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Bioenergy Feedstocks at Low Risk for Invasion in the USA: a “White List” Approach

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Abstract Proposed introductions of non-native bioenergy feedstocks have resulted in disagreements among industry, regulators, and environmental groups over unintended consequences, including invasion. Attempting to ban or “black list” known or high probability invasive species creates roadblocks without offering clear alternatives to industry representatives wishing to choose low invasion risk feedstocks. Therefore, a “white list” approach may offer a proactive policy solution for federal and state agencies seeking to incentivize the cultivation of promising new feedstocks without increasing the probability of non-native plant invasions in natural systems. We assessed 120 potential bioenergy feedstock taxa using weed risk assessment tools and generated a white list of 25 non-native taxa and 24 native taxa of low invasion risk in the continental USA. The list contains feedstocks that can be grown across various geographic regions in the USA and converted to a wide variety of fuel types. Although the white list is not exhaustive and will change over time as new plants are developed for bioenergy, the list and the methods used to create it should be immediately useful for breeders, regulators, and industry representatives as they seek to find common ground in selecting feedstocks.

Keywords Biofuel · Energy crop · Invasive plant · Weed risk assessment · White list

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Introduction

In an effort to meet alternative energy mandates set by the 2007 Energy Independence and Security Act, bioenergy companies are investing in novel and, in many cases, non-native feedstocks that promise high yields on unproductive land [1]. However, these feedstocks can share key traits with invasive plant species, including high rates of establishment, rapid biomass accumulation, and the ability to thrive in low resource environments [2, 3]. Furthermore, current estimates suggest that dedicated energy crops could be planted on over 60 million hectares in the USA [4], potentially providing an immense propagule load [5] from production sites and along transport routes. Although several of the proposed feedstocks present relatively low invasion risk [6–11], the prevailing message from ecologists and environmental groups has been highly precautionary [12, 13]. Such a precautionary approach may be justified, considering that over 90 % of all economically and ecologically damaging invasive plant species are thought to have originated from intentional introductions [14–21].

Concerns about invasion risk are increasingly highlighted in the regulation of new feedstocks at the state and federal levels. For example, public outcry over invasion risk, in part, prompted the US Environmental Protection Agency (EPA) to adopt new standards to prevent escape by the approved feedstocks *Arundo donax* (giant reed) and *Pennisetum purpureum*

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(elephant/napier grass) [13, 22]. In addition, in the 2014 Farm Bill, congress strengthened an earlier provision that prohibits the US Department of Agriculture (USDA) from supporting potentially invasive feedstocks through its Biomass Crop Assistance Program (BCAP) [23]. At the state level, Florida (F.S.A. § 581.083) and Mississippi (Miss. Code Ann. § 69-25-10) have enacted laws that require permitting and bonding of non-native bioenergy plantations to mitigate invasion risk [24, 25]. In Oregon, the state agriculture department requires permits and containment practices for *A. donax* plantations and has restricted areas where the species can be cultivated (OAR 603-052-(1206-1250)). In addition, state and federal noxious weed regulations must be consulted prior to feedstock selection [11, 26]. Avoidance of noxious weeds is not sufficient to prevent invasion, however, since these lists poorly represent invaders outside cultivated areas [27, 28] and likely omit incipient invaders that are established in low numbers.

Regulation of invasive species directly affects bioenergy companies, particularly when large investments are made in the development of feedstocks that are later deemed problematic by regulators. For example, the company that petitioned for *A. donax* to be approved as a new fuel pathway has been forced to delay commercialization for over 2 years due to the unexpected requirement for risk mitigation planning and documentation (D. Richardson, Chemtex Group, personal communication, 2014). Although market factors such as profitable biomass yields are likely to dominate decisions regarding feedstock selection, there is interest from industry in using low invasion risk feedstocks that will avoid delays in approval and the responsibility for introducing potentially invasive species (J. Klingenberg, Repreve Renewables, LLC, personal communication, 2014). Existing risk assessment literature largely emphasizes the dangers of high-risk feedstocks, however, and provides few useful alternatives. Instead of creating a "black list" of prohibited high-risk feedstocks, a "white list" of low invasion risk feedstocks offers a positive approach for both companies and government agencies and could be used to fast-track approval of or reduce liability for producers using low-risk feedstocks. An example of a white list for bioenergy feedstocks already exists in the State of Florida (Non-native Species Planting Permits [5B-57.011]), where taxa produced for food, forage, or fiber, and those considered to have a low risk for invasion are white-listed and can be exempted from the state's permitting requirements [23]. This approach is intended to incentivize the use of non-invaders in Florida. Here, we offer an initial white list of low invasion risk native (indigenous to the USA) and non-native feedstocks, extending Florida's approach to the continental USA. Of note is that our list is based solely on invasion risk and does not evaluate other potential ecological concerns associated with bioenergy feedstocks.

Creating a White List of Low Invasion Risk Feedstocks for the USA

To generate a feedstock white list with taxa representing a diversity of growth habits, industrial uses, and climates, we first compiled a database of vascular feedstocks being used or considered for bioenergy production. We identified 120 candidate taxa (Table 1) that were mentioned as feedstocks in state and federal government documents and databases [26–28 FL Rule 5B-57.011], environmental and industry groups' white papers [4, 10, 11, 26, 29–31], feedstock-related books [32], and primary literature on invasion potential of bioenergy crops, including existing invasion risk assessment papers on the subject [6–9, 33, 34].

We did not include algae in the database, despite examples of biofuel development from algae in the USA [35–37], because we are unaware of an invasion risk assessment tool for non-vascular species. Although we sought to make the list comprehensive, the rapid development of the industry means that it should not be considered static or exhaustive. Additionally, not all of these taxa will meet the industry's yield or profitability demands in all regions of the continental USA

After compiling our database of potential feedstocks, we consulted the weed risk assessment literature and public databases [including 38–40] to identify the invasion risk level associated with each taxon of interest. Although a small number of demographic and climate models have been completed to predict potential invasion of bioenergy feedstocks [41–44], we selected the Australian Weed Risk Assessment (WRA) system as the basis of our white list. This WRA has proven accuracy (>90 %) in predicting major invaders across a range of geographies [45–47], and unlike other types of predictive models, results for a large number of species are accessible in public databases. For example, many of the taxa in our database have existing cultivation histories for food, forage, or fiber, which increases the data on which risk assessment could be based. The WRA defines specific score thresholds that differentiate taxa predicted to have a low probability (≤0) from those with high probability (≥7) of becoming invasive. Intermediate scores (1–6) indicate taxa requiring further evaluation before risk can be determined [46]. Species receiving this latter outcome may be run through an additional screening tool [48], which has been consistently demonstrated to resolve the risk for a large proportion of species with intermediate scores [45].

Regardless of the geographic focus of the test, WRA scores for species often result in consistent conclusions of high or low risk [49]. An explicit test of the accuracy of scores generated in other regions for risk assessment in Singapore resulted in the conclusion that WRA scores are transferrable to

Table 1 All taxa considered for a biofuel white list, with Australian Weed Risk Assessment (WRA) conclusions (i.e., low risk, evaluate further, or high risk), scores (possible range −14 to 29); see text for score cutoff points for each conclusion), and literature sources, in square brackets. *Denote conclusions made after secondary screening (see text for further explanation)

Taxon	Conclusion
Agave spp.	US native
Aleurites moluccana	Low risk (6*[75]), evaluate (3*) [76], high risk (12) [38]
Andropogon gerardii	US native
Arachis glabrata	Low risk (−11 [76] −1 [38])
Arachis hypogaea	Low risk (−2 [38])
Arundo donax	High risk (11 [6, 8], 12 [38], 19 [78])
Arundo formosana	Evaluate (5[46])
Attalea speciosa	Low risk (−2 [39])
Azadirachta indica	High risk (10 [38])
Beta vulgaris ssp. *vulgaris* convar. *saccharifera*	Low risk (−6 [38])
Brassica juncea	High risk (15 [38])
Brassica napus	High risk (16 [38])
Brassica rapa; syn. *B. campestris*	Low risk (4* [39])
Calotropis gigantea	High risk (15 [38])
Calotropis procera	High risk (8 [46], 15 [38])
Camelina sativa	Low risk (4* [39]), High risk (9.5 [38])
Cannabis sativa	High risk (8.5 [38], 11.5 [7])
Casuarina equisetifolia	High risk (11 [75], 15 [7], 21 [38], 23 [78])
Chrysopogon zinzanioides (fertile); syn. *Vetiveria zizanioides*	High risk (9 [38])
Chrysopogon zinzanioides var. “Sunshine” (sterile); syn. *Vetiveria zizanioides*	Low risk (−9 [39],−8 [38])
Cocos nucifera	Low risk (−4 [38], −3 [75])
Coffea arabica	Low risk (−3 [75]), High risk (1* [78], 2* [38])
Copaifera langsdorffii	Evaluate (4* [38])
Crotalaria juncea	Evaluate (1* [38]), High risk (7 [39])
Cuphea viscosissima	US native
Diospyros virginiana	US native
Diospyros kaki	High risk (1* [78])
Elaeis guineensis	High risk (8 [75], 9 [7], 10 [38])
Eucalyptus amplifolia	Low risk (−2 [39], 0 [9]), evaluate (2* [8])
Eucalyptus camaldulensis	High risk (12 [8], 18 [9], 19 [39])
Eucalyptus dorrigoensis	Low risk (−4 [39], −3 [9])
Eucalyptus dunnii	Low risk (−3 [39], −2 [9], 0 [38])
Eucalyptus globulus	High risk (10 [38], 18 [9])
Eucalyptus grandis	High risk (8 [8], 9 [39], 10 [9], 11 [38])
Eucalyptus gunnii	Low risk (1* [39], 2* [9]), evaluate (2* [38])
Eucalyptus macarthurii	Evaluate (6* [9])
Eucalyptus nitens	Low risk (0 [39], 1* [9])
Eucalyptus robusta	Low risk (−1 [75], 3* [38]), high risk (11 [9])
Eucalyptus saligna	High risk (7 [38], 9 [39])
Eucalyptus smithii	Low risk (1* [9])
Eucalyptus torelliana	Evaluate (4* [38]), high risk (13 [9])
Eucalyptus “*urograndis*” (*E. urophylla*×*grandis*)	Low risk (1* [38]), evaluate (3* [39], 4* [9])
Eucalyptus urophylla	Low risk (4* [38], 6* [77]), evaluate (6* [7]), high risk (7 [9])
Eucalyptus viminalis	High risk (9 [39], 10 [9])
Euphorbia lathyris	High risk (8 [7], 9 [38])
Festuca arundinacea	High risk (17 [38])
Fraxinus uhdei	High risk (11 [38])
Gleditsia triacanthos	US native
Glycine max	Low risk (−3 [7])
Gossypium barbadense	Evaluate (5* [38])
Gossypium hirsutum	High risk (9 [38])
Gynerium sagittatum	High risk (13 [39])
Helianthus annuus	US native
Hordeum vulgare	Low risk (0 [75])
Ipomoea batatas	Low risk (2* [38])
Jatropha curcas	High risk (11 [80], 17 [38], 19 [8])
Lespedeza cuneata	High risk (17 [38])
Lesquerella fendleri	US native
Leucaena leucocephala	High risk (11 [80], 15 [38], 21 [8], 26 [78])
Linum usitatissimum	High risk (9.5 [38])
Liriodendron tulipifera	US native
Macadamia integrifolia	Low risk (−1 [38])
Maclura pomifera	US native
Manihot esculenta	Low risk (3* [38])
Milletia pinnata; syn. *Pongamia pinnata*	High risk (7 [38], 9 [7])
Miscanthus×*giganteus*	Low risk (−9 [8], −7 [6])
Miscanthus sacchariflorus	High risk (20 [39])
Miscanthus sinensis	High risk (14 [76])
Moringa oleifera; syn. *M. pterygosperma*	Low risk (1* [38]), high risk (9 [39])
Morus alba	Evaluate (2.5* [79])
Oenothera spp.	US native
Olea europaea	Evaluate (2 [80])

Table 1 (continued)

Taxon	Conclusion
Olea europaea ssp. *cuspidata*	High risk (11 [38])
Olea europaea ssp. *europaea*	Evaluate (5* [38])
Panicum maximum; syn. *Urochloa maxima*	High risk (17 [38])
Panicum virgatum	US native
Paraserianthes falcataria	High risk (8 [7])
Paulownia elongata	Low risk (−1 [38], 6* [39])
Paulownia tomentosa	Evaluate (4* [74]), high risk (7 [80], 9 [38], 14 [39])
Pennisetum purpureum	High risk (10 [80], 16 [38], 18 [8, 78])
Pennisetum purpureum× *glaucum*	Evaluate (5* [39])
Perilla ocymoides	High risk (14 [39])
Persea americana	Low risk (0 [75], 3* [38])
Phalaris arundinacea	High risk (25 [39])
Pinus echinata	US native
Pinus elliottii	US native
Pinus palustris	US native
Pinus radiata	US native
Pinus taeda	US native
Pittosporum resiniferum	Evaluate (6* [38])
Platanus occidentalis	US native
Populus spp.	US native
Prosopis juliflora	High risk (19 [38])
Prosopis spp.	US native
Psidium cattleianum	High risk (16 [75], 18 [38])
Pueraria montana var. *lobata*	High risk (9 [80], 24 [38])
Quercus acutissima	Evaluate (2* [39])
Ricinus communis	High risk (8 [80], 9 [78], 21 [38], 24 [8])
Robinia pseudoacacia	US native
Rubus fruticosus	High risk (29 [39])
Saccharum hybrid L 79-1002	Low risk (−1 [39])
Saccharum arundinaceum	Low risk (3* [8])
Saccharum officinarum	Low risk (−2 [38], 5* [8]), high risk (5* [78])
Saccharum spontaneum	High risk (17 [38], 19 [39])
Salix spp.	US native
Sesbania grandiflora	Low risk (2* [38]), high risk (10 [39])
Simmondsia chinensis	US native
Sorghastrum nutans	US native
Sorghum bicolor "grain sorghum" syn. *S. vulgare*	Low risk (6* [38]), evaluate (3 [80]), high risk (7 [39])
Sorghum bicolor "shattercane"	High risk (17.5 [38], 18 [39])
Sorghum bicolor "sweet"	Low risk (3* [8])
Sorghum halepense	High risk (25 [80])
Spartina spp.	US native
Thlaspi arvense	High risk (19 [38])
Thysanolaena latifolia	High risk (11 [39])
Triadica sebifera; syn. *Sapium sebiferum*	High risk (14 [38], 18 [76])
Triticum aestivum	Low risk (3* [74])
Ulex europaeus	High risk (20 [38], 26 [80])
Zea mays	Low risk (−1 [74]), evaluate (2 [46])
Ziziphus mauritiana	High risk (9.5 [38], 12 [80])

Continental US natives (noted in conclusion column) and low-risk taxa with known industrial uses for bioenergy were retained in our white list and are found with additional information in Table 2. Note that *Eucalyptus amplifolia* has two scores from the same group of authors (references [8, 9]); the later conclusion ("low risk (0 [9])") reflects a reanalysis prompted by additional data that were not available for the earlier assessment ("evaluate (2* [8])"). Sources of WRA scores and conclusions are noted by numbers inside the brackets as listed in the "Reference" section. Where references in individual papers cite the same scores as are available on on-line databases [8, 9, 12], the databases are cited as they make available the full WRA results

new geographies with similar environmental conditions [47]. Given the broad range of environmental conditions within the continental USA, we included all available WRA scores for our study, including scores generated specifically for the USA as well as those focused on other locations worldwide. However, using scores from any new US-based WRAs would benefit future iterations of the white list, particularly if the white list is adapted for use in specific US regions or states.

To encourage the selection of native feedstocks wherever possible, we automatically included taxa native to the continental USA (24 of the 120 species identified) on the white list (Table 2). The use of native genotypes within their native range reduces the risk of escaped plants having negative impacts in recipient native communities, especially relative to non-native taxa [50], whose impacts can be less predictable. Low risk non-natives (n=25) were also placed on the white list. Taxa receiving high risk scores (≥7) or listed on the federal noxious weeds list (e.g., *Rubus fruticosus* and *Saccharum spontaneum*) [51] were not considered for the white list (Table 1). Several species received WRA scores between 1 and 6 ("evaluate further"). Where use of the secondary screen [48] resulted in a low risk determination, the taxon was included on the white list; otherwise, it was removed from further consideration pending data availability to resolve the risk category.

The data we used were based on WRAs conducted on non-native taxa at the species level unless specific hybrids, cultivars, or other subspecific taxa with sufficient trait data were identified. Many novel genotypes, including hybrids, cultivars, and genetically modified organisms, are being developed or are already available as feedstocks [e.g., 52]. Such taxa may have traits that reduce or increase invasion potential compared to the parent species (e.g., sterile vs. fertile varieties of

Table 2 "White list" of native and low-risk non-native taxa for feedstock development in the USA

Feedstock	Common name	Industrial uses	Preferred climate	US Nativity	Source
Agave spp.	Agave	EtOH	Arid temp	Southwest, but varies with species. *A. sisalana* invasive in Southeast	DOE (2013)
Andropogon gerardii	Big bluestem	EtOH, BD, comb	Temp	Continental USA except ID, NV, WA, OR, CA, and HI	DOE BTU (2011); DOE (2013)
Arachis glabrata	Rhizoma peanut	BD	Temp, subtr	Non-native	Buddenhagen et al. (2009)
Arachis hypogaea	Peanut	BD	Temp, subtr	Non-native	GISP (2007)
Attalea speciosa syn. Orbignya barbosiana	Babassu palm	BD	Subtr, trop	Non-native	Sanford et al. (2009)
Beta vulgaris	Sugar beets	EtOH	Temp, subtr	Non-native	DOE BTU (2011); Halford et al. (2010)
Brassica rapa	Field mustard	BD	Temp	Non-native	DOE BTU (2011)
Chrysopogon zinzanioides var. "*Sunshine*"; syn. *Vetiveria zizanioides* var. "*Sunshine*"	Vetiver grass	EtOH	Subtr	Non-native	FLDACS (2013)
Cocos nucifera	Coconut palm	EtOH, comb	Trop, subtr	Non-native	Buddenhagen et al. (2009); GISP (2007); Sanford et al. (2009)
Cuphea viscosissima	Blue waxweed	BD	Temp, subtr	Eastern USA: Mid-Atlantic, Southeast, lower Midwest, and eastern plains	Sanford et al. (2009)
Diospyros virginiana	Persimmon	EtOH, comb	Temp	Continental USA except north-central, northwest, and most of southwest	GISP (2007)
Eucalyptus amplifolia	Cabbage gum	EtOH, comb	Subtr	Non-native	Gordon et al. (2011 & 2012)
Eucalyptus dorrigoensis	Dorrigo white gum	EtOH, comb	Subtr	Non-native	FLDACS (2013); Gordon et al. (2012)
Eucalyptus dunnii	Dunn's white gum	EtOH, comb	Subtr	Non-native	FLDACS (2013); Gordon et al. (2012)
Eucalyptus nitens	Shining gum	EtOH, comb	Subtr	Non-native	FLDACS (2013); Gordon et al. (2012)
Eucalyptus smithii	Gully gum	EtOH, comb	Subtr	Non-native	FLDACS (2013); Gordon et al. (2012)
Gleditsia triacanthos	Honey locust	EtOH, comb	Temp	Continental USA except WA and OR	GISP (2007)
Glycine max	Soybean	EtOH	Temp	Non-native	Buddenhagen et al. (2009); DOE BTU (2011); EPA (2011); GISP (2007); Halford et al. (2010); Sanford et al. (2009)
Helianthus annuus	Sunflower	BD	Temp	Continental USA; use with caution: NOXIOUS In IA	Buddenhagen et al. (2009); DOE BTU (2011); GISP (2007); Halford et al. (2010); Sanford et al. (2009)
Hordeum vulgare	Barley	EtOH	Temp	Non-native	DOE BTU (2011)
Ipomoea batatas	Sweet potato	EtOH	Temp, subtr, trop	Non-native	GISP (2007)
Lesquerella fendleri	Fendler's bladderpod	BD	Temp, subtr	AZ, CO, KS, NM, OK, TX, and UT	Sanford et al. (2009)
Liriodendron tulipifera	Tulip or yellow poplar	EtOH, comb	Temp	Eastern USA	DOE (2013)
Macadamia integrifolia	Macadamia nut	BD	Trop, subtr	Non-native	Buddenhagen et al. (2009)
Maclura pomifera	Hedge apple/osage orange	BD	Temp, subtr	Continental USA except MN, ND, MT, WY, ID, NV, and AZ	GISP (2007)

Table 2 (continued)

Feedstock	Common name	Industrial uses	Preferred climate	US Nativity	Source
Manihot esculenta	Cassava	EtOH	Trop, subtr	Non-native	GISP (2007)
Miscanthus × giganteus (sterile)	Giant Miscanthus ("Illinois")	EtOH, comb	Temp, subtr	Non-native	Low et al. (2008); Barney et al. (2008); DOE BTU (2011); EPA (2011); GISP (2007); Gordon et al. (2011); Halford et al. (2010)
Oenothera spp.	Evening primrose	BD	Temp	Varies with species	Sanford et al. (2009)
Panicum virgatum	Switchgrass	EtOH, comb	Temp	Continental USA except WA, OR, CA, and HI	Barney et al. (2008); Buddenhagen et al. (2009); DOE BTU (2011); DiTomaso et al. (2007); DOE (2013); EPA (2011); GISP (2007); Halford et al. (2010)
Paulownia elongata	Paulownia	comb	Temp	Non-native	FLDACS (2013)
Persea americana	Avocado	BD	Trop, subtr	Non-native	Buddenhagen et al. (2009)
Pinus echinata	Shortleaf pine	EtOH, comb	Subtr	Mid-Atlantic, Southeast, portions of the Midwest and plains	DOE BTU (2011)
Pinus elliottii	Slash pine	EtOH, comb	Subtr	AL, FL, GA, LA, MS, NC, SC, and TX	DOE BTU (2011)
Pinus palustris	Longleaf pine	EtOH, comb	Subtr	AL, AR, FL, GA, LA, MS, NC, SC, TX, and VA	DOE BTU (2011)
Pinus radiata	Monterey pine	EtOH, comb	Subtr	CA	DOE (2013)
Pinus taeda	Loblolly pine	EtOH, comb	Subtr	Southeast and south central USA	DOE BTU (2011)
Platanus occidentalis	American Sycamore	EtOH, comb	Temp	Eastern USA	DOE (2013)
Populus spp.	Cottonwood/poplar	EtOH, comb	Temp	Varies with species	Low et al. (2008); DOE BTU (2011); DOE (2013); Halford et al. (2010)
Prosopis spp.	mesquite	EtOH, comb	Subtr	Southwest, but varies with species	GISP (2007)
Robinia pseudoacacia	Black locust	EtOH, comb	Temp	Mid-Atlantic and southern Midwest; use with caution: NOXIOUS in MA, invasive in 12 states	DOE (2013)
Saccharum "L 79-1002" hybrid*	Hybrid sugarcane	EtOH	Trop, subtr	Non-native	FLDACS (2013)
Saccharum arundinaceum	Hardy sugarcane	EtOH	Trop, subtr	Non-native	Gordon et al. (2011)
Salix spp.	Willow	EtOH, comb	Temp	varies with species	Low et al. (2008); DOE BTU (2011); Halford et al. (2010)
Simmondsia chinensis	Jojoba	BD	Temp	CA, AZ, and UT	Buddenhagen et al. (2009); Sanford et al. (2009)
Sorghastrum nutans	Indian grass	EtOH, comb	Temp	Continental US except ID, NV, WA, OR, CA, and HI	DOE BTU (2011)
Sorghum bicolor "sweet"	Sweet sorghum	EtOH	Temp, subtr	Non-native	DOE (2013); Gordon et al. (2011)
Spartina spp.	Cordgrass	EtOH	Temp	Varies with species; use with caution: some spp. are invasive	Low et al. (2008)
Triticum aestivum	Wheat	EtOH	Temp	Non-native	DOE BTU (2011); GISP (2007); Halford et al. (2010)
Zea mays	Corn	EtOH	Temp	Non-native	

Table 2 (continued)

Feedstock	Common name	Industrial uses	Preferred climate	US Nativity	Source
					DOE BTU (2011); EPA (2011); Halford et al. (2010); Sanford et al. (2009)

Neither the list of species nor industrial uses (*BD* biodiesel, *comb* combustion, *EtOH* ethanol) should be considered exhaustive. Preferred climates (*subtr* subtropical, *temp* temperate, *trop* tropical) are listed to assist in siting potential production areas. Source of native region was the USDA NRCS PLANTS database [59]. Reference to a species as "invasive" in the US Nativity column is derived from such a designation on state or regional invasive plant council lists; reference to a "noxious" designation denotes that the species is regulated and prohibited in certain states. Any genotype of a species included in this white list that is known to be invasive is not recommended for use

Miscanthus × *giganteus* (giant Miscanthus) and sterile vs. fertile cultivars and hybrids of *Pennisetum purpureum* [53, 54]. While the proprietary nature of taxa developed for commercial purposes often limits the data available for WRA at subspecific levels, the risk assessment process can and should be modified for such taxa [e.g., see 39, 55] when data become available.

In many cases (n=48), we found multiple scores for the same species, assessed by different sources. Different scores can result from application of the WRA in different geographies, inclusion of data not available when earlier assessments were conducted, or differences in interpretation of the WRA [45]. In 33 % of those cases (16/48), the risk conclusions from multiple sources were inconsistent. In those cases, we did not include the species on our white list, even if one source concluded that the species was low risk. We made the single exception to this rule for *Zea mays* (corn or maize), because of its long-term cultivation without evidence of invasive tendencies [56]. Further data are needed to resolve the risk category for species with conflicting results.

Understanding the White List

Feedstocks with low invasion risk status and favorable agronomic properties will be most attractive to the bioenergy industry. Our white list (Table 2) offers 49 native and non-native low-risk options that will meet these requirements across much of the USA (e.g., *Panicum virgatum* (switchgrass)) or in more specific "niche" growing conditions (e.g., *Agave* spp. (agave) in the arid southwest). Table 2 also indicates the sources that mention the bioenergy potential of each taxon. Those taxa associated with a greater number of sources or with more industry-relevant sources (e.g., Department of Energy (DOE)) are likely to be the taxa with the strongest potential for government support and the greatest potential returns on investment. These include *Glycine max* (soybean), *Helianthus annuus* (wild sunflower), sterile *Miscanthus* × *giganteus*, *Panicum virgatum*, native *Populus* spp. (poplar), *Sorghum bicolor* "sweet" (sweet sorghum), and *Zea mays*.

Native plants bred for bioenergy production and grown in monoculture outside of their native range carry some of the same invasion and impact risks as non-natives [2, 57, 58]. Therefore, we provide the native region (Table 2; derived primarily from the USDA's PLANTS database [59]) and stress that native genotypes should be grown *only* in those states or regions to avoid any unintended ecological impacts resulting from escape. Examples exist of species or biotypes that are invasive outside of or even within their native regions in the USA [60, 61]. For example, *Helianthus annuus* is native to the entire continental USA but is listed as a noxious weed in Iowa and was found to be a high risk species in Hawaii (WRA score=10.5 [7]). In addition, several native taxa or close relatives on our list are known invaders elsewhere, including Hawaii, so it is important to reemphasize that the current list is intended to provide low-risk solutions for the continental USA only. For example, native *Pinus elliottii* (slash pine) spreads spontaneously to uncultivated areas on at least two continents [62] and received high risk scores for New Zealand and Great Britain [63] and an "evaluate further" outcome for Hawaii [38]. Genera with native members (e.g., *Populus* spp.) appear on the white list with the assumption that producers will grow only native genotypes and only within their native regions. For many of the non-native species on our list, climate-matching models are unavailable for the USA. Therefore, potential production regions will have to be tested and assigned based on relatively broad estimates of each taxon's preferred climate (see Table 2).

Further Safeguards

White list taxa are predicted to have low invasion risk but are not guaranteed to remain low-risk in changing climates or as novel genotypes are developed through traditional breeding or genetic modification. For example, several companies are near commercialization of fertile *Miscanthus × giganteus* feedstocks, which are likely to pose greater invasion risk than the sterile hybrid on our white list [6, 34, 44, 64]. Rather than potentially increasing invasion risk by inducing fertility, plant breeders could introduce traits to minimize potential escape, including sterility, indehiscence or non-shattering of propagules, or reduced brittleness of perennating vegetative structures [34, 65]. Varieties of *Sorghum bicolor* sweet, for example, naturally allocate more photosynthate to sugars than to starch and to stem than seed tissues, resulting in lower risk of invasion than *Sorghum bicolor* "grain" or the highly invasive *Sorghum bicolor* "shattercane" [56]. Similarly, the fertile wild-type of *Chrysopogon zizanioides* (syn. *Vetiveria zizanioides*; vetiver grass) is invasive, but the sterile "Sunshine" genotype from southern India has low invasion risk [38]. Regardless of the type of "improvement," any and all novel genotypes of white listed species, including native species, would require new assessments before being added to future iterations of the list. In addition, new assessments should be completed prior to any planned relocation or expansion of production regions. For example, the recent spatial shifts in USDA Hardiness Zones [http://www.ars.usda.gov/is/pr/2012/120125.htm] demonstrate that climate changes are likely to influence the future distributions of both native and non-native taxa.

A set of specific management practices, including monitoring and eradication of any off-site colonization, should also be developed for all feedstocks grown commercially—even those on the white list. The USDA's BCAP program has set a precedent for the requirement of such practices for a low-risk feedstock (sterile Miscanthus×gigante*us*) [66]. We concur with other authors in recommending similar requirements at the state and/or federal levels [25] and encourage industry to voluntarily adopt safeguards to prevent escape in advance of regulatory changes [23, 67]. Management practices should be applied at all stages of bioenergy production–from planting through processing—and may include timing harvests to minimize spread of seeds, maintaining clean equipment, using closed transportation systems to transfer feedstocks to processing facilities, and putting an eradication plan into place before production [26, 68].

Policy Implications

This white list offers a starting point to guide policies at the federal and/or state levels, potentially reducing emerging conflicts among agencies that support bioenergy and those that manage invasive species. Inconsistencies in recommendations among federal agencies risk violating Executive Order 13112 [69], which explicitly requires integration and consistency of invasive species policy at the federal level [23]. For example, *A. donax* has been assessed as a high-risk species by the USDA Plant Epidemiology and Risk Analysis Laboratory [70], and the USDA Agriculture Research Service is working to identify an effective biological control agent to manage invasions [71]. However, *A. donax* has been approved for cultivation under the Renewable Fuel Standard implemented by EPA [22], highlighting the fact that conflicts among agencies and with the Executive Order have not been resolved. The non-governmental Invasive Species Advisory Committee (ISAC) has recommended that inconsistencies in federal policy related to invasiveness and biofuels be identified and addressed and that the federal government take steps to minimize the risk of bioenergy feedstocks becoming invasive, including evaluating candidate feedstocks and promoting low-risk taxa [4]. The use of a white list can allow agencies to fast-track taxa that have been assessed as low-risk.

A clear liability regime is needed to reduce incentives for using high-risk bioenergy feedstocks by assigning negligence liability to feedstock producers for damages from and remediation of invasions by bioenergy feedstocks [10, 27, 28]. Policy approaches should reduce potential liability for producers using white-listed feedstocks cultivated under specific management practices to further reduce invasion risk. These actions would be evidence that due diligence was practiced even in the unlikely event that feedstocks escape and become harmful invaders.

Conclusion

The invasion risk-based white list we have created for the USA contains 49 taxa representing a wide variety of growth habits, harvestable yields, favored climates, agronomic traits, and cultivation practices. The white list approach not only provides producers with clearly identified low invasion risk options, but it additionally can and should be used in federal and state policy to incentivize the use of low invasion risk feedstocks [25]. Use of taxa from the white list may reduce conflicts between objectives for increasing renewable fuel production and reducing unintended impacts and costs resulting from propagation of invasive plants. Additionally, because a small proportion of the species we examined require further evaluation or had conflicting results, future investigation may augment the list relatively quickly. To reduce the potential for biomass feedstocks to become invasive, we recommend that prior to major investment and commercialization, all potential bioenergy feedstocks be screened with science-based tools as we have done here [28, 57], tested experimentally for invasion risk [28, 53], and reassessed regularly [39] as novel genotypes are developed and as climate change shifts potential production regions. All of these processes should be stipulated in state and federal statutes and regulations [25].

Here, we have focused on invasion risk, but other unintended environmental, economic, and health impacts of bioenergy crops should not be discounted. For example, while some *Eucalyptus* species pose a low risk for invasion [9], their high productivity is accompanied by high water use, which may have unintended impacts in water-limited systems[72, 73]. These additional considerations should be used to refine geographic and management criteria for bioenergy crop cultivation.

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