

New pasture plants intensify invasive species risk

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Agricultural intensification is critical to meet global food demand, but intensification threatens native species and degrades ecosystems. Sustainable intensification (SI) is heralded as a new approach for enabling growth in agriculture while minimizing environmental impacts. However, the SI literature has overlooked a major environmental risk. Using data from eight countries on six continents, we show that few governments regulate conventionally bred pasture taxa to limit threats to natural areas, even though most agribusinesses promote taxa with substantial weed risk. New pasture taxa (including species, subspecies, varieties, cultivars, and plant-endophyte combinations) are bred with characteristics typical of invasive species and environmental weeds. By introducing novel genetic and endophyte variation, pasture taxa are imbued with additional capacity for invasion and environmental impact. New strategies to prevent future problems are urgently needed. We highlight opportunities for researchers, agribusiness, and consumers to reduce environmental risks associated with new pasture taxa. We also emphasize four main approaches that governments could consider as they build new policies to limit weed risks, including (i) national lists of taxa that are prohibited based on environmental risk; (ii) a weed risk assessment for all new taxa; (iii) a program to rapidly detect and control new taxa that invade natural areas; and (iv) the polluter-pays principle, so that if a taxon becomes an environmental weed, industry pays for its management. There is mounting pressure to increase livestock production. With foresight and planning, growth in agriculture can be achieved sustainably provided that the scope of SI expands to encompass environmental weed risks.

agriculture policy | biological invasions | environmental weed | invasive species | sustainable intensification

Livestock production is already the largest land use on earth, accounting for 30% of global land area (1). Nevertheless, growing demand means that production must rise more than 50% by 2050 (2) as global population size and per capita consumption increase (2–5). Responding to this demand, agribusiness* is developing and marketing new taxa† of forage plants designed to increase pasture productivity. Through artificial selection and hybridization, public and private organizations are developing plant taxa that are more productive and more tolerant of disease and environmental extremes. At the same time, there is a strong campaign for sustainable intensification (SI) of agriculture. One approach to SI is to increase production on some lands while sparing others for conservation (5, 6). Agricultural intensification using new pasture taxa may thus be an efficient way to help meet rising demand and reduce some of the social and environmental costs of traditional agriculture (5). However, perversely, it may drive another environmental problem because pasture plants can invade the native ecosystems that “land sparing” is designed to protect (7).

Environmental weeds are invasive alien plants that establish in natural areas (e.g., remnant native vegetation and conservation reserves), usually to the detriment of native species (8). Environmental weeds threaten biodiversity, compromise ecosystem function, and cost billions of dollars to manage each year (9–15). Many have been introduced as pasture forages (7). For example, in Australia, the introduced pasture species *Andropogon gayanus* (gamba grass) increases wildfire intensity fivefold, reducing carbon stores and transforming species-rich native savannah to exotic-dominated grassland. Predicted to invade up to 380,000 km² of northern Australia (16), gamba grass invasion has increased the cost of fire management by an order of magnitude, from less than AUD\$2000 for each fire to as much as AUD\$43,000 per fire (16). The possibility that SI may worsen problems like these warrants serious consideration, yet the topic remains controversial and the risks are not fully acknowledged (Fig. 1) (5, 17).

Significance

Governments spend billions of dollars each year managing invasive plant species. Many invasive plants have escaped from pastures and now degrade natural areas and transform ecosystems. New pasture taxa are promoted to help achieve sustainable intensification of agriculture by increasing production without using more land. However, plant characteristics that increase production also increase invasion risk. Combined with inadequate regulation and management to establish large feed-plant populations, new taxa will likely exacerbate problems with invasive species. Livestock production accounts for 30% of the world's land area. Risks associated with invasive feed-plants have been largely overlooked, even by studies explicitly critiquing the environmental risks of sustainable intensification. We suggest a suite of protocols to reduce these risks in sustainable intensification of agriculture.

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*Any private or government organization that develops pasture taxa for eventual commercial deployment or that sells seeds of pasture taxa.

†Any taxon developed or marketed for pasture, including species, subspecies, varieties, cultivars, and plant-endophyte associations.



Fig. 1. The Undoolya Wattle *Acacia undoolyana*, nationally listed as vulnerable, standing dead in a sea of invasive pasture grasses (largely buffelgrass *Pennisetum ciliare*). This species occurs in several small populations in a 165-km² area of the East McDonnell Ranges in central Australia. Fires in 2013 killed many of the trees in the N'Dahla Gorge population (pictured). Although the wattle is threatened by hot fires, the dominant role that buffelgrass plays in altering the fire regime is not mentioned on the information board. Introduced pasture grasses are contentious in the Australian rangelands because they are used by the cattle industry, but also are highly invasive, fueling intense fires that kill woody plants and transform ecosystems. Photograph by D.A.D.

Here, we take a global perspective to consider whether new pasture taxa are likely to become environmental weeds (hereafter “environmental weed risk”) and whether there are mechanisms in place to limit potential risks. Although we focus specifically on the risk of new pasture taxa becoming environmental weeds, we acknowledge that very similar risks, and likely solutions, apply to other systems of production including bio-energy (18, 19), carbon sequestration (20), forestry (21), and horticulture (21, 22). We find that increased environmental weed risk from new pasture taxa presents a major challenge to increasing livestock production in a way that is consistent with SI (5). Nevertheless, there are practical solutions to reduce these risks that can be informed by new research and extend from government regulation to responsible product development and consumer choice (Fig. 2).

What Are the Risks?

A previous track record as an environmental weed is often used as a key indicator that an introduced taxon could become

a problem in a new area (23). Many pasture taxa currently on the market have a track record as environmental weeds. From our survey of plants developed or promoted by 17 organizations in eight countries on six continents (Tables S1–S3), the majority of taxa assessed were known to be environmental weeds somewhere in the world. On average, 91% (SD, 10%) of taxa developed by agribusinesses were listed as weeds, with 141 weed taxa of 178 taxa in total (excluding repeats; Tables S1 and S3). Further, many taxa were recognized as environmental weeds in the country where they were being actively developed and marketed, including in Australia, Canada, Chile, India, New Zealand, and the United States (13/35 taxa; Table S2).

The risk that pasture plants will invade natural areas can be further elevated through pasture management. Taxa that are a good match to local environments are deliberately selected, and pastures are managed to ensure large populations become established. Large, vigorous populations facilitate invasion because stochastic extinctions are avoided (12) and masses of seeds can flow into surrounding environments, increasing propagule pressure (24–26). Although pasture management sometimes aims to minimize seed production, this aim may not always be achieved. Further, self-seeding may be a key to longer-term pasture persistence, particularly for annual species (27). Pastures are often managed to achieve high densities of seeding plants over large land areas, which means that high propagule pressure is likely to increase the risk of pasture taxa becoming environmental weeds (28).

Although predicting which plants may be invasive and become environmental weeds is difficult (12, 23), it is well established that particular plant characteristics are associated with invasion and environmental impacts (29–32). Pasture breeding organizations actively select for characteristics that might inadvertently lead to environmental impacts outside of pastures, including higher growth rates and tolerance to environmental stress (Table S2) (29). Using polyploidy or endophytes (symbiotic fungi and bacteria; Tables S1 and S2), plant breeders alter features such as growth, reproduction, disease resistance, and risk of seed predation (33–35). Altering these characteristics has the potential to create forage plants that are more environmentally damaging (35, 36).

Widespread establishment of enhanced pasture taxa is likely to exacerbate the current environmental weed problem (17, 34, 35, 37). New taxa may interbreed with existing weed populations, with potential to worsen environmental impacts (37–39). Increased genetic diversity in pasture plants and other weeds enhances their capacity to invade natural areas across a broad range of conditions (40–42). A diverse genetic base also facilitates adaptation and subsequent invasion. For example, in a CO₂ enrichment experiment, *Bromus madritensis* (introduced for pasture in parts of the United States) (43) rapidly adapted to drier conditions, increasing its potential to spread in arid ecosystems as CO₂ increases (44). Introducing new taxa of existing environmental weeds is therefore likely to increase impacts (35, 37) and facilitate spread into areas previously unsuitable due to environmental limitations such as those found in mountains (45) or regions with high salinity (46, 47), soil deficiencies (42), low rainfall (44), or low temperature (48).

We acknowledge that risks will vary among regions. For example, the two Czech companies that were sampled promoted 14 native and 7 alien taxa (Table S1), none of which are regarded as invasive in the Czech Republic. For some European countries, plant development for livestock industries may not pose a major environmental weed threat due to a reliance on native pasture species. Nevertheless, European countries should not be complacent. Increasing aridity in Europe motivates introduction of C4 grasses in pastures, and several C4 species from the New World (e.g., knotgrass *Paspalum paspaloides*) have become invasive in parts of the continent (49).

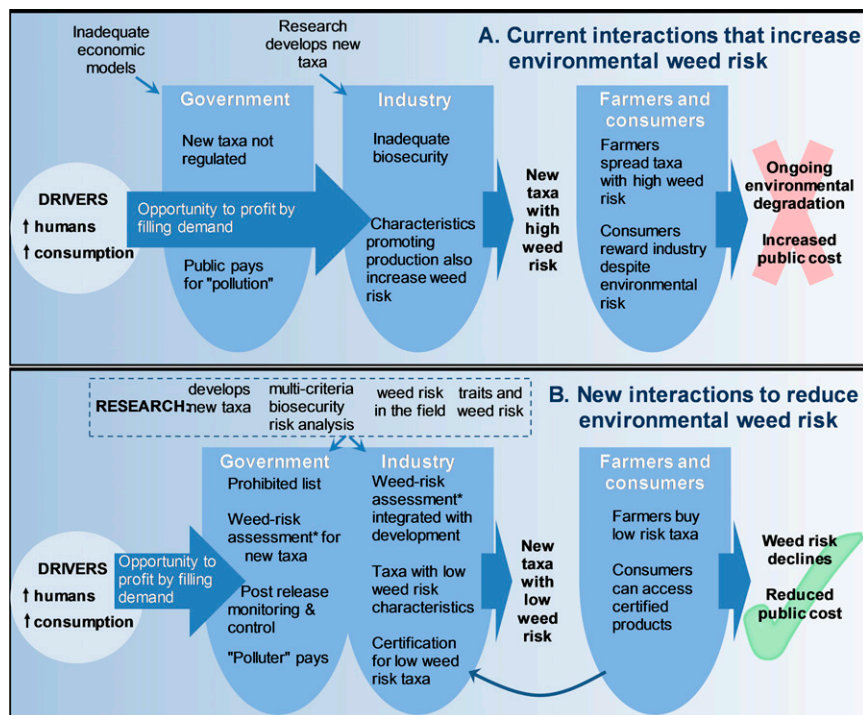


Fig. 2. Pathways influencing the risk that pasture taxa will invade natural areas and become environmental weeds. Currently, (A) economic models inadequately accommodate long-term social and environmental costs. Governments impose few or no regulations on new pasture taxa despite having to provide public funds to manage environmental weeds that were initially introduced as pasture. Most research into new taxa does not consider environmental weed risk. With little self-regulation, agribusiness may therefore inadvertently increase the environmental weed risk. Solutions to these problems (B) include closer interaction and feedback among researchers, government, and industry, government initiatives to promote low-risk pasture development, and industry-led certification enabling consumers to reward environmentally responsible pasture development. *See Fig. 3 regarding protocols for weed risk assessment.

Does Agribusiness Guard Against Environmental Weed Risk?

Despite the risks of new pasture taxa becoming environmental weeds, only 1 of the 17 organizations we reviewed undertook formal weed risk assessments of the taxa that it promoted [the Australian Future Farm Industries Cooperative Research Centre (FFICRC); Table S1]. Under FFICRC policy, if the weed risk was rated very high, promotion ceased. This policy was a world-leading advance, illustrating how agribusiness could take responsibility for the products that it develops, using policy that links environmental risk to development and management choices. Although this system may not always have prevented weeds from escaping into natural areas (*SI Text*), it demonstrated an important step forward and laudable industry precedence. The only other evidence that agribusiness considers the environmental weed risk of their products are weed risk assessments of *Kochia* spp. in the United States (Table S1) and weed risk research in an Australian organization that is conducted separately from pasture development research (Table S1). Unfortunately, the innovative approach pioneered by the FFICRC has not received continued funding, and thus its long-term legacy in screening potential weed risks is unknown.

The vast majority of agribusinesses, including government agencies and private companies, do not manage the environmental weed risk of taxa they promote (Table S1). Why is this the case? The answer probably lies in the way costs are allocated and assessed. Agribusiness is not accountable for environmental costs: it is not financially liable for environmental impacts or control of pasture taxa that invade natural areas (50). Instead, the public pays to manage environmental weeds that have escaped from pastures (7, 51). The risks for agribusiness are minimal, and therefore there is little incentive to address potential environmental impacts of new pasture taxa.

Although the public purse bears the cost of weed management, government-based or funded agribusinesses rarely consider the environmental weed risk of their products. The capacity for cost-effective decision-making at a whole-of-government level is undermined by limited environmental policy integration (52). There is often inadequate communication among different parts of government, and different sections have vastly different cultures, funding sources, and motivations (53, 54). The agribusiness section of government is often entirely separate from the section addressing environmental weed risk. Government agribusiness is protected from any environmental costs and therefore has the same lack of incentive to consider environmental weed risk as private agribusiness. The lack of motivation for agribusiness to consider environmental weed risk stems from the regulatory frameworks set by governments.

Does Government Guard Against Environmental Weed Risk?

All of the countries we examined regulate entry of at least some plant species (*SI Text*). Weed risk assessment is a cost-effective biosecurity measure (55, 56) and is a component of plant regulation in Australia, Canada, New Zealand, South Africa, and the United States. These countries also maintain lists of prohibited species that cannot be imported. A key feature of these lists is that environmental issues are considered when evaluating prohibited species. Chile also has a risk assessment and a list of prohibited species, although the assessments are biased toward maintaining agricultural productivity rather than addressing environmental concerns. Although a large number of pasture species could become environmental weeds (Table S1), the number prohibited from countries we surveyed ranged from 0 (Czech Republic) to 22 (South Africa) (*SI Text*). Consequently, many environmental weeds are not prohibited from most

countries that we surveyed, although most countries assess the weed risk of new species proposed for import. At a subspecies level, there are few barriers to importing new taxa of permitted pasture species (SI Text and Table S2).

With the exception of a voluntary system in Canada, new taxa resulting from the development of species already present in a country are not subject to risk assessment (SI Text). Plant developers in Canada may seek risk assessments for subspecific taxa with novel traits, including traits arising through conventional breeding. However, relying on proponents to self-nominate likely reduces the effectiveness of this legislation. To date, no conventionally bred taxa have been nominated. Notwithstanding Canada's progressive approach, the paucity of regulation surrounding new plant taxa poses serious biosecurity risks (17, 34, 35, 40).

Governments might be justified in not regulating most pasture taxa if the benefits substantially outweigh the costs (57), but current methods of cost-benefit analysis face major challenges. Economic assessments have had limited value for developing national strategies for invasive species because the assessments tend to be poorly implemented, focus on postinvasion effects, and do not address prevention or uncertainty (58). Economic assessments are also challenged because nonmarket goods like habitat loss and ecosystem transformation can be hard to value in monetary terms (59). In addition, it is unclear what discount rate (used to transform future costs or benefits into present value) should be applied to environmental values (55, 59). However, combined with the lag time in environmental impacts (60), the values set for the discount rate can determine the outcome of economic assessments (51). Resolving these uncertainties is critical before cost-benefit approaches can effectively support decisions about planned introductions. New approaches to decision-making that can equitably accommodate environmental, social, and economic values are needed. In this respect, multicriteria decision analyses have the potential to be important tools in the future (61-63).

What Needs to Be Done?

Opportunities for Researchers. We identify three research needs that are a priority for helping to prevent future weed problems. First, further development of methods for biosecurity risk analysis is a priority because these can help guide better policy decisions immediately. Approaches such as multicriteria methods can accommodate long-term, indirect, and off-site environmental and social costs, enabling new plant taxa to be fairly and accurately assessed (Fig. 2) (51, 64). Accurate assessment also depends on accurate information. Therefore, a second priority is to develop and routinely apply improved methods for assessing environmental weed risks, such as tiered approaches that use field and glasshouse trials, species distribution modeling, and weed risk assessment questionnaires (37, 65).

A third research priority is to identify plant characteristics that distinguish between the naturalization and spread impact stages of invasion (23, 36). This distinction is crucial because pastoralists desire feed-plants that form self-sustaining populations (i.e., naturalization), whereas limiting the spread and impact of taxa will reduce environmental costs. Improved understanding is therefore needed of how traits associated with increased survival, growth and dispersal influence naturalization, spread, and impact (23, 36). Learning how those traits interact with ecosystem characteristics such as soil nutrients, disturbance, or herbivory is also important (66-68). These areas of research will have the most impact if undertaken in conjunction with pasture developers (Fig. 2).

Opportunities for Governments. Besides addressing the fundamental drivers of the problem (Fig. 2), governments could build on examples from around the world to regulate and discourage

environmental weed risks. There are four components to a comprehensive regulatory framework that might be considered (Fig. 3) (18, 19): (i) a prohibited list of taxa that considers impacts on the environment and society; (ii) weed risk assessment for new taxa, considering evidence of past impacts in

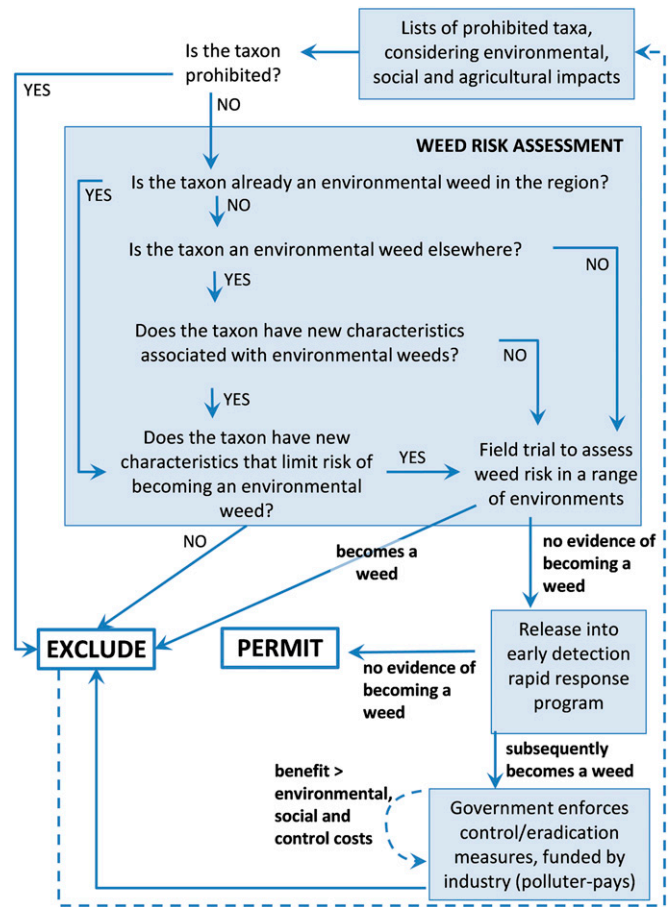


Fig. 3. Proposed regulatory framework to reduce the risk that pasture taxa will invade natural areas (including new species, subspecies, varieties, cultivars, and plant-endophyte combinations). The framework includes four key components (shaded boxes): (i) a list of prohibited taxa; (ii) a weed risk assessment; (iii) postrelease early detection monitoring with the capacity for rapid control if the taxon becomes a weed; and (iv) a polluter-pays system to pay for control or eradication of taxa that become environmental weeds. The protocol illustrates how weed history and characteristics related to weed risk can be used to inform decisions to exclude taxa. There are well-established and tested criteria for undertaking weed risk assessments (70, 74, 78). Weed risk assessment provides a basis for determining which taxa are accepted for field trials. In our simplified example of the weed risk assessment stage, taxa that have no record of invading natural areas, have no new characteristics that are associated with environmental weeds, or have characteristics that would limit the risk of becoming an environmental weed can proceed to field trials. If field trials reveal no evidence that natural areas adjacent to experimental fields are invaded, taxa proceed to the release stage. However, continued monitoring is essential because field trials do not always identify the invasive capacity of a taxon (23). If economic assessments fully account for long-term environmental, social, and other costs, agribusiness has the option to pay those costs so that they can continue using commercially valuable but environmentally damaging pasture plants (curved dashed line). Assessments to exclude a taxon may lead to revision of the list of prohibited taxa (straight dashed line). New research continually informs the weed risk assessment, including improved assessments of the characteristics linked to weed risk. Where benefits are smaller than the cost of field trials or the cost of an early detection and control program, development of that taxon would cease.

natural areas, risks associated with particular plant characteristics (updated regularly as new research is completed), and evidence from experimental trials (37, 69, 70); (iii) a strong postrelease monitoring program for early detection and rapid control (necessary because it remains difficult to accurately predict which species will become environmental weeds despite research gains in this area; 23, 71, 72); and (iv) if a taxon becomes an environmental weed, industry pays for its management, with costs allocated to industry organizations, government and private plant breeders, seed companies, and farmers relative to their culpability and ability to pay (Fig. 3). Insurance or environmental bonds may be practical mechanisms for linking the risk of environmental impacts with commercial responsibility (50, 51), following the well-established polluter-pays principle (64, 73). This fourth component will likely motivate agribusiness to pursue strategies that reduce environmental risk.

Almost all government regulation currently occurs at the species level and is applied at national borders (*SI Text*). A key regulatory challenge is to develop policy mechanisms to also regulate taxa below the species level (subspecies, varieties, cultivars, plant–endophyte combinations) and to develop postborder regulation. The Canadian approach to regulating novel taxa serves as a useful starting point to build effective pre- and postborder regulation of pasture taxa below the species level of classification.

Another role for government is to determine the spatial scale over which weed risk assessments should be made and to which the outcomes apply. Methods for weed risk assessment can be adjusted to suit local flora and climates (74). Such adjustments provide the scope for new taxa to be permitted in regions with low environmental weed risk but excluded from other regions within the same country where the risk is high. However, local release of plants with the potential to become weeds in other places faces major challenges (*SI Text*). First, changing climates may alter the geographic location of high-risk areas (75). Second, increases in extreme weather (76), trade, and human movement (77) mean that the chances of transportation outside of the target production region is likely to grow. It will be very difficult to contain taxa within specific regions within a country or continent in the absence of major biogeographic barriers to prevent natural spread and strict quarantine enforcement to prevent human-assisted spread. One implication is that all governments, at all levels, will need to cooperate to ensure that taxa permitted in one jurisdiction do not spread to other jurisdictions where they are prohibited.

Opportunities for Agribusiness. Agribusiness could make their products safer by integrating weed risk assessment with development of new taxa and by only releasing taxa where the risk of invading natural areas is low. Low invasion risk could be achieved by developing species with a track record of naturalization but not spread or impact, by using taxa native to the area, and by breeding for characteristics that will limit environmental weed risk (18). Identifying characteristics that limit weed risk requires research investment. Industry organizations (e.g., International Seed Federation) could develop a certification scheme for plant taxa with low environmental weed risk. Companies that achieve industry certification could be rewarded with a market advantage via product eco-labeling.

Opportunities for Farmers and Consumers. Farmers could champion plants that are not environmental weeds by raising awareness and through their purchasing choices, such as buying seeds of taxa with low risk of becoming environmental weeds. Farmers and other land managers may contribute to early detection and rapid response programs through industry-funded and government-regulated land management agreements. Consumers could also contribute to supporting sustainable intensification of agriculture if eco-labeling extended to animal products from farms that use pastures with low environmental weed risk.

Effective communication among these stakeholders will be essential for addressing the feed-or-weed challenge; there are opportunities to build on existing protocols for achieving this (17). Reducing the risk of further invasions of natural areas by pasture taxa is important to avoid escalating costs of weed control and minimize future environmental impacts. To claim sustainability, the scope of sustainable intensification must expand to include potential environmental weed risk.

Methods

In eight countries located across six continents (Australia, Canada, Chile, Czech Republic, India, New Zealand, South Africa, and the United States), we assessed biosecurity measures and pasture plant development and sales. Countries were selected to represent each continent and where (i) the pasture industry was well organized; (ii) biosecurity was a serious consideration of government; and (iii) the environmental weed flora was well assessed (*SI Text*). Our selected countries include temperate and tropical climates. Compared with nonsurveyed countries, our sample spans a wide range of meat production rates and proportion of land area under grazing (Fig. S1). In each country, two of the largest private or public organizations involved in pasture development or sales were identified. Three companies were used in Chile because one company specializes in a single species. More than two thirds of these organizations have international sales and purchasing links, emphasizing that our results have implications beyond the eight countries that we surveyed (Table S1). Of the taxa developed or sold for pasture by each organization, three were randomly selected using a random number generator. If available, information about the characteristics of each taxon and biosecurity measures was gathered from the organization's website (accessed November 2013), the most recent annual report, publications, and discussion with senior members of each organization. Publications were searched for using Google Scholar with the search terms: organization name ("invasive" OR "biosecurity" OR "weed") and the plant name. We gathered details about government biosecurity measures, with a focus on the extent to which new taxa are regulated, from government websites and by discussion with staff in agencies that manage national biosecurity in each country.

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