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Predicting Biofuel Invasiveness: A Relative Comparison to Crops and Weeds

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Concern raised against using highly competitive, exotic, large-statured, perennial grasses with fast growth rates as bioenergy crops has led to calls for risk assessment before widespread cultivation. Weed risk assessments (WRAs) are decision support tools commonly used throughout the world to determine the invasion risk of new plant taxa—primarily used as a pre-entry screen. Here, we compare the common Australian (A-WRA) and newer U.S. (US-WRA) models to evaluate the invasion risk of 16 candidate bioenergy crops and to compare their WRA scores to 14 important agronomic crops and 10 invasive species with an agronomic origin. Of the 40 species assessed, the A-WRA and US-WRA ranked 34 and 28 species, respectively, as high risk, including the major crops alfalfa, rice, canola, and barley. Surprisingly, in several cases, both models failed to effectively parse weeds from crops. For example, cereal rye received scores above (US-WRA) or comparable to (A-WRA) kudzu, a widespread damaging invader of the Southeastern United States introduced as forage. Our results indicate that these models are unable to accurately address broad, intraspecific variation and that species introduced for agronomic purposes pose special limitations to WRAs. This further supports other calls for postborder evaluation (e.g., field testing) following WRA screening. We should be cautious of the role of WRAs in setting policy, as illustrated by this relative evaluation of novel crops.

Nomenclature: Kudzu, *Pueraria montana* var. *lobata* (Willd.) Maesen & S.M. Almeida; cereal rye (*Secale cereale* L.); alfalfa, *Medicago sativa* L.; barley, *Hordeum vulgare* L.; canola, *Brassica napus* L.; rice, *Oryza sativa* L.

Key words: Bioenergy, invasive species, weed risk assessment.

Invasive species are found on every continent and affect nearly every landscape globally (Molina-Montenegro et al. 2012). Most of our worst invasive plants were intentionally introduced, cultivated, and dispersed (Simberloff 2008) and cause widespread, and sometimes irreversible, ecosystem change (Pimentel et al. 2000; Vilà et al. 2011). When driving down many roads in the southeastern United States, the catastrophic intentional introductions of species, such as kudzu [*Pueraria montana* var. *lobata* (Willd.) Maesen & S.M. Almeida] and johnsongrass [*Sorghum halepense* (L.) Pers.], serve as reminders of our historic cavalier approach to species introduction. Once invasive plants become established and widespread, eradication is generally not practical or successful (McNeely et al. 2003; Panetta 2009), necessitating screening procedures to assess invasion risk before new species are widely introduced. Preborder decision-support tools have been adopted in many parts of the world (Cousens 2008; Hulme 2012).

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Unlike traditional, domesticated crops, bioenergy crops are selected for their rapid aboveground biomass production, low input requirements, broad climatic suitability, and performance on marginal land (Lewandowski et al. 2003); traits shared by many of our worst invasive plants (Raghu et al. 2006). For example, giant reed (*Arundo donax* L.), a noxious weed in four U.S. states (Quinn et al. 2013), lines the banks of the Rio Grande River in Texas, where it is the focus of an active biocontrol program (Seawright et al. 2009), yet some propose plantations in the southeastern United States (http://www.biofuelscenter.org/feedstocks/energy-grasses?showall=1&limitstart=). Giant Miscanthus [*Miscanthus* × *giganteus* J.M. Greef & Deuter ex Hodkinson & Renvoize], formerly known only as a sterile (triploid) hybrid of the invaders eulaliagrass (*Miscanthus sinensis* Anderss.) and Amur silvergrass [*Miscanthus sacchariflorus* (Maxim.) Franch.] (Dougherty et al. 2014), now includes a fertile (tetraploid) line that can produce an estimated 1.3 billion spikelets ha^{-1} yr^{-1} (3.21 billion spikelets ac^{-1} yr^{-1}) (Smith et al. 2015)—a clear enhancement of its escape potential. The U.S. Department of Agriculture (USDA) Biomass Crop Assistance Program has already subsidized the establishment of > 42,000 ha of biomass feedstocks, 22% of which are exotics. Future projections of a cultivated area 1.4 times the size of California (Robertson et al. 2008)

Management Implications

The U.S. bioenergy industry seeks to cultivate dedicated energy crops to meet increasing demands for bio-based energy sources. Many of these potential crops are not native to the United States and are large-statured, perennial species with fast growth rates that effectively compete with resident vegetation—all traits shared by many invasive plants. Therefore, there have been repeated calls to prevent the introduction and wide cultivation of invasive species for bioenergy. One method widely used to identify the invasion risk of new species are weed risk assessments, with the Australian (A-WRA) and United States (US-WRA) versions being the most widely used. To identify the invasion risk of bioenergy crops, we compared their A-WRA and US-WRA scores to those of the 14 of the most-common agronomic crops and 10 invasive species originally introduced for agriculture. This allowed us to compare the biofuels to crops, which we expected to have low WRA scores and to known invaders, which we expected to have high WRA scores. Both WRAs found most species to be high risk, including many crops. The WRAs suffer from many limitations, including being unable to deal with species that include high intraspecific variation, like *Sorghum bicolor*, which is both a crop and weed. Therefore, WRAs should be used cautiously in setting policy, even when only serving as the first tier of a multistep, risk-assessment process.

presents opportunity for widespread invasion without careful risk assessment and mitigation.

In the case of economically important new crops, such as bioenergy feedstocks, the ability to distinguish invaders from noninvaders is imperative and has broad social, economic, environmental, and biosecurity implications (Cousens 2008). Much like the forage improvement programs in Australia and elsewhere, the bioenergy industry could provide substantial economic gain and enhance national security (Robertson et al. 2008). However, lacking precautionary forethought, the introduction of forages has resulted in numerous weedy escapes, 23% of which have become serious environmental weeds (Virtue et al. 2004), and may continue to get worse (Driscoll et al. 2014). Humans have been introducing exotic species since the invention of agriculture, but the land area proposed for novel bioenergy crop cultivation reaches a scale that concerns many (Barney and DiTomaso 2008; Raghu et al. 2006). Thus, the adoption of biosecurity tools is necessary to limit entry and widespread planting of damaging plants (e.g., Pheloung et al. 1999; Stone et al. 2008).

Historically, the U.S. policy regarding species introductions has largely been seen as arbitrary and subjective (Simberloff 2005), which is reflected in weak noxious weed policies (Eiswerth and Van Kooten 2000; Quinn et al. 2013). In contrast, Australia uses stringent preintroduction and quarantine procedures (Pheloung et al. 1999; Stone et al. 2008). In an effort to reduce the spread and environmental impact of exotic introductions, Australia has been a leader in the development of weed risk assessment (WRA) tools, which are used to determine whether or not to allow importation of an exotic species (Stone et al. 2008). The Australian WRA (A-WRA) has become the global standard (Pheloung et al. 1999). The recent USDA Plant Protection and Quarantine WRA (US-WRA) is the new regulatory benchmark in the United States, which is based on the A-WRA (Koop et al. 2012). The ability to parse the weeds from benign species seems a foreboding task, yet these tools boast $> 90\%$ accuracy in predicting which species have high invasive potential (Gordon et al. 2008). The broad adoption of scientifically backed assessments rooted in ecological principles could add consistency across federal and state regulatory agencies, while preventing environmental degradation, alleviating economic losses, and helping to target critical management practices (Quinn et al. 2013). However, these widely used tools are not without criticism (Hulme 2012; Lonsdale 2011).

WRA models have been criticized for their subjective nature, coupled with their disregard for low base rates ($< 0.1\%$ of introductions become invasive (Williamson and Fitter 1996)). Hulme (2012) argues that "[t]he accuracy of weed risk assessment protocols is usually insufficient, given inherent low base-rates even when the costs and benefits of decisions are taken into account, and implies that the predictive value of weed risk assessment is questionable." Some of the Hulme (2012) criticisms have been addressed in the newer US-WRA, including uncertainty and acknowledgement of base rates (Koop et al. 2012). Despite known limitations, WRAs are commonly used decision support tools (Cousens 2008; Davis et al. 2010; Koop et al. 2012; Quinn et al. 2013), making evaluation of their principles, implementation, and limitations vital.

Invasiveness is not universal for all populations of a species in all geographic locations, and all taxa have some nonzero probability of becoming invasive under the "right plant, right place, right time" axiom (Barney and Whitlow 2008). Therefore, all species exist along a spectrum of invasiveness, which varies based on the receiving environment (Smith and Barney 2014). In general, many exotic agronomic crops, such as corn (*Zea mays* L.) and soybeans [*Glycine max* (L.) Merr.], are thought of as having a low invasiveness probability (Martin et al. 2006). Conversely, previous agricultural introductions, such as johnsongrass and kudzu, are highly competitive species with invasive populations across the southeastern United States (Holm et al. 1977; Warwick and Black 1983). Thus, relative comparisons of taxa within an introduction pathway (e.g., agriculture) would aid interpretation and best identify strengths and weaknesses of WRAs by identifying clear, testable predictions (e.g., corn should have a low WRA score).

WRAs can be useful tools for evaluating invasion risk under many scenarios. With numerous U.S. states contemplating adoption of the US-WRA methodology for screening plants and updating noxious weed lists (Barney 2014), and the recent suggestion to use WRAs in the creation of "white lists" (Quinn et al. 2015), further evaluation of WRA use for agricultural crops is prudent. Others have commented on the role of WRAs for bioenergy (Barney 2014; Cousens 2008; Davis et al. 2010), but none have examined the potential limitations of the WRAs when applied to crops. Therefore, here, we evaluate leading candidate bioenergy crops for their potential to be invasive in the United States, using the A-WRA and US-WRA, and compare with well-established crops and species introduced for agriculture that have become invasive species. We hypothesized that agronomically introduced invasives would be rejected (have high risk), whereas crops undergoing centuries of domestication would be low risk, with bioenergy crops falling in between.

Materials and Methods

We compared the invasive potential, as determined by A-WRA and the US-WRA, of candidate bioenergy crops to well-established agronomic crops and invasive plants of agronomic origin (Table 1). We selected 16 leading bioenergy crops, which included large-statured perennial and annual grasses, short-rotation trees, and oil-crop species—all profiled as the taxa most likely to be used for bioenergy in the United States (Glaser and Glick 2012; Perlack et al. 2005). We performed two separate WRAs for *Miscanthus* × *giganteus*, sterile and fertile, because both are possible, unique bioenergy crops, yielding 17 bioenergy assessments. Recent studies have shown the importance of comparing species that vary in their known invasiveness (Buddenhagen et al. 2009; Smith and Barney 2014; Smith et al. 2015). We chose 14 of the most-common agronomic crops [e.g., corn, wheat (*Triticum aestivum* L.), and tobacco (*Nicotiana tabacum* L.)]—all of which have a long and well-documented cropping history in the United States (Martin et al. 2006)—to serve as so-called negative controls because we hypothesized they would have low WRA scores. We also identified 10 invasive species of agronomic origin, such as cogongrass [*Imperata cylindrica* (L.) Beauv], *S. halepense*, and *P. montana*), to serve as positive controls because we hypothesized they would have high WRA scores since they are all well-known invasive plants. In this framework we are comparing a variety of taxa, all of which were (or will be) introduced and cultivated for agricultural purposes.

Scoring and methodology for both the A-WRA, which has been widely and successfully tested on five continents and numerous geographic regions (Daehler et al. 2004; Gordon et al. 2008, 2010; Nishida et al. 2009; Pheloung et al. 1999), and the relatively new US-WRA have been thoroughly described in the literature (Koop et al. 2012). Therefore, we only provide a brief description of both models and their scoring. For the A-WRA, we followed the detailed outline in Gordon et al. (2010). For the US-WRA, we followed Koop et al. (2012) as well as an intensive weeklong training program at the Plant Epidemiology and Risk Analysis Laboratory in Raleigh, NC, attended by L.L.S. and J.N.B. The A-WRA uses an additive design, comprising 49 yes/no questions on the topics of biogeographical and historical accounts (i.e., current geographic and habitat distribution, history of domestication, and status as a weed elsewhere in the world) and biology and ecology (i.e., species traits, reproduction, dispersal mechanisms, and persistence attributes) (Gordon et al. 2008; Pheloung et al. 1999). The US-WRA was created using the A-WRA as a template and incorporates a new set of questions, designed to assess regional impacts in three types of biological systems: natural environments, anthropogenic systems, and production systems (Koop et al. 2012). The US-WRA generates Establishment/Spread and Impact scores, which yield an integrated outcome score (Koop et al. 2012). Each response receives an uncertainty rating, based on the availability and quality of supporting information specified by the analyst. Monte Carlo simulations use these uncertainty ratings to generate confidence intervals around each score. The model also incorporates an automatic secondary-screening process, when further evaluation is needed (Koop et al. 2012).

We conducted an extensive literature survey for each species over the course of 2 yr. We evaluated each taxon at the species level, meaning any information for that species, including cultivars or feral populations, was included (see Barney et al. [2015] for the effect of modifying domestication and sterility on WRA scores). All available data were documented and incorporated into each model and used to generate scores with both the A-WRA and the US-WRA. When clear answers to each question were not available, we answered "?" with maximum uncertainty for the US-WRA, or left the question blank for the A-WRA, as a nonanswer does not influence the additive-based scoring of the A-WRA. Our evaluation was conducted for the continental United States. Both models require some level of geographic climate matching. Therefore, we used three variables to determine regions of the United States that would be suitable for establishment of each taxon. Data from the USDA Plant Hardiness Zones (NAPPFAST, ZedX Inc.), Köppen-Geiger climate classes (Peel et al. 2007), and annual precipitation data (NAPPFAST) were matched with coordinates of species occurrence records in both the native and introduced range. Current distribution maps for each species were accessed using the Global Biodiversity Information Facility (http://www.gbif.org).

We did not assess expert opinion nor analyst variability on WRA scores as some have done (e.g., Cousens 2008; Pheloung et al. 1999) because of the inherent large

Table 1. Species with their details, including CO_2 fixation pathway, taxonomic family, life form, native range, and approximate time of introduction to North America, selected for evaluation using the Australian and U.S. weed risk assessment models.

Designation	Species	Common name	CO_2 fixation	Life Form/ Family	Native range	Approximate introduction
Bioenergy crops	*Arundo donax* L.	Giant reed	C_3	Grass/Poaceae	East Asia, Mediterranean	early 1800s[a]
	Camelina sativa (L.) Crantz	Largeseed falseflax	C_3	Forb/Brassicaceae	Europe	1863[b]
	Miscanthus sacchariflorus (Maxim.) Ranch.	Amur silvergrass	C_4	Grass/Poaceae	East Asia, Pacific Islands	after 1935[c]
	Miscanthus sinensis Anderss.	Eulaliagrass	C_4	Grass/Poaceae	East Asia, Pacific Islands	1893[d] 1960
	Miscanthus × *giganteus* J.M. Greef & Deuter ex Hodkinson & Renvoize 'Illinois'	Giant Miscanthus	C_4	Grass/Poaceae	East Asia, Pacific Islands	1960[e]
	Panicum virgatum L.	Switchgrass	C_4	Grass/Poaceae	North America	native[f]
	Pennisetum purpureum Schumach.	Napiergrass	C_4	Grass/Poaceae	Africa	1913[g]
	Phalaris arundinacea L.	Reed canarygrass	C_3	Grass/Poaceae	Asia, Europe, North America	native[f]/1885[h]
	Saccharum spontaneum L.	Wild sugarcane	C_4	Grass/Poaceae	South Asia	Unknown
	Sorghum bicolor (L.) Moench ssp. *arundinaceum* (Desv.) de Wet & Harlan	Shattercane				
	Sorghum bicolor (L.) Moench ssp. *bicolor*	Sorghum	C_4	Grass/Poaceae	Northern Africa	after 1850[h]
	Thlaspi arvense L.	Field pennycress	C_3	Forb/Brassicaceae	Eurasia	1700[i]
	Eucalyptus globulus Labill.	Tasmanian blue gum	C_3	Tree/Mertaceae	Australia, Tasmania	1856[a]
	Jatropha curcas L.	Barbados nut	C_3	Tree, shrub/ Euphorbiaceae	Central America, Caribbean	Unknown
	Paulownia tomentosa (Thunb.) Sieb. & Zucc. ex Steud.	Royal paulownia	C_3	Tree/Scrophulariaceae	China	1844[j]
	Robinia pseudoacacia L.	Black locust	C_3	Tree/Fabaceae	Eastern United States	native[f]
	Triadica sebifera (L.) Small	Chinese tallowtree	C_3	Tree/Euphorbiaceae	China	1772[k]
Agronomic invasives	*Cannabis sativa* L.	Hemp	C_3	Forb/Cannabaceae	Central Asia	16-1700[h]
	Cynodon dactylon (L.) Pers.	Bermudagrass	C_4	Grass/Poaceae	Asia	16-1700[j]
	Dactylis glomerata L.	Orchardgrass	C_3	Grass/Poaceae	Western, central Europe	1750[l]
	Elymus repens (L.) Gould	Quackgrass	C_3	Grass/Poaceae	Europe	1600[k]
	Imperata cylindrica (L.) Beauv.	Cogongrass	C_4	Grass/Poaceae	East Africa	1912[k]
	Pennisetum clandestinum ex Chiov.	Kikuyugrass	C_4	Grass/Poaceae	East Africa	1918[l]
	Phalaris aquatica L.	Harding grass	C_3	Grass/Poaceae	Europe, Mediterranean	1914[m]
	Pueraria montana var. *lobata* (Willd.) Maesen & S.M. Almeida	Kudzu	C_3	Vine/Fabaceae	China, Japan	1876[h]
	Schedonorus phoenix (Scop.) Holub.	Tall fescue	C_3	Grass/Poaceae	Europe	early 1800s[n]
	Sorghum halepense (L.) Pers.	Johnsongrass	C_4	Grass/Poaceae	Mediterranean	1830[h]

Table 1. Continued

Designation	Species	Common name	CO_2 fixation	Life Form/ Family	Native range	Approximate introduction
Agronomic crops	*Avena sativa* L.	Oat	C_3	Grass/Poaceae	Europe	1602[o]
	Brassica napus L.	Canola	C_3	Forb/Brassicaceae	Mediterranean	1940[h]
	Glycine max (L.) Merr.	Soybean	C_3	Forb/Fabaceae	East Asia	1804[h]
	Gossypium hirsutum L.	Cotton	C_3	Forb/Malvaceae	Africa, China, central America	1607[h]
	Hordeum vulgare L.	Barley	C_3	Grass/Poaceae	Middle East	1602[h]
	Linum usitatissimum L.	Common flax	C_3	Forb/Linaceae	Asia, Mediterranean	1600–1700[h]
	Medicago sativa L.	Alfalfa	C_3	Forb/Fabaceae	Southwestern Asia	1736[h]
	Nicotiana tabacum L.	Tobacco	C_3	Forb/Solanaceae	Mexico, south/central America	1612[h]
	Oryza sativa L.	Rice	C_3	Grass/Poaceae	India, Southeast Asia	1685[h]
	Saccharum officinarum L.	Sugarcane	C_4	Grass/Poaceae	New Guinea	1751[h]
	Secale cereale L.	Cereal rye	C_3	Grass/Poaceae	Southwest Asia	Unknown
	Solanum tuberosum L.	Irish potato	C_3	Forb/Solanaceae	Andean highlands	1621[h]
	Triticum aestivum L.	Wheat	C_3	Grass/Poaceae	Middle East	1602[h]
	Zea mays L.	Corn	C_4	Grass/Poaceae	Central America	before 1492[h]

[a] USDA Forest Service: http://www.fs.fed.us/database/feis/plants/.

[b] Canadian Food Inspection Agency: http://www.inspection.gc.ca/plants/.

[c] Greef and Deuter 1993.

[d] Dougherty 2013.

[e] http://www.kurtbluemel.com/Miscanthus_giganteus.html.

[f] USDA PLANTS Database: http://plants.usda.gov/.

[g] University of Florida Extension: http://edis.ifas.ufl.edu/ag302.

[h] Martin et al 2006.

[i] University of Minnesota: http://www1.umn.edu/news/news-releases/2013/UR_CONTENT_452676.html.

[j] Invasive Plant Atlas of New England: http://www.eddmaps.org/ipane/ipanespecies/.

[k] USDA National Agricultural Library: http://www.invasivespeciesinfo.gov/.

[l] Oregon State University: http://forages.oregonstate.edu/fi/publications.

[m] Bureau of Land Management: http://www.blm.gov/ca/st/en/fo/hollister/noxious_weeds/nox_weeds_list/.

[n] Texas A&M Extension: http://aggie-horticulture.tamu.edu/archives/parsons/turf/publications/bermuda.html.

[o] Iowa State Department of Agronomy: http://agronwww.agron.iastate.edu/Courses/agron212/Readings/Oat_wheat_history.htm.

variability in expert opinions. For example, Cousens (2008) found that scores for canola ranged from 1 to 19, with none reaching an "accept" decision. Thus, as Cousens (2008) concludes, adding "expert" opinion only adds variation, but it does draw attention to the subjective interpretations of WRA questions. For this study, we made assessments independently and then collectively, while documenting justification for all answers (Koop et al. 2012).

Because ecological impact should be central to invasiveness evaluation and management prioritization (Barney et al. 2013; Lewis and Porter 2014), we hypothesized that taxa with long residence times would have greater effects than more recently introduced taxa (Dostál et al. 2013). To test this, we performed linear regression analyses between the US-WRA impact scores and time since introduction (Table 1). We also performed linear regression of the US-WRA impact score against the total number of data source references for each species in the Global Compendium of Weeds (GCW), which has been used as a proxy for global invasiveness (e.g., Dawson et al. 2013). We hypothesized that species with more references (i.e., more-common invasives) would have higher impact scores.

Results

It was our goal to compare the A-WRA and US-WRA scores of species in three groups within one introduction pathway—agriculture: candidate bioenergy crops; agronomically introduced invasives; and long-established and economically important agronomic crops. As predicted, all of the invasives received a "high risk" or "reject" from the US-WRA and A-WRA tools (Table 2). We found that 16 of the 17 bioenergy crop assessments resulted in a rejection from the A-WRA; only sterile *Miscanthus* × *giganteus* received an outcome of "evaluate further" (Table 3). However, the US-WRA predicted that 13 of the bioenergy crops were "high risk," 3 still required further evaluation after the secondary screening or may just have minor invasive potential, and sterile *Miscanthus* × *giganteus* was predicted to be a low risk (Table 3). Surprisingly, of the 14 crops evaluated, only corn, cotton, and soybean were identified as low risk/acceptable by both models (Table 2). The A-WRA rejected 9 of 14 crops, and the US-WRA found 4 of those crops "high risk" as well. All other crops were classified as needing further evaluation.

It is clear that the A-WRA is the more-conservative model (Tables 2 and 3), accepting only 3 of the 40 species.

Table 2. Weed risk assessment scores and results for intentionally introduced agronomic invasives and crops, using the U.S. (US-WRA) and the Australian (A-WRA) models.

			US-WRA		
Designation	Scientific name	Common name	Result	Secondary screening	A-WRA result
Agronomic invasives	*Cannabis sativa*	Hemp	Evaluate further	High risk	Reject
	Cynodon dactylon	Bermudagrass	High risk	—	Reject
	Dactylis glomerata	Orchardgrass	High risk	—	Reject
	Elymus repens	Quackgrass	High risk	—	Reject
	Imperata cylindrica	Cogongrass	High risk	—	Reject
	Pennisetum clandestinum	Kikuyugrass	High risk	—	Reject
	Phalaris aquatica	Harding grass	Evaluate further	High risk	Reject
	Pueraria montana	Kudzu	High risk	—	Reject
	Schedonorus arundinaceus	Tall fescue	High risk	—	Reject
	Sorghum halepense	Johnsongrass	High risk	—	Reject
Agronomic crops	*Avena sativa*	Oats	Evaluate further	Evaluate further	Reject
	Brassica napus	Canola	High risk	—	Reject
	Glycine max	Soybean	Low risk	—	Accept
	Gossypium hirsutum	Cotton	Low risk	—	Accept
	Hordeum vulgare	Barley	High risk	—	Reject
	Linum usitatissimum	Flax	Evaluate further	Evaluate further	Reject
	Medicago sativa	Alfalfa	High risk	—	Reject
	Nicotiana tabacum	Tobacco	Low risk	—	Evaluate further
	Oryza sativa	Rice	High risk	—	Reject
	Saccharum officinarum	Sugarcane	Evaluate further	Evaluate further	Evaluate further
	Secale cereale	Rye	High risk	—	Reject
	Solanum tuberosum	Potato	Evaluate further	Evaluate further	Reject
	Triticum aestivum	Wheat	Evaluate further	Evaluate further	Reject
	Zea mays	Maize	Low risk	—	Accept

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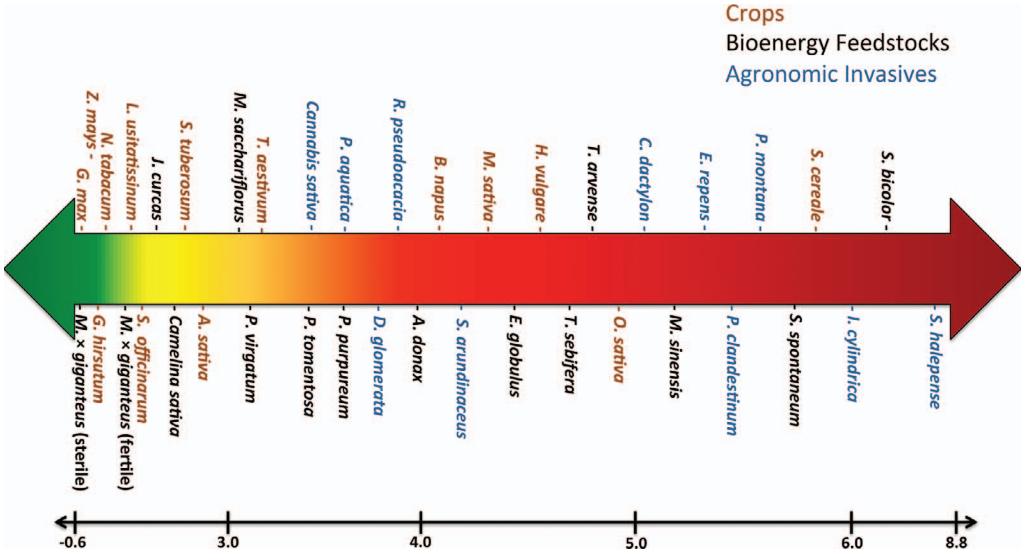

Figure 1. Distribution of U.S. weed risk assessment (US-WRA) scores. The spectrum of US-WRA scores for 40 species in three species designations: crops, bioenergy crops, or agronomic invasive. The scale indicating the range of composite risk scores from −0.6 to 8.8 is shown just below the spectrum. (Color for this figure is available in the online version of this paper.)

Contrary to our expectations, we observed a spectrum of scores with species from each of the three categories spanning all risk categories (Figure 1). We found no relationship between time since introduction or GCW references with US-WRA impact scores ($P > 0.05$). This is not entirely surprising because the GCW indicates introduction rather than establishment, and we did not account for distribution or abundance, as suggested by Dawson et al. (2013). Given the broad range of times since introduction, we hypothesized that the most recent introductions would be the least impactful, or conversely, our oldest agronomic crops would have undergone extensive breeding and selection, reducing their impact scores. Neither conclusion was validated. Our results agree that model outcomes are primarily driven by the establishment-spread portion of the model, with a history

Table 3. Weed risk assessment scores and results for candidate bioenergy crops, using the new U.S. (US-WRA) and Australian (A-WRA) models.

		US-WRA		
Scientific name	Common name	Result	Secondary screening	A-WRA result
Arundo donax	Giant reed	High risk	—	Reject
Camelina sativa	Largeseed falseflax	Evaluate further	Evaluate further	Reject
Miscanthus sacchariflorus	Amur silvergrass	Evaluate further	High risk	Reject
Miscanthus sinensis	Eulaliagrass	High risk	—	Reject
Miscanthus × *giganteus* (sterile)	Giant Miscanthus	Low risk	—	Evaluate further
Miscanthus × *giganteus* (fertile)	Powercane	Evaluate further	Evaluate further	Reject
Panicum virgatum	Switchgrass	Evaluate further	Evaluate further	Reject
Sorghum bicolor	Sorghum	High risk	—	Reject
Pennisetum purpureum	Napiergrass	Evaluate further	High risk	Reject
Phalaris arundinacea	Reed canarygrass	High risk	—	Reject
Saccharum spontaneum	Wild sugarcane	High risk	—	Reject
Thlaspi arvense	Field pennycress	High risk	—	Reject
Eucalyptus globulus	Tasmanian blue gum	High risk	—	Reject
Jatropha curcas	Barbados nut	Evaluate further	High risk	Reject
Paulownia tomentosa	Royal paulownia	Evaluate further	High risk	Reject
Robinia pseudoacacia	Black locust	High risk	—	Reject
Triadica sebifera	Chinese tallowtree	High risk	—	Reject

of invasion elsewhere being the most important driver (Koop et al. 2012).

Discussion

Our most important agricultural crops are exotic species introduced, domesticated, and widely cultivated to meet our food, feed, fiber, construction, and energy needs (Sax et al. 2005). Charges and fears of invasiveness should not be based on nativeness (Davis et al. 2011), rather the primary determinant should be the likelihood that a new introduction will cause more harm than benefit (e.g., Yokomizo et al. 2012). This potential ecological vs. economic antagonism makes predicting invasiveness and regulatory decisions inherently difficult (Cousens 2008).

Risky Guesses? Our results show that WRAs differ in their assessment and tolerance of risk, and do not pragmatically handle large, intraspecific variation. The high number of high risk/reject scores for both models was surprising, especially for the agronomic crops. Importantly, had we not assessed crops and invasives in conjunction with candidate bioenergy feedstocks, our conclusions may have been altogether different: do not cultivate the high-risk bioenergy crops. However, comparing species that vary in invasiveness, critical for the interpretation of relevant studies (e.g., Smith and Barney 2014), clearly indicates that both models failed to effectively parse the weeds from the crops (Figure 1). All species have some probability of becoming invasive (Smith and Barney 2014), yet a model that places cereal rye (*Secale cereale* L.) between the widespread and damaging invaders, kudzu and cogongrass, must be questioned for its ability to drive policy decisions, especially when potentially economically valuable, novel crops are concerned (Barney 2014).

It is surprising that some crops have a higher US-WRA impact score than several common invasive species (Table 2). We offer two explanations for why the crops have surprisingly high-risk outcomes. First, the WRAs are unable to account for high, intraspecific variation, including important functional trait differences within a species. Importantly, we conducted each WRA at the species level. For example, sorghum [*Sorghum bicolor* (L.) Moench ssp. *bicolor*] and shattercane [*Sorghum bicolor* (L.) Moench ssp. *arundinaceum* (Desv.) de Wet & Harlan] vary in seed shattering, seed dormancy, seed longevity, and plant height—differences which favor shattercane persistence (Fellows and Roeth 1992). In our analysis of *S. bicolor*, any information for shattercane was included in the analysis for grain sorghum since they are the same species. WRAs are traditionally conducted at the species level (Gordon et al. 2010), and crops appear to present a challenge to WRA analyses as the level of infraspecific variation can be quite high, especially given the development of diverse cultivars or hybrids (Martin et al. 2006).

However, it is not at all clear how WRAs could incorporate such variation reliably. For example, *Miscanthus sinensis* has been considered both as a bioenergy crop but more likely as potential germplasm for breeding programs. More than 100 named varieties of ornamental *Miscanthus* spp. have been introduced to the United States since the late 1800s and are widely available for purchase (Quinn et al. 2010). Yet, varieties of *M. sinensis* show remarkable differences in reproductive potential (Meyer and Tchida 1999; Smith et al. 2015); differences that are not evident by performing a single risk assessment at the species level. Considering the numerous varieties of many of our agricultural commodities, evaluation at the cultivar level would not only be impractical but subtle differences in traits may not be well studied or successfully conveyed by the WRA models. Functional traits have an important role in invasiveness (Cousens 2008; van Kleunen et al. 2010), but important subtleties belie our ability to use them predictively, except in rare circumstances (e.g., Rejmanek and Richardson 1996).

Second, strikingly little data exist on the ecological impacts of invasive plants (Barney et al. 2013), whereas crops tend to be well studied, especially their weedy escapes (e.g., Pekrun et al. 2005). We agree that impact should have a primary role in risk determination by the WRAs, serving as a risk axis in the US-WRA. However, given that the impact for most invasives remains unstudied (Hulme et al. 2013), let alone for new species or crops, does it make sense to use impact as a predictive variable? How should we treat noninvasives and invasives that have similar WRA impact scores but for different reasons: one causes no impact, and the other is just unmeasured? Current WRAs are unable to reckon such important challenges.

As discussed, these models were designed and calibrated (Hulme 2012) for taxa that are not regularly subject to intensive management (i.e., annual harvest). Grower decisions that could directly influence propagule pressure and establishment success are largely different for agricultural crops than they are for horticultural and landscape plantings. Altering models to incorporate management or a combination of management strategies (i.e., reduce propagule pressure, harvest timing) could lower the overall risk score suggested by our outcome of the risk of sterile *Miscanthus* × *giganteus* being lower than that of the fertile cultivars. However, management implementation is left to the trust and reliability of the industry, which may be insufficient or too inconsistent to overcome known risks.

WRAs result in categorical outcomes of invasiveness, typically applied across large, heterogeneous landscapes (Koop et al. 2012). However, in reality, invasiveness is a continuous property that can easily change based on a number of contingencies (Barney and Whitlow 2008). For example, *A. donax* was intentionally introduced into riparian areas for bank stabilization and erosion control in the southwestern United States (Bell 1997) and had a robust source of vegetative propagules easily transportable along waterways, which resulted in invasion (Quinn and Holt 2008). Proper field siting could greatly reduce escape risk in the southeast and elsewhere, that is, away from riparian areas, which appear to be the primary means of dispersal.

Some have applied WRAs at smaller, more climatically homogenous spatial scales (e.g., Buddenhagen et al. 2009; Gordon et al. 2011). However, WRA outcomes may be inappropriately applied even at this resolution, which includes heterogeneous landscapes varying in invasibility (Cousens 2008; Smith and Barney 2014). Even in high-risk scenarios, in some circumstances, landscape and crop management can effectively mitigate risk (Buckley et al. 2005); considerations that WRAs do not consider. Therefore, climate appropriateness, spatiotemporal grain size, and management scenarios are existing challenges to the robustness of existing WRAs (Hulme 2012b).

A Folly of (In)Appropriate Risk Assessment. Economic projections show the A-WRA has a net positive economic benefit to Australia (Keller et al. 2007). Unfortunately, commercial species were not considered, and blacklisting many agronomic species would be economically ruinous. The US-WRA has managed to address the false-positive species (benign species labeled invasive) to some level, but if we are going to take these scores at face value, the inability to perfectly separate weeds from crops must be judged. For example, no ecologist, agronomist, or conservationist would suggest a ban on rice cultivation for fear of potential escapes! When it comes to economically important crops, a WRA system that ranks crops, such as rice, barley, and alfalfa (*Medicago sativa* L.), among some of our most-devastating invasive weeds (Figure 1) lacks the ability to address important socioeconomic issues. Broader considerations, including economic revitalization, alternative energy choices, climate change, and sustainability, especially at the local scale, must be part of the dialogue. However, accounting for nonecological variables is a challenge that needs to be met to address important socioeconomic–ecological issues.

In an attempt to address these challenges, some have called for a tiered risk assessment approach, with WRA models serving as the starting point (Barney 2014; Cousens 2008; Davis et al. 2010; Quinn et al. 2013). However, based on our findings a tiered approach would eliminate 77% of the bioenergy feedstocks and five agronomic crops at the first tier (Tables 2 and 3; Davis et al. 2010). The tiered systems address some of the predictive limitations of the WRAs but do not address the challenges we present above. Others have suggested adopting horticultural practices of selecting specific cultivars for extensive observational field trials (Cousens 2008; Mack 2005). Although informative, that would be a timely and expensive process, especially for perennial species.

This exercise was not intended to address or repair all shortcomings of WRAs nor did we assess all possible crops, biofuels, or invasive species. Our aim rather, was to evaluate candidate bioenergy crops, as a subset of species introduced in the agricultural pathway and to determine the rigor of WRAs in their evaluation of new crops. Based on the results of both models in assessing important agronomic crops, a "white list" of crops developed from risk assessment alone could not only be economically devastating, but introduces the potential to create regulatory loopholes in state and federal noxious-weed laws. For example, Quinn et al. (2015) propose a list of low-risk taxa (25 of which are exotic) based on WRA results, which include known invaders like *Spartina* spp. Just as we found some crops to be rated high risk by the WRAs that we recognize as safer in practice, assuming that species are inherently safe in all scenarios is equally unrealistic.

As they stand, WRAs should not be the singular element in risk management when novel crops are concerned (Cousens 2008). An inclusive cost–benefit analysis that addresses economic, ecological, and social advantages and disadvantages, grounded in ecological theory that integrates the body of invasion science would attend to the broader risk ledger when introducing and cultivating exotic species. For example, the cost–benefit analysis devised by Yokomizo et al. (2012) uses information–gap theory to evaluate when commercial value of an introduction outweighs potential impacts under high uncertainty, an important step in this direction.

Without adopting an extreme policy, such as restricting the cultivation of new crops to native plants, we will never truly reduce the risk of invasive accessions. In the same way the precautionary principle has been applied to genetically modified crops (CAST 2013), our fear of widespread bioenergy crop adoption may be less detrimental than our failure to develop sustainable sources of alternative energy. Introductions of new species should not be met with reckless abandon, but our current level of knowledge requires careful and balanced evaluation beyond qualitative risk assessments. Clearly, weed risk assessments must become a transdisciplinary effort to achieve management and policy goals to protect our natural capital while balancing economic growth.

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