. leucocephala</i> *).	No evidence found
India	Agribusiness 11. Private company. A subsidiary of one of the world's leading grass seed organizations that markets into almost 100 countries.	Forage species: <i>Lolium multiflorum</i> *. <i>Schedonorus arundinaceus</i> *, <i>Panicum maximum</i> *, several <i>Sorghum</i> * hybrids, <i>Trifolium alexandrinum</i> *, makhana grass ( <i>Brachiaria ramosa</i> *), Tall fescue ( <i>Festuca arundinacea</i> *), Annual ryegrass ( <i>Lolium multiflorum</i> *), Perennial ryegrass ( <i>Lolium perenne</i> *), Orchard grass ( <i>Dactylis glomerata</i> *), Meadow grass ( <i>Festuca pratensis</i> *), Timothy ( <i>Phleum pratense</i> *), Annual brome ( <i>Bromus japonicus</i> *), Smooth brome ( <i>Bromus inermis</i> *), Kentucky bluegrass ( <i>Poa pratensis</i> *), Wheat grass ( <i>Agropyron</i> * sp), Red clover ( <i>Trifolium pratense</i> *), White clover ( <i>Trifolium repens</i> *), Chicory ( <i>Cichorium intybus</i> *), <i>Sorghum</i> * spp, Multicut ( <i>Pennisetum</i> sp.), Oats ( <i>Avena sativa</i> *), Lucerne ( <i>Medicago sativa</i> *).	No evidence found

Table S1. Cont.

Country	Organization	Description of taxa being developed	Description of biosecurity assessments
New Zealand	Agribusiness 12. Private company. Researches, develops and markets pasture taxa in NZ and Australia.	<p>Develops multiple varieties of diploid and tetraploid perennial Ryegrasses (<i>Lolium perenne</i>*), and hybrids with annual ryegrasses (<i>L. multiflorum</i>*), three additional grasses (cockfoot (<i>Dactylis glomerata</i>*), <i>Bromus catharticus</i>*, <i>Festuca arundinacea</i>*, ribwort plantain <i>Plantago lanceolata</i>*, Chicory (<i>Cichorium intybus</i>*), five species of clover (<i>Trifolium repens</i>*, <i>T. pratense</i>*, <i>T. fragiferum</i>* , <i>T. michelianum</i>* , <i>T. resupinatum</i>*), and the legume <i>Medicago sativa</i>*. Varieties in common with Agribusiness 13.</p> <p>Pasture plants include diploid, tetraploid and hybrid <i>Lolium x boucheanum</i> Kunth (<i>Lolium multiflorum</i>* x <i>L. perenne</i>*) perennial ryegrass (<i>Lolium perenne</i>*), some with endophytes, Italian and annual ryegrasses (<i>Lolium multiflorum</i>*), all with multiple cultivars available. Six other grass species (<i>Bromus valdivianus</i>, <i>Bromus catharticus</i>*, cockfoot (<i>Dactylis glomerata</i>*), tall fescue (<i>Schedonorus arundinaceus</i>*), wild oats (<i>Avena sativa</i>*), timothy (<i>Phleum pratense</i>*). Nongrasses are chicory (<i>Cichorium intybus</i>*), plantain (<i>Plantago lanceolata</i>*), white clover (<i>Trifolium repens</i>*) and red clover (<i>T. pratense</i>*). Varieties in common with Agribusiness 12.</p> <p>Preceding organization developed <i>Eragrostis curvula</i>*<sup>1</sup>, <i>Eragrostis tef</i>*, <i>Schedonorus arundinaceus</i>*, <i>Lolium x boucheanum</i> (<i>Lolium multiflorum</i>* x <i>L. perenne</i>*), <i>Lolium multiflorum</i>*, <i>Lolium perenne</i>*, <i>Raphanus sativus</i>* var. <i>oleiformis</i> and <i>Trifolium repens</i>*. Also sells <i>Avena sativa</i>*, <i>Chloris gayana</i>*<sup>1</sup>, <i>Dactylis glomerata</i>*, <i>Digitaria eriantha</i>*<sup>1</sup>, <i>Hordeum vulgare</i>*, <i>Medicago sativa</i>*, <i>Panicum maximum</i>*<sup>1</sup>, <i>Paspalum notatum</i>*, <i>Pennisetum clandestinum</i>*, <i>Pennisetum glaucum</i>*, <i>Sorghum</i>* hybrids, <i>Triticum x Secale</i> hybrids, <i>Trifolium alexandrinum</i>* , <i>Trifolium pratense</i>*.</p>	No evidence found
New Zealand	Agribusiness 13. Private company. Plant breeding and research linked to one of the world's leading grass seed organizations that markets into almost 100 countries.		No evidence found
South Africa	Agribusiness 14. Private company, sells seeds developed by a preceding organization. Buys seed from Africa, the Americas, Australia and New Zealand. Exports to > 30 countries.		No evidence found
South Africa	Agribusiness 15. Private company. New cultivars are developed on a contract basis with universities or research centers, or by the company itself. Sells into many African countries, with branches establishing in Zambia, Rwanda, Zimbabwe, Mozambique, Angola, Kenya and Tanzania.		No evidence found

**Table S1. Cont.**

Country	Organization	Description of taxa being developed	Description of biosecurity assessments
USA	Agribusiness 16. Privately funded organization. Conducts pasture development research. Has staff in 25 countries, and collaborates with two international consortia that sell into USA, Canada, Mexico, Argentina, Australia, Brazil, Finland, U.K., and Uruguay.	In their plant breeding research program they are developing cultivars of fodder crops and grasses (oat ( <i>Avena sativa</i> *), rye ( <i>Lolium perenne</i> *), tall fescue ( <i>Schedonorus arundinaceus</i> *), orchardgrass ( <i>Dactylis glomerata</i> *), switchgrass ( <i>Panicum virgatum</i> * <sup>†</sup> ), Cereal rye ( <i>Secale cereale</i> *), Triticale spp. and <i>Digitaria</i> * spp.), and three forage legumes ( <i>Trifolium pratense</i> *, <i>T. repens</i> *, <i>Medicago sativa</i> *).	No evidence found
USA	Agribusiness 17. Government organization. Does not sell directly to other countries, but collaborates with agribusiness in China, and products are sold through seed consortia.	A broad range of state-based programs, including work on: <i>Agropyron fragile</i> *, <i>Dactylis glomerata</i> *, <i>Kochia prostrata</i> *, <i>Panicum virgatum</i> * <sup>†</sup> , <i>Agropyron cristatum</i> *, <i>Pseudoroegneria spicata</i> <sup>†</sup> , <i>Pascopyrum smithii</i> * <sup>†</sup> , <i>Astragalus filipes</i> <sup>†</sup> , <i>Dalea purpurea</i> <sup>†</sup> , <i>Achillea millefolium</i> * <sup>†</sup> , <i>Leymus cinereus</i> <sup>†</sup> , <i>Nassella viridula</i> * <sup>†</sup> , <i>Achnatherum hymenoides</i> <sup>†</sup> , <i>Poa secunda</i> <sup>†</sup> , <i>Elymus trachycaulus</i> * <sup>†</sup> , <i>Elymus wawawaiensis</i> <sup>†</sup> , <i>Elymus elymoides</i> * <sup>†</sup> , <i>Bromus biebersteinii</i> *, <i>Psathyrostachys juncea</i> *. Collaborative research includes trials and development of 581 species in Mongolia, with 123 seed collections returned to the USA for use in breeding programs. Work also includes endophytes in tall fescue ( <i>Schedonorus arundinaceus</i> *) and <i>Festuca</i> * interspecific hybrids.	This Research Lab has published two papers on invasion risk of <i>Kochia prostrata</i> . They conclude limited spread potential with some exceptions.

Data are based on our review of the websites, the most recent annual report, publications, and discussions with senior staff of each agribusiness. Agribusinesses with international sales and purchasing links are indicated. All agribusinesses are subject to the general biosecurity legislation appropriate to each country (SI Text). Agribusinesses are listed anonymously because our intention is not to criticize individual companies but to highlight the global evidence that environmental weeds are widely developed and promoted for use in pastures, often across multiple countries.

\*Environmental weeds listed in Randall's *Global Compendium of Weeds* ([www.hear.org/gcw/](http://www.hear.org/gcw/)).

<sup>†</sup>Native in at least part of this country.

**Table S2. Sample of taxa developed or sold by agribusinesses from eight countries, highlighting the plant characteristics currently possessed by, or being developed in, pasture taxa**

Species*	Common name	Country	Organization (taxon name) <sup>†</sup>	Developed characteristics associated with weed risk <sup>‡</sup>	Other species characteristics	Recognized as weed in country (regulatory response) <sup>§</sup>	Global weed status <sup>¶</sup>
<i>Agropyron cristatum</i> (L.) Gaertn.	Crested wheatgrass	USA	Agribusiness 17	1: high nutrient content; 6: high establishment, high survival		No	CE
<i>Agropyron fragile</i> (Roth) P. Candargy	Siberian wheatgrass	USA	Agribusiness 17	1: drought tolerance; 6: high establishment, high survival		No	
<i>Agrostis gigantea</i> Roth	Redtop	Czech Republic	Agribusiness 9	4: high growth rate; 5: high yield	Palatable	No	ACEN <sup>  </sup>
<i>Agrostis stolonifera</i> L.	Creeping bentgrass	Czech Republic	Agribusiness 8		Ornamental	No	ACE
<i>Alopecurus pratensis</i> L.	Meadow foxtail	Czech Republic	Agribusiness 8	no information provided	Easier sowing	No	ACE
<i>Astragalus cicer</i> L.	Cicer Milkvetch	Canada	Agribusiness 3	1: cold tolerance; 5: high yield; 6: high survival	Competitive	Yes (nothing)	AC
<i>Bromus stamineus</i> Desv.	Roadside brome, Grazing brome	Chile	Agribusiness 5 ( <i>Bromus valdivianus</i> )	4: high growth rate; 5: larger, high yield; 6: high survival, fecund		No	E
<i>Dactylis glomerata</i> L.	Orchardgrass, Ascherson's orchardgrass; cocksfoot	Australia	Agribusiness 1. Future Farm Industries Cooperative Research Centre	1: drought tolerance, broad edaphic tolerance		Yes (management information provided by FFICRC)	ACEN
<i>Dactylis glomerata</i> L.	Orchard grass, cocksfoot	Canada	Agribusiness 3	1: high nutrient content, cold tolerance; 6: fecund, disease resistance	Palatable	Yes (nothing)	ACEN
<i>Dactylis glomerata</i> L.	Orchardgrass, Ascherson's orchardgrass; cocksfoot	New Zealand	Agribusiness 12	1: drought tolerance; 4: high growth rate	Palatable	Yes (nothing)	ACEN
<i>Dactylis glomerata</i> L.	Orchardgrass, Ascherson's orchardgrass; cocksfoot	New Zealand	Agribusiness 13	5: larger, high yield		No	ACEN
<i>Dactylis glomerata</i> L.	Orchardgrass, Ascherson's orchardgrass; Cocksfoot	USA	Agribusiness 17	1: cold tolerance, high elevation tolerance, broad edaphic tolerance; 5: larger; 6: high survival		Yes (nothing)	ACEN
<i>Eragrostis curvula</i> (Schrad.) Nees	Weeping lovegrass	South Africa	Agribusiness 15	1: broad edaphic tolerance		No	ACEN
<i>Eragrostis tef</i> (Zuccagni) Trotter	Teff	South Africa	Agribusiness 14	1: drought tolerance, broad edaphic tolerance; 2: larger leaves; 3: high above-ground biomass; 4: high growth rate; 5: larger, high yield		No	A
<i>Leucaena leucocephala</i> (Lam.) de Wit	Leucaena; White leadtree	India	Agribusiness 10	4: high growth rate; 6: high survival		Yes (nothing)	ACEN <sup>  </sup>
<i>Lolium perenne</i> L.	Perennial ryegrass	New Zealand	Agribusiness 12	1: endophyte manipulation		No	ACE
<i>Lolium perenne</i> L. ssp. <i>multiflorum</i> (Lam.) Husnot	Italian ryegrass; Annual ryegrass	Chile	Agribusiness 7 ( <i>Lolium multiflorum</i> )	1: endophyte manipulation, cold tolerance; 3: high above-ground biomass; 4: high growth rate; 5: larger; 6: high survival	Palatable	Yes (nothing)	ACE



**Table S2. Cont.**

Species*	Common name	Country	Organization (taxon name) <sup>†</sup>	Developed characteristics associated with weed risk <sup>‡</sup>	Other species characteristics	Recognized as weed in country (regulatory response) <sup>§</sup>	Global weed status <sup>¶</sup>
<i>Lolium perenne</i> L.	Italian ryegrass; Annual ryegrass	Czech Republic	Agribusiness 9 ( <i>L. multiflorum</i> )	4: high growth rate		No	ACE
<i>Lolium perenne</i> L. (Lam.) Husnot	Italian ryegrass; Annual ryegrass	India	Agribusiness 11 ( <i>L. multiflorum</i> )	1: high nutrient content, cold tolerance; 3: high above-ground biomass; 4: high growth rate; 5: larger, high yield; 6: fecund		No	ACE
<i>Lolium perenne</i> L. (Lam.) Husnot	Italian ryegrass; Annual ryegrass	New Zealand	Agribusiness 13 ( <i>L. multiflorum</i> )	5: larger; 6: high establishment	Tetraploid; palatable	No	ACE
<i>Lolium x boucheanum</i> Kunth	Hybrid rye	South Africa	Agribusiness 14 ( <i>L. multiflorum</i> x <i>L. perenne</i> )	1: cold tolerance, enhanced photosynthesis; 3: high above-ground biomass; 4: high growth rate; 5: larger, high yield; 6: disease resistance survival; disease resistance		No	—
<i>Medicago sativa</i> L.	Alfalfa	Canada	Agribusiness 4	1: broad edaphic tolerance; 6: high survival; disease resistance		No	ACE
<i>Medicago sativa</i> L.	Alfalfa	Chile	Agribusiness 6	4: high growth rate; 5: larger, high yield; 6: high survival		No	ACE
<i>Onobrychis viciifolia</i> Scop.	Sainfoin	Canada	Agribusiness 3	1: drought tolerance, cold tolerance; 5: high growth rate; 6: high survival		No	AC
<i>Ornithopus sativus</i> Brot.	Common bird's-foot; Pink serradella	South Africa	Agribusiness 15	1: broad edaphic tolerance, grazing tolerance		No	ACE
<i>Pennisetum ciliare</i> (L.) Link	Buffelgrass	India	Agribusiness 10 ( <i>Cenchrus ciliaris</i> )	1: drought tolerance; 4: high growth rate; 6: high survival		No	ACE <sup>  </sup>
<i>Phalaris aquatica</i> L.	Bulbous canarygrass, Hardinggrass	Australia	Agribusiness 2	1: drought tolerance, cold tolerance; 6: high survival		Yes (nothing)	ACEN
<i>Phalaris arundinacea</i> L.	Reed Canarygrass	Australia	Agribusiness 2	1: drought tolerance, cold tolerance; 6: high survival		Yes (nothing)	ACEN <sup>  </sup>
<i>Schedonorus arundinaceus</i> (Schreb.) Dumort., nom. cons.	Tall fescue	Australia	Agribusiness 1. Future Farm Industries Cooperative Research Centre ( <i>Lolium arundinaceum</i> )	1: drought tolerance, broad edaphic tolerance, high nutrient content; 4: high growth rate; 6: high survival		Yes (nothing)	ACEN <sup>  </sup>
<i>Schedonorus arundinaceus</i> (Schreb.) Dumort., nom. cons.	Tall fescue	Chile	Agribusiness 7 ( <i>Festuca arundinacea</i> )	1: drought tolerance, endophyte manipulation, cold tolerance, flood tolerance; 3: high above-ground biomass; 4: high growth rate; 5: larger; 6: high survival		Yes (nothing)	ACEN
<i>Schedonorus arundinaceus</i> (Schreb.) Dumort., nom. cons.	Tall fescue	South Africa	Agribusiness 14 ( <i>Festuca arundinacea</i> )	1: drought tolerance; 6: high survival, disease resistance		No	ACEN

Table S2. Cont.

Species*	Common name	Country	Organization (taxon name) <sup>†</sup>	Developed characteristics associated with weed risk <sup>‡</sup>	Other species characteristics	Recognized as weed in country (regulatory response) <sup>§</sup>	Global weed status <sup>¶</sup>
<i>Schedonorus arundinaceus</i> (Schreb.) Dumort., nom. cons.	Tall fescue	USA	Agribusiness 16	1: endophyte manipulation		Yes (nothing)	A
<i>Secale cereale</i> L.	Cereal rye; Rye	USA	Agribusiness 16	1: grazing tolerance; 5: high yield; 6: high survival	Palatable	Yes (warning information provided)	ACEN
<i>Stylosanthes hamata</i> (L.) Taubert	Cheesytoes	India	Agribusiness 10	1: grazing tolerance; 4: high growth rate	Tetraploid; high growth under elevated carbon dioxide	No	AE
<i>Trifolium pratense</i> L.	Red clover	Chile	Agribusiness 5	4: high growth rate; 5: larger; 6: high survival		No	ACE
<i>Trifolium repens</i> L.	White clover; Ladino clover; Dutch clover	Czech Republic	Agribusiness 8	1: nutrient use efficiency		No	ACE <sup>  </sup>
<i>Trifolium repens</i> L.	White clover; Ladino clover; Dutch clover	Czech Republic	Agribusiness 9	1: drought tolerance, nutrient use efficiency; 4: high growth rate; 5: larger, high yield; 6: high survival, disease resistance	Competitive	No	ACE <sup>  </sup>
<i>Trifolium repens</i> L.	White clover; Ladino clover; Dutch clover	New Zealand	Agribusiness 13	1: drought tolerance; 2: larger leaves; 5: larger, high yield; 6: disease resistance		No	ACE <sup>  </sup>
<i>Trifolium repens</i> L.	White clover; Ladino clover; Dutch clover	South Africa	Agribusiness 15	1: grazing tolerance		No	ACE <sup>  </sup>
<i>Trifolium repens</i> L.	White clover; Ladino clover; Dutch clover	USA	Agribusiness 16	5: larger; 6: high survival	Competitive	Yes (nothing)	ACE <sup>  </sup>
<i>Trifolium subterraneum</i> L.	Subterranean clover	Australia	Agribusiness 2	1: nutrient use efficiency; 3: high above-ground biomass; 4: high growth rate		Yes (nothing)	AE

The weed status of each taxon globally and within the country it is developed or sold in is also indicated. —, no species-specific information.

\*Authority: USDA Plants Database ([plants.usda.gov/java/](https://plants.usda.gov/java/)), accessed 1 December 2013).

<sup>†</sup>Taxon name used by organization provided in brackets if it differs from the species name, although some commercial names excluded.

<sup>‡</sup>We classified characteristics that are associated with weed risk based on the meta-analysis by van Kleunen et al. (9): 1, physiology; 2, leaf-area allocation; 3, shoot allocation; 4, growth rate; 5, size; 6, fitness.

<sup>§</sup>The current status of species in each country was determined according to the following criteria: Y, legally recognized as a weed risk (appears on a weed list that carries legislative force for the country or at least one jurisdiction within that country); y, recognized as an environmental weed risk in published material (scientific literature, floras, weed lists curated by plant societies, environmental management agencies and experts) in the country or a region within that country, but not legally recognized; n, no evidence that it is an environmental weed risk (the taxon is absent from the reference material above or specifically reported as not invading native ecosystems in the material listed above). The regulatory response (by government unless otherwise indicated) associated with species listed or known to be environmental weed risks is in brackets.

<sup>¶</sup>The status of each species globally was based on Randall's *Global Compendium of Weeds* ([www.hear.org/gcw/](http://www.hear.org/gcw/)). A, agricultural weed; E, environmental weed; N, noxious weed.

<sup>||</sup>Species listed in the Global Invasive Species Database ([www.issg.org/database/welcome/](http://www.issg.org/database/welcome/)), accessed 1 December 2013).

**Table S3. Enumeration of taxa developed or sold for each agribusiness and whether those taxa are recognized as weeds, based on data in Table S1**

Agribusiness no.	Number of taxa developed or sold	Number listed as weeds*	Weeds/total
1	12	10	0.83
2	3	3	1.00
3	4	4	1.00
4	2	2	1.00
5	6	6	1.00
6	1	1	1.00
7	15	12	0.80
8	15	12	0.80
9	10	9	0.90
10	52	39	0.75
11	22	21	0.95
12	13	12	0.92
13	12	12	1.00
14	22	21	0.95
15	61	55	0.90
16	11	10	0.91
17	21	14	0.67
Mean (SD)			0.91 (0.10)
No. taxa	178	141	0.79

No. taxa indicates the total number of unique taxa in the data set; taxa used by more than one agribusiness were only counted once.

\*Environmental weeds listed in Randall's *Global Compendium of Weeds* ([www.hear.org/gcw/](http://www.hear.org/gcw/)).