

REVIEWS

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Global approaches to addressing biofuel-related invasive species risks and incorporation into U.S. laws and policies

KRISTIN C. LEWIS^{1,3} AND READ D. PORTER²

¹*Volpe National Transportation Systems Center, 55 Broadway, Cambridge, Massachusetts 02142 USA*

²*Environmental Law Institute, 2000 L Street NW, Suite 620, Washington, D.C. 20036 USA*

Abstract. Biofuels are being pursued for their potential greenhouse gas (GHG) emissions benefits, among other reasons. In order to maximize productivity, avoid food–fuel conflicts, and minimize GHG emissions, many advanced biofuel feedstock crops, such as those desired by the aviation community, are under consideration based on traits, such as high biomass and/or seed production, tolerance of marginal cultivation conditions, and short generation times, that may also be predictors of potential invasiveness risk. Biofuel-related invasion risks can be mitigated through careful feedstock crop selection and cultivation techniques developed from the invasion science literature. Existing voluntary best practices and some state and federal regulatory requirements in the United States recommend and/or require the use of such risk mitigation strategies. However, other policies and programs allow or provide incentives for biofuel production without conditions requiring the use of these strategies. We have synthesized information on the scientific knowledge of invasive species predictors and their use (or absence) in voluntary codes and U.S. regulatory frameworks and incentive programs. We highlight the existing tools and approaches for assessing invasion risk and avoiding the introduction and spread of invasive species as a result of biofuel feedstock cultivation. A well-coordinated combination of species restrictions, biosecurity requirements, and incentives for selection of less risky biofuel crops may effectively balance the desire for increased biofuel production while minimizing invasion risk.

Key words: *alien species; bioenergy; biomass; feedstock; invasion; nonnative species; pest risk assessment; weed risk assessment.*

INTRODUCTION

Recent studies indicate that biofuel species may pose a particular invasion risk because many of the traits that are sought in biofuel feedstock crops to solve other issues facing the biofuels industry may also predict higher likelihood of invasion risk (Raghu et al. 2006, Buddenhagen et al. 2009, ISAC 2009). Some proposed biofuel feedstock species have become invasive in the United States or elsewhere, and two, *Arundo donax* (giant reed) and *Psidium cattleianum* (strawberry guava), are listed as among 100 of the worst global invaders by the International Union for the Conservation of Nature (IUCN) for serious impact on biological diversity and/or human activities (Lowe et al. 2000). The potential to introduce or exacerbate the spread of invasive species

therefore is an important consideration when selecting and cultivating bioenergy crops.

The challenge of feedstock selection and cultivation has become particularly important as fuel producers and purchasers strive to avoid concerns about the use of food crops (which tend to be well-known and rarely invasive) as biofuel feedstocks and to avoid the use of prime agricultural land by selecting species that can tolerate marginal growing conditions. The aviation industry, which anticipates being dependent on hydrocarbons for the foreseeable future, has shown particularly strong interest in advanced biofuels from nonfood crops, which led the Commercial Aviation Alternative Fuels Initiative (CAAFI) to work with USDA on the development of the Feedstock Readiness Level Tool, which maps out the development of a new bioenergy crop for advanced biofuels (Steiner et al. 2012). However, while novel bioenergy crops provide the potential to produce advanced, drop-in fuels in synergy with food production, these new crops may pose a threat

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³ E-mail: kristin.lewis@dot.gov

to native species and ecosystem functions if not properly screened for potential invasion risk.

Understanding the role played by species-specific traits, contextual factors, and their interactions in determining invasion potential is important for biofuel feedstock crop selection and cultivation. Once identified, these characteristics can be used to support risk assessment and management to enable selection of biofuel feedstock crops that pose little risk of invasion and to prevent the escape and establishment of species under cultivation. Risk assessment and management tools may also determine the applicability of legal limitations and incentives that influence when, where, and how bioenergy crop production occurs.

Weed Risk Assessment (WRA) tools have been developed to assess the environmental risks associated with plant species through consideration of predictive species characteristics and compatibility with ecological conditions (e.g., Pheloung et al. 1999, Daehler et al. 2004, Daehler and Virtue 2010, Davis et al. 2010, Koop et al. 2012). Researchers are using WRA tools extensively to evaluate candidate biofuel feedstock species (Daehler and Carino 2000, Barney and DiTomaso 2008, Crosti et al. 2008, 2010, Gordon et al. 2008b, Nishida et al. 2008, Buddenhagen et al. 2009, Davis et al. 2010, 2011b, Gassó et al. 2010, McClay et al. 2010, Gordon et al. 2011; see also Weed risk assessments for Florida database, *available online*).⁴

WRA tools have both regulatory and nonregulatory uses. In a few countries, such as Australia, WRA outcomes are used to determine whether to allow importation of nonnative species that are not already present. In the United States, on the other hand, WRA tools are used as a decision support tool in few regulatory programs, and species with WRA outcomes indicating high risks are not always subjected to regulatory restrictions intended to mitigate those risks. WRA tools can also be used without a regulatory linkage, such as to identify or avoid high-risk species. Voluntary best practice guidelines for biofuel production call for producers to consider WRA outcomes when selecting feedstock species; widespread adoption of these guidelines can reduce invasion risk.

Feedstock crops may escape into the environment during cultivation or transport to a processing facility. Invasions often exhibit a time lag after introduction as the species becomes established outside of cultivation (Nuzzo 1993, Kowarik 1995, Mack et al. 2000), offering an opportunity for early detection and rapid response (EDRR). EDRR effectiveness can be enhanced through the use of cultivation practices such as buffer zones, monitoring, and financial assurance. Both voluntary guidelines and some regulatory programs call for the use of such practices, which may vary by geographic location, native status, and/or type of organism.

We summarize the science of terrestrial plant invasion prediction and its associated risk assessment and risk management tools, and we assess how these tools, findings, and recommendations are incorporated into U.S. legal regimes affecting terrestrial biofuel crop selection and cultivation. Our analysis highlights the extent to which scientific evaluations of invasion risk are used across various levels of regulation. It is not intended to recommend exclusion of any individual feedstock species, but rather to identify gaps in policy that result in inconsistent treatment of species that pose potential invasion risks. We focus our legal analysis on the United States because applicable legal regimes differ substantially from country to country, and few international regulatory tools are available for a unified approach to invasive species prevention (Keller and Perrings 2011). Similar analyses are needed to understand the interaction of invasive species prediction insights and regulatory requirements in other countries and regions. Additional work is also needed to address the unique biological and legal implications of aquatic species cultivation for biofuels, including algae, which are excluded from the present study.

A note on terminology

The term invasive species is defined variously by different sources in different contexts (e.g., Richardson et al. 2000, Davis and Thompson 2001, Colautti and MacIsaac 2004, ISAC 2006, European Commission 2008, Simberloff 2010, IUCN 2011). A clear definition of invasive species is needed to avoid confusion and misplaced criticism (Davis et al. 2011a, Simberloff 2011). This study adopts the definition of invasive species used in Executive Order 13112 (1999), which identifies invasive species as (1) not native to an ecosystem, and (2) species that cause or are likely to cause economic or environmental harm or harm to public health when introduced to a location where they are not native. Some researchers have suggested removal of the requirement for harm from the definition of invasive species (Richardson et al. 2000, Pyšek et al. 2004), and some of the literature identifying predictors of invasion may use alternate definitions. However, nonnative status and harm are common to many definitions in the scientific and policy literatures and are the basis for regulation of these species; we therefore adopt both nonnativeness and harm here. Without harm, there is little or no reason to address invasive species risks with pre-importation evaluations, best management practices, or regulatory constraints.

In addition, we define bioenergy crops as crops that are specifically grown for power generation, process fuel, or conversion into liquid biofuels. Cellulosic biomass refers to woody or herbaceous plant material that can be used for bioenergy purposes (e.g., pyrolysis, Fischer-Tropsch), whereas oilseeds are crops for which the primary use is the extraction of oil from mature seed for

⁴ <http://www.hear.org/wra/tncflwra/>

conversion to liquid fuels, such as for biodiesel or hydroprocessed esters and fatty acids.

PREDICTORS OF INVASION

Scientific knowledge about the potential risk posed by novel species can inform decisions about the importation and use of biofuel feedstock species. Researchers have long attempted to identify characteristics that predict whether a species is likely to become established and spread when introduced to new locations (e.g., Lewontin 1965, Bazzaz 1986, Gray 1986, Vitousek 1986, Carson 1987, Rejmánek 1996, 2000, Rejmánek and Richardson 1996, Williamson and Fitter 1996b, Daehler 1998, Ellstrand and Schierenbeck 2000, Kolar and Lodge 2001, Lockwood et al. 2001, Leishman et al. 2007, Moles et al. 2008, Bradley et al. 2009, Van Kleunen et al. 2010). Many of the identified traits are interrelated; for example, a trait considered a predictor in one study (e.g., rapid growth rate) may result from other factors (e.g., lack of predators, environmental tolerance) used elsewhere as predictors. Predictive characteristics include reproductive traits, species history, environmental tolerance, interactions/competition, genetic factors, phylogenetic factors, and ecosystem characteristics. No single characteristic can predict invasion risk; therefore, WRA tools combine a subset of identified characteristics (generally, predictors that are easier to measure prior to introduction than other, interrelated factors) to determine invasion potential. This section highlights traits linked to invasion potential, focusing on those utilized in WRA systems. The subsequent section discusses how these predictors are applied in WRA tools.

Reproductive traits

Reproductive traits can enhance invasiveness by reducing barriers to reproduction in a new location or by enhancing population growth. Short generation times (Rejmánek 1996, Rejmánek and Richardson 1996, Rejmánek 2000) and high seed/propagule production (Williamson and Fitter 1996a, Kolar and Lodge 2001, Moyle and Marchetti 2006) rapidly increase the number of individuals present in the new location. Early reproduction and high fecundity are sought in biofuel feedstock crops, particularly in the case of oilseed crops (such as *Camelina sativa*; see Plate 1), to increase fuel yield per hectare. Combined with repeated or widespread introductions, these traits may increase feedstock crop propagule pressure and the likelihood of successful establishment outside of cultivation.

Seed dispersal enhances the ability of a species to escape cultivation and spread. High seed dispersal is not desirable for oilseed feedstock crops, but many candidate cellulosic biomass feedstock species are grasses, which tend to have wind-dispersed seeds and, therefore, are more likely to escape cultivation. Recent work has shown that both *Miscanthus sinensis* and *M. × giganteus* exhibit long distance seed dispersal by wind, particularly at elevated wind speeds (Quinn et al. 2011). To enable

cultivation outside their home range, introduced biofuel feedstock species also are likely to have generalist pollinators and other mutualists that may enhance invasiveness potential. Self-compatible species and those with nonspecialized pollinator (Daehler 1998, Rejmánek 2000) and seed disperser (Rejmánek 1996, 2000) relationships are more likely to reproduce and spread than self-incompatible species or those that rely on a specialized mutualist for seed or pollen transport. The ability of seeds to form a seed bank will allow the species to establish whenever conditions are favorable (Rejmánek 2000) and make eradication difficult. While this trait is not sought in biofuel feedstock species, seed longevity may be a useful consideration for reducing invasion risk.

Species that can reproduce vegetatively, especially from fragments, are likely to increase rapidly and spread in a new location. For example, the biofuel feedstock species *Arundo donax* (giant reed) spreads during flooding events via dispersal of rhizome fragments (Bell 1997). Although vegetative reproduction is not specifically sought in biofuel feedstock crops, its role in facilitating invasion should be considered when selecting among possible feedstock species.

Hybridization with native species or among disparate populations of introduced conspecifics may facilitate local adaptation (Ellstrand and Schierenbeck 2000, Mack et al. 2000). Hybridization may contribute to the invasiveness of *Sorghum alnum* (Columbus grass, a congener of the potential biofuel feedstock species *S. bicolor*) and several *Cardamine* (cress) species (in the Brassicaceae, the same family as *Camelina*; Ellstrand and Schierenbeck 2000). However, hybridization with less fit relatives may also reduce invasion potential. Intentional hybridization also may influence potential invasiveness, but the direction of this influence will depend on the traits sought through hybridization. *Miscanthus × giganteus* is a sterile hybrid bred for high biomass production that is considered less likely to be invasive than *M. sinensis*, one of the parent species; thus, hybridization may be a negative or positive predictor of invasive potential depending on whether the traits that arise from hybridization are specifically selected for noninvasive characteristics (such as *M. × giganteus*) or whether the hybridization results in increased weedy or invasive characteristics. Sterile *M. × giganteus* is considered low risk; however, recent efforts to generate a fertile-seeded *M. × giganteus* (Ross 2011) may result in a high-risk version of this hybrid.

Distribution and historical factors

Distributional and historical factors provide clues to a species' behavior within and outside of its native range that can indicate its likelihood of escape and spread.

Species known to have invaded or become naturalized in new environments in the past are strong candidates to do so in the future (Kolar and Lodge 2001, Lockwood et al. 2001, Moyle and Marchetti 2006), even among widely varying environments (Lockwood et al. 2001). Multiple

biofuel feedstock candidate species have a history of invasiveness in the United States and elsewhere, including *Miscanthus sinensis* (Chinese silvergrass), *Arundo donax* (giant reed), *Pueraria montana* var. *lobata* (kudzu), *Phalaris arundinacea* (reed canary grass), and others (Lowe et al. 2000, Raghu et al. 2006).

Species abundance in the native range appears to predict abundance in new locations (Crawley 1987, Firn et al. 2011), suggesting that species that successfully dominate their existing habitat for any reason are often able to translate their success to other environments. This correlation is particularly strong for grasses (Firn et al. 2011), many of which are under consideration as biofuel feedstock crops due to their excellent biomass production.

Domestication history may exacerbate or mitigate invasion potential. Cultivated species with a long domestication history are often bred to reduce undesirable characteristics (Pheloung 1999, Pheloung et al. 1999) and enhance rare traits that are not necessarily successful in the wild (e.g., dwarfism, nondispersing seeds to aid in automated harvesting, loss of seed dormancy) but may reduce invasion potential (Gressel 2005, Warwick and Stewart 2005). Domestication of the candidate feedstock species *Phalaris arundinacea* (reed canarygrass) does not seem to have exacerbated invasiveness compared with undomesticated strains (Jakubowski et al. 2011). However, other traits selected for in domestication, including generalist pollination, adaptation to disturbed habitats, polyploidy, and high vegetative vigor, are shared between domesticated species, agricultural weeds (Warwick and Stewart 2005), and invasive species affecting natural areas (Daehler 1998, Rejmánek 2000, Yamashita et al. 2000, Grotkopp et al. 2002, Shea and Chesson 2002, Bradley et al. 2009, Van Kleunen et al. 2010, te Beest et al. 2011). Thus, extensive domestication may reduce or increase invasion potential depending on the characteristics selected for and the extent of selection/domestication.

Finally, species from taxa unrepresented in the native flora of the new location may also be better invaders (Rejmánek 1996, Daehler 2001, Lockwood et al. 2001, Ludsins and Wolfe 2001, but see Diez et al. 2008). Some candidate feedstock species may not have native congeners in their new location; such species could pose an enhanced risk of invasion in comparison to species with native congeners.

Environmental tolerance

Species that tolerate a broad range of environments (Williams and Black 1993, Williams et al. 1995, Durand and Goldstein 2000, Yamashita et al. 2000, Moyle and Marchetti 2006), including disturbed habitats (Yamashita et al. 2000, Shea and Chesson 2002, Bradley et al. 2009) and locations with low resource availability (e.g., marginal lands, shade; Pattison et al. 1998, Shea and Chesson 2002), are more likely to be invasive than species with limited environmental tolerance due to their ability to outcompete

other species under a variety of conditions. Biofuel proponents have suggested the use of biofuel feedstock species that tolerate a variety of growing conditions and can be grown on marginal or nonprime agricultural land in order to avoid displacement of food crops. Species selected on this basis may have increased likelihood of escape from cultivation into the environment.

Broad ecological tolerance is often due to high phenotypic plasticity (the ability to adjust physiology, resource allocation, or morphology based on local conditions), which itself is a predictor of colonizing ability (Bazzaz 1986, Gray 1986, but see Palacio-López and Gianoli 2011, Rejmánek 2011). Although recent work has questioned the ultimate fitness impact of the high plasticity of invasive species, particularly in low resource environments (Davidson et al. 2011), highly plastic species that prosper under marginal conditions may perform even better under high-resource conditions or have traits that are absent in the local flora and enable them to take advantage of marginal conditions. Thus, highly plastic crops grown on marginal lands may not stay on marginal lands. The candidate feedstock species *Miscanthus sinensis* has been shown to tolerate a wide array of soil and moisture conditions, and conditions occupied in its native range are different from those occupied in areas where it is invasive (Quinn et al. 2012), which could indicate local adaptation or high plasticity as a contributor to invasiveness. A study of *Triadica sebifera* (Chinese tallow, a potential biofuel feedstock species) indicates that invasive populations in North America have greater relative growth rate and greater allocation to aboveground biomass and leaf area than in its Asian home range (Zou et al. 2007), suggesting a flexible response to conditions in the new range that may confer an advantage over natives.

Climate change may favor species that can adapt to changes in resource availability. Some proposed biofuel feedstock species have shown an ability to invade, in part, due to their tolerance of conditions that may be found under climate change; the success of *Pennisetum setaceum* (fountain grass) in invading a variety of habitats on Hawaii has been attributed to its broad temperature tolerance (Williams and Black 1993).

Competitive ability and other interactions

Many invasive species adopt strategies to enhance their competitiveness in a variety of environments (D'Antonio and Vitousek 1992, Mack et al. 2000, Levine et al. 2003). For example, invasive species generally have higher growth rates than the native species (Grotkopp et al. 2002, Shea and Chesson 2002, Van Kleunen et al. 2010), probably due to factors previously discussed (including environmental tolerance), relief from herbivores and diseases, and unique competitive characteristics such as allelopathy. Fast growth allows a species to crowd out or shade its competitors and is considered highly desirable in bioenergy feedstock species. Plants can improve their

competitive ability and increase their potential invasiveness by investing fewer resources to construct tissues (e.g., having high leaf area per unit mass) (Williams and Black 1993, Williamson and Fitter 1996a, Pattison et al. 1998, Baruch and Goldstein 1999, Durand and Goldstein 2000, Nagel and Griffin 2001, Smith and Knapp 2001, Grotkopp et al. 2002, McDowell and Turner 2002, Maron et al. 2004) and maintaining storage tissues underground (particularly those that enable resprouting). Climbers that shade or smother other plants are likely to be invasive (Daehler 1998), as are those that form dense stands that prevent native species from co-occurring with them (e.g., the potential biofuel feedstock species *Pueraria montana* var. *lobata* [kudzu]).

Competition with native species can be influenced by other types of biotic interactions. Introduced plant species generally experience a period of very low attack from herbivores, parasites, and pathogens that may provide a competitive advantage over native species that are more heavily attacked (Schierenbeck et al. 1994, Torchin et al. 2003, Torchin and Mitchell 2004, Hawkes 2007, Blumenthal et al. 2009). Pest resistance and/or the absence of local pests generally are advantageous for biofuel feedstock species because they limit the need for pesticides and reduce the associated negative environmental effects and life-cycle greenhouse gas emissions. However, these benefits may be offset by an increased risk of invasion.

Plants may also obtain a competitive advantage by causing direct damage to other species. Species that cause damage to neighboring plants through parasitism, such as those in the genus *Striga*, are likely to be effective invaders (Mohamed et al. 2006). Allelopathic plants exude chemicals from foliage or roots that hinder the growth or germination of competitors. Introduced allelopathic plants may have a particular advantage over native species in new environments because native species may not have evolved tolerance to their allelopathic compounds (Prati and Bossdorf 2004). Furthermore, allelopathy may occur through disruption of local mutualisms, reducing performance of native species and thereby increasing the invaders' competitive success. The invasive species *Alliaria petiolata* (garlic mustard) does not utilize mycorrhizal fungi to assist nutrient uptake (which most plants do), and furthermore exudes a chemical that interferes with the mycorrhizal relationships of neighboring tree seedlings (Stinson et al. 2006), thus reducing competitor performance. Allelopathic traits are unlikely to be actively sought in biofuel feedstock species; however, some *Eucalyptus* are under consideration as biofuel feedstock species due to their rapid growth, and some *Eucalyptus* have allelopathic effects (del Moral and Muller 1970, May and Ash 1990).

Phylogenetic factors

Several meta-analyses have utilized phylogeny to identify taxa that are consistently overrepresented

among invasive species in order to utilize family or genus as a screening tool (Crawley 1987, Daehler 1998, Rejmánek 2000, Kolar and Lodge 2001). Poaceae (grasses) and Fabaceae (legumes) are overrepresented in invasive floras (Daehler 1998), as are the Brassicaceae (mustard family; e.g., *Camelina*, canola), which include a number of species that are identified as highly invasive in the United States. (Crawley 1987). A global analysis found these families to be unusually widespread, whether native or introduced (Stohlgren et al. 2011). These groups are likely overrepresented due to family-level traits that increase invasiveness, such as wind-dispersed seeds (e.g., many grasses).

The phylogenetic position of many potential biofuel feedstock species may raise invasiveness concerns, although species-level characteristics may be more important predictors of invasion than this higher level information (Diez et al. 2008). A recent meta-analysis suggested that over half of proposed biofuel feedstock species come from four highly weedy/invasive families: Euphorbiaceae (spurge family, e.g., *Jatropha curcas*), Fabaceae (including soybean, *Pongamia*, *Acacia*, and others), Myrtaceae (myrtle family, including *Eucalyptus*), and Poaceae (*Miscanthus*, switchgrass, sweet sorghum, etc.; Buddenhagen et al. 2009).

Genetic factors

High genetic variability among individuals may predict invasion success (Bazzaz 1986, Gray 1986, Rejmánek 1996) by providing the raw material for rapid evolutionary change under novel selective pressures as a result of range expansion, thus potentially enabling a species to invade (Bazzaz 1986, Badyaev and Hill 2000, Badyaev et al. 2000, Mack et al. 2000, Sakai et al. 2001, Maron et al. 2004). For example, in the proposed biofuel feedstock species *Phalaris arundinacea* (reed canary grass), enhanced genetic variation due to multiple introductions has led to enhanced plasticity, local adaptation, and invasiveness (Lavergne and Molofsky 2007). The intentional introduction of seed from multiple sources to develop crop seed stocks may increase the risk of similar genetic changes in other biofuel feedstock species.

Chromosomal duplication (polyploidy), a common event in plants that can result in rapid changes in species physiology, morphology, and ecology, including colonizing ability, and can mask the expression of detrimental traits, may be related to invasiveness (Pandit et al. 2011, te Beest et al. 2011). A meta-analysis of 81 invasive species and over 2300 congeners (species in the same genera as the invaders) indicated that polyploid species or populations of a species are more likely than diploid species to be invasive, whereas species that are diploid are more likely to be endangered (Pandit et al. 2011). Comparisons of native and invasive populations of the same species with existing variation in ploidy levels in both locations show that invasive populations are more likely to be dominated by variants with higher ploidy

levels (te Beest et al. 2011). Polyploidy is not specifically sought in biofuel feedstock crops, but is easily measured and could be used in screening potential feedstock species.

Cultivation of genetically modified biofuel feedstock species may pose unique invasion risks. Genetically engineered (GE) organisms are not necessarily more likely to escape cultivation than nonmodified organisms, as many of the traits engineered into crop species facilitate success in cultivation (e.g., herbicide resistance) rather than enhancing likelihood of escape into natural areas. Traits that may increase invasiveness potential, such as resistance to pests or pathogens, are already accounted for as predictors of invasion (see Table 1). Therefore, genetic engineering per se does not predict invasiveness, although it may influence other predictive traits. GE crop use may also exacerbate the risk of invasiveness in co-occurring species, as transfer of or selection for traits such as herbicide resistance may confer advantages on weedy species that may prevent effective control in natural areas (Cerdeira and Duke 2006), resulting in a novel invasion risk. For example, the extensive, low-intensity use of herbicides on herbicide resistant GE crops has resulted in selection for herbicide resistance in the weed *Sorghum halapense* in Argentina (Binimelis et al. 2009). On the other hand, GE seed stocks tend to be more pure than naturally collected seed and may therefore reduce the unintentional introduction of contaminant seeds that may cause new invasions (Cerdeira and Duke 2006). Nevertheless, GE crops may warrant detailed assessment for invasion risk that may go beyond application of WRA tools (Koop et al. 2012) to avoid causing or exacerbating the spread or impacts of invasive species.

Ecosystem characteristics

No species can invade a new location unless it can tolerate and thrive in the new environment. In addition to the ability of a species to respond to disturbance and tolerate a range of environmental conditions, characteristics of recipient ecosystems (including but not limited to diversity, disturbance regime, and climate) and their compatibility with the needs of a given introduced species strongly affect invasion risk.

Ecologists have long theorized that highly diverse ecosystems are less easily invaded than disturbed ecosystems due to high competition for resources and space among established natives (e.g., Elton 1958, Kennedy et al. 2002). Plant community invasibility is affected by both disturbance regime and the availability of bare ground (resources) on which new plants can establish (Crawley 1987). On the other hand, a number of highly diverse communities have been found to be vulnerable to invasion (Lonsdale 1999, Levine 2000, Lyons and Schwartz 2001, Moyle and Marchetti 2006, Stohlgren et al. 2011), although this may depend on the individual species that are present (van Ruijven et al. 2003). In addition, time since introduction may play an

important role in the perceived relationship between abundance of invaders (invasion success) and native species diversity; invaders may do well right after disturbance, followed by an increase in native species diversity (Clark and Johnston 2011). Thus, disturbance regime and species diversity may influence the ability of a new species to escape and invade a given location.

Cultivation intentionally lowers ecosystem resistance to localized invasion of crop species: crops are inherently introduced to locations with compatible climatic conditions, soils, possibly limited pests and pathogens, and other factors, thus overcoming ecosystem barriers to invasion (Richardson and Blanchard 2011). Biofuel feedstock species will be grown as crops and thus are likely to successfully establish within cultivation sites. The use of diversity and disturbance regime to predict escape from cultivation and potential invasion by biofuel feedstock species is difficult due to the scale of intentional introduction and the mosaic of habitats and disturbance regimes that the species may encounter in habitats surrounding cultivation sites.

USE OF INVASIVENESS PREDICTORS IN PRE-INTRODUCTION WEED RISK ASSESSMENT

In practice, prediction of invasiveness is difficult because species have numerous traits that enhance or reduce the risk that they will become invasive and because local environmental conditions may influence species behavior. However, the retroactive definition of important traits associated with invasive species described in the previous section has enabled development of effective tools to assess invasion risk proactively (e.g., Pheloung et al. 1999, Daehler and Carino 2000, Stohlgren and Schnase 2006, Parker et al. 2007, Koop et al. 2012). These tools were first developed and continue to be used to apply scientific knowledge to decisions about whether and under what conditions importation of nonnative plant species should be allowed (Pheloung et al. 1999). Limits on importation are likely to be the most effective tools for preventing the introduction or spread of invasive species, and in fact have been shown to produce net economic benefits (Keller et al. 2006). These tools can be used to formally and consistently predict invasion risk associated with biofuel feedstock species and thereby reduce the risks of the industry as a whole. Biofuel producers can proactively use WRA tools to inform feedstock crop selection and select low-risk feedstock species that minimize the environmental and economic issues associated with cultivation of potential invasive species.

The Australian WRA tool (Pheloung et al. 1999) is the most widely used system for predicting invasive species from among a pool of already established introduced species due to its accuracy and ease of use. It categorizes species for rejection, acceptance, or further study based on the answers to 49 questions about species-specific, climate matching, and other traits (Pheloung et al. 1999; included predictors are summarized in Table 1). The

major categories of criteria are domestication/cultivation history, climate and distribution, history of weediness, undesirable traits (e.g., toxicity, spines), plant type, reproductive traits, dispersal, and likelihood of persistence. The answers to these questions result in a single numerical score that is used to categorize species as accept (≤ 0), evaluate further (1–6), or reject (> 6).

The majority of the criteria in the Australian WRA are species specific rather than Australia specific, and therefore, the tool is readily adapted to other locations. Only Section 2 (climate and distribution), and questions 4.10 (grows on infertile soils as found in Australia) and 8.05 (effective natural enemies present in Australia) need to be modified in order to use the tool in other ecosystems.

The Australian WRA model has been applied extensively to determine whether to allow importation of introduced species and potential introductions in Australia (Australia Quarantine and Inspection Service 2011) with rejection of 84% of existing major and minor weeds (of those rejected by expert opinion without use of the WRA) and only 7% of non-weeds rejected. Nearly one-third of species (29%) fell into the evaluate further category. This same model has also been tested and found to be effective (with slight modifications) in New Zealand (rejected 93% of species categorized as weeds by expert opinion; Pheloung et al. 1999).

Further refinements and modifications have been undertaken to improve the accuracy and utility of the Australian WRA and adapt it for regions outside of Australia. These include changes to adjust for local habitat matching (Daehler and Carino 2000). The Australian WRA has been adapted by researchers for use in the Pacific Islands (Daehler et al. 2004; Hawaii-Pacific Weed Risk Assessment System, *available online*)⁵ and the continental United States (Gordon et al. 2008b, 2011; also see footnote 4), as well as in Japan (Nishida et al. 2008) and the Mediterranean region (Crosti et al. 2010, Gassó et al. 2010). Daehler et al. (2004) developed a secondary decision tree for Hawaii and the Pacific Islands that assesses species that fall into the evaluate further category under the modified Australia WRA in order to accurately move those species into the accept or reject categories. This added component rejects trees and tall shrubs that are shade tolerant and form dense stands, are clearly bird or wind dispersed, and have a short generation time (less than four years). Herbaceous species or low shrubs are rejected if they are reported agricultural weeds and are unpalatable to grazers or known to form dense stands. Davis et al. (2010) suggest that secondary screening may be important for species qualifying for accept, as well as evaluate further, in order to reduce the potential for accepting a highly invasive species; their proposed follow-up screens include postintroduction quarantine cultivation trials and monitoring. Two different metastudies have found

that the Australian WRA is an effective screening tool across geographic regions (with adaptations for climate matching and the other geography-specific questions highlighted above) and suggest that Australian WRA species evaluations from one location can be used with reasonable confidence for other areas with similar climate (Gordon et al. 2008a, Chong et al. 2011), although the cross-regional correlation is more accurate for major invaders than minor (Gordon et al. 2008a).

The Australian WRA heavily weights aquatic organisms as likely invaders (Pheloung et al. 1999) because there are so many existing, successful aquatic invaders, but some modifications have been proposed that reduce the bias against aquatic species (Gordon and Gantz 2011). New Zealand has created an analogous risk assessment framework for aquatic plants that has been modified for the United States and found to be 91% accurate (Gordon et al. 2012). While this paper only discusses terrestrial species, the potential for algal and other proposed aquatic biofuel crops (e.g., duckweed, water hyacinth) to become invasive will need to be addressed in future analyses for the same reason.

In addition to adaptations for local environmental conditions and secondary screening, efforts have been made to adjust the scoring methodology to better reflect existing risk management approaches. Daehler and Virtue (2010) utilized a standard risk assessment model structure, grouping the Hawaii-adapted Australian WRA criteria into two categories, risk of introduction and impacts (likelihood and consequences in risk assessment terms), and using a multiplicative model to improve the accuracy (up to 91% rejection of weeds). These adaptations/expansions of the Australian WRA incorporate the Australian WRA criteria by reference or explicitly and therefore are not included in Table 1.

The Australian WRA system is simple to use and aims to use as little subjective evaluation as possible. However, expert users may still disagree on important scoring traits (Pheloung et al. 1999, Davis et al. 2010); thus detailed justifications for scoring should be incorporated into WRAs. The Australian government uses the system to determine whether to allow importation of particular plant species and what, if any, conditions may be required for importation to occur. The system is consistent with the International Plant Protection Convention (IPPC; IPPC 1997) and the Agreement on the Application of Sanitary and Phytosanitary Measures (SPS Agreement, part of the General Agreement on Tariffs and Trade; WTO 1994), which call on signatories to protect plant resources from the spread of pests while minimizing interference with international trade (Campbell 2001, Schrader and Unger 2003).

USDA developed its own weed-initiated pest risk assessment (PRA) methodology (APHIS 2004) intended to comply with international law governing restrictions on trade. PRA is a broad term intended to encompass potential insect pests and other organisms; USDA weed-initiated PRA is a WRA methodology focusing on

⁵ www.hpwra.org

TABLE 1. Identified predictors of invasiveness in introduced species, their incorporation in four Weed Risk Assessment models, and whether the characteristic is sought in new biofuel feedstock crops.

Predictor	References	Australia (Pheloung et al. 1999)	USDA (APHIS 2004)	USDA (Koop et al. 2011)	Parker et al. (2007)	Sought in biofuel feedstocks
Reproductive traits						
High/generalized propagule dispersal	1, 2	X	X	X	X	
High propagule production	3, 4, 5	X	X	X	X	X
Vegetative reproduction/spread	1, 2, 4, 6	X	X		X	
Dormancy/seed bank formation	2	X	X	X	X	
Short generation times	1, 7, 2	X	X	X		X
Self-compatible		X		X		
Hybridization	8, 9	X				
Seed size	1, 7, 10, 11, 12				X	
Distribution and historical factors						
Weedy/invasive behavior (agricultural or natural settings, locally or elsewhere)	4, 13, 5	X	X		X	
Congener invasive (locally or elsewhere)		X	X	X		
Weedy relatives	6	X	X	X		
Domestication history	3	X		X	X	
Naturalized (locally or elsewhere)	4, 5	X		X		
Abundance/dominance in home range	14, 3, 15		X			
Novel taxon in new range	1, 3, 13					
Environmental tolerance						
Tolerates marginal lands/low resource availability	16, 17	X	X		X	X
Preadapted to climate/habitats	1, 5	X	X	X	X	X
Broad environmental tolerance	18, 19, 20, 21, 5	X	X	X	X	X
Tolerates disturbance	9, 22, 2, 23	X	X	X		X
Aquatic		X	X	X		
Takes advantage of resource pulses/changes/climate change	21, 17, 24				X	
Phenotypic plasticity	25, 26, 27, 28, 19, 1, 2, 21, 29					
Low construction cost tissues (e.g., high specific leaf area)	18, 3, 16, 30, 20, 31, 32, 11, 33, 34, 35 (but see 20)					
Growth habit						
Storage tissues underground		X	X			X
Climbing/smothering growth habit	6	X		X	X	
Novel community structure component			X	X	X	
Competition/defense						
Rapid growth rate	11, 17, 23	X	X			X
Highly competitive for resources	36, 9, 37	implied			X	X
Forms dense stands	14	X		X		
Biotic interactions						
Escape from herbivores	38, 39, 40, 30, 41, 42, 43	X	X		X	X
Escape from parasites	44, 45	X	X			X
Escape from pathogens	46, 43, 47	X	X			X
Allelopathy	48, 49, 50, 51 (but see also 52, 53, 54)	X	X	X		
Parasitic	55	X	X	X		
Host (vector) for pests/pathogens		X		implied	X	
Disruption of ecosystem resource availability	56, 57, 58		X		X	
Independence from mutualists	6, 2, 59 (but see also 60, 61)	X		X		X
Disruption of local mutualism	62, 59				X	
Phylogenetic factors						
Phylogenetic factors	7, 6, 4, 13					
Poaceae (grasses)	6, 13	X		X	X	X
Fabaceae (legumes)	6	X		X	X	
Related to GE crop					X	
Other concerns						
Toxic/allergenic to humans		X	X		X	
Toxic to local herbivores		X		X	X	

TABLE 1. Continued.

Predictor	References	Australia (Pheloung et al. 1999)	USDA (APHIS 2004)	USDA (Koop et al. 2011)	Parker et al. (2007)	Sought in biofuel feedstocks
Increases fire risk	(reviewed in 36)	X		X	X	
Thorns/spines/burrs		X			X	
Genetic factors						
High genetic variability	26, 27, 1, 29					
Rapid evolutionary change	26, 63, 64, 9, 65, 34, 29					
Ploidy level	66					

Sources: 1, Rejmánek (1996); 2, Rejmánek (2000); 3, Williamson and Fitter (1996a); 4, Kolar and Lodge (2001); 5, Moyle and Marchetti (2006); 6, Daehler (1998); 7, Rejmánek and Richardson (1996); 8, Ellstrand and Schierenbeck (2000); 9, Mack et al. (2000); 10, Gerlach (2001 and refs.); 11, Grotkopp et al. (2002); 12, Stohlgren et al. (2011); 13, Lockwood et al. (2001); 14, Crawley (1987); 15, Firn et al. (2011); 16, Pattison et al. (1998); 17, Shea and Chesson (2002); 18, Williams and Black (1993); 19, Williams et al. (1995); 20, Durand and Goldstein (2000); 21, Yamashita et al. (2000); 22, Radford and Cousens (2000); 23, Van Kleunen et al. (2010); 24, Bradley et al. (2009); 25, Lewontin (1965); 26, Bazzaz (1986); 27, Gray (1986); 28, Scheiner and Teeri (1986); 29, Lavergne and Molofsky (2007); 30, Baruch and Goldstein (1999); 31, Nagel and Griffin (2001); 32, Smith and Knapp (2001); 33, McDowell and Turner (2002); 34, Maron et al. (2004); 35, Leishman et al. (2007); 36, D'Antonio and Vitousek (1992); 37, Levine et al. (2003); 38, Elton (1958); 39, Schierenbeck et al. (1994); 40, Blossey and Notzold (1995); 41, Keane and Crawley (2002); 42, Wolfe (2002); 43, Hawkes (2007); 44, Torchin et al. (2003); 45, Torchin and Mitchell (2004); 46, Mitchell and Power (2003); 47, Blumenthal et al. (2009); 48, Bais et al. (2003); 49, Weir et al. (2003); 50, Thelen et al. (2005); 51, Abhilasha et al. (2008); 52, Prati and Bosdorf (2004); 53, Blair et al. (2006); 54, Duke et al. (2009); 55, Mohamed et al. (2006); 56, Busch and Smith (1995); 57, Gordon (1998); 58, Mack and D'Antonio (2003); 59, Stinson et al. (2006); 60, Vitousek et al. (1987); 61, White and Backhouse (2007); 62, Christian (2001); 63, Badyaev and Hill (2000); 64, Badyaev et al. (2000); 65, Sakai et al. (2001); 66, Pandit et al. (2011).

potential plant invaders. USDA's weed-initiated PRA took into account many of the same predictors as the Australian WRA, but was more qualitative and required more subjective evaluation by the user. Most recently, USDA developed a new WRA tool that incorporates questions from the Australian WRA as well as from other tools and sources (Koop et al. 2012). Like other WRA systems, the new USDA tool groups traits associated with establishment/spread or impact. However, this tool also incorporates Monte Carlo simulations to test how likely it would be that the outcome of the analysis would change if the answers to questions for which there is high uncertainty (i.e., little data) were different. This approach allows the user to see how robust the analysis is by identifying confidence intervals for the results (Plant Epidemiology and Risk Analysis Laboratory 2012). The tool also estimates extent of potential range in the United States based on general ecological information about precipitation, general climate classification, and tolerance of minimum winter temperatures (Plant Epidemiology and Risk Analysis Laboratory 2012).

In a direct comparison with the Australian WRA (adapted for the United States), this tool shows a similar level of rejection of major invaders and improved acceptance of non-invaders. The predictors utilized by the original USDA PRA tool and the new tool are identified in Table 1. The USDA intends to use the new tool as "the first in a series of defenses against invasive species" (Koop et al. 2012), by enabling rapid screening of invasion risk to inform and feed into regulatory processes (see *Regulation of harmful plant species*).

Another quantitative, likelihood-by-consequences multiplicative model to assess weeds for the United States as a whole was developed by Parker et al. (2007).

This tool categorizes predictors into four major groups: invasiveness potential (based on weediness/invasiveness history, reproductive traits, palatability, and responsiveness to and tolerance of environmental conditions), geographic/climate matching potential, entry potential, and impacts potential. Scoring is based on individual species predictors within each category, and the resulting scores are multiplied to arrive at the final score. Species are then ranked by score rather than categorized as accept/reject/evaluate. The predictors incorporated into this tool are indicated in Table 1.

Other weed risk assessment tools have been developed for use at the state and local level. In Indiana, for example, the Invasive Plant Species Assessment Working Group has developed a weed risk assessment protocol that specifically focuses on current impact, rate of spread, introduction history, and habitat matching for the state. It also covers many of the same biological predictors of invasion as the Australian WRA, including reproductive characteristics, competitive ability, and formation of a seed bank. Application of this tool to various introduced species in Indiana can be found online (Indiana Department of Natural Resources 2011), but has no regulatory implications. Likewise, Alaska's Natural Heritage Program utilizes a WRA form that covers many of the same predictors as the Australian WRA (Carlson et al. 2008, Alaska Natural Heritage Program 2011) and is used to rank invasiveness potential in Alaska on a scale of 0 to 100, but does not have a direct linkage to legal requirements.

The specific criteria from the scientific literature that are incorporated into several of the WRA tools described previously are shown in Table 1, as well as whether the trait is actively sought in biofuel feedstock species. The Australian WRA system has been the most

widely used tool to date, particularly for the assessment of potential biofuel feedstock species, and therefore the following discussion of weed risk assessments relevant to biofuels focuses on application of the Australian WRA system to biofuel feedstock species.

Of the seven most commonly used indicators (appearing in all four screening tools), four of the criteria (high seed/propagule production, short generation time, broad environmental tolerance, and preadaptation to a given climatic region) are traits that are also sought in biofuel feedstock species. Of additional traits found in three screening tools, two (escape from herbivores and tolerance of marginal lands) are sought in biofuel feedstock species. Only one predictor commonly sought in biofuel feedstock species is not explicitly incorporated in the Australian WRA: high competitive ability. However, this predictor is implied in some of the Australian WRA criteria, such as questions in Section 3 on weediness. Climate matching is a key component of most WRA systems (but see Koop et al. 2012), because a species introduced into challenging conditions may have limited invasion opportunities. As crop species, biofuel feedstock species will inherently be introduced to favorable locations. Therefore, climate matching may be of limited predictive use in the case of an intentionally introduced feedstock species.

Domestication history is utilized in different ways in three WRA tools. Extensive domestication is considered a low-risk trait for the purposes of the Australian WRA and the new USDA PRA because crops are assumed to be selected for nonweedy traits (Pheloung 1999, Koop et al. 2012). However, due to high propagule pressure as a result of high reproduction and repeated introductions (Williamson and Fitter 1996a), Parker et al. score weedy species already in cultivation as more likely to become invasive (Parker et al. 2007). Only the original, qualitative USDA tool currently considers abundance in the home range as a predictor in its scoring system.

These WRA tools incorporate a subset of the traits that have been identified to predict invasiveness, and they focus on criteria that are easily evaluated in advance of introduction. Table 1 lists additional predictors that may be incorporated into predictive tools in the future. Plasticity and resource allocation flexibility are not addressed explicitly in these four WRA tools, although they may be implied by the inclusion of broad environmental tolerance. The ability to respond to changes in resource availability due to climate change is specifically used as a predictor in the Parker WRA model but not in the other tools. Relatedness to GE crops may be a predictor because of the risk of receiving transgenes that facilitate invasion or hinder control efforts, but this characteristic has not been incorporated into any of these WRA tools and may require more detailed case-by-case risk assessment based on the GE traits involved and the potential for outcrossing with related species. Ecosystem disturbance regime and diversity level relationships are difficult to assess unless

the assessment is focused on a very small area and are likewise not included in the WRA tools covered here. Thus, there are traits that may be considered voluntarily during feedstock species selection and/or that may be accommodated in voluntary best practices during cultivation that may not currently enter into formal weed risk assessment.

USE OF WRA TOOLS TO PREDICT INVASION BY BIOFUEL FEEDSTOCK SPECIES

Due to growing concern about the potential for introduction and spread of invasive species as a result of biofuel feedstock production, a number of recent studies have used the Australian WRA (adapted to the United States or Europe, with or without refinements) to evaluate the invasive potential of biofuel feedstock species (Daehler and Carino 2000, Barney and DiTomaso 2008, Crosti et al. 2008, 2010, Gordon et al. 2008b, 2011, Nishida et al. 2008, Buddenhagen et al. 2009, Davis et al. 2010, 2011b, Gassó et al. 2010, McClay et al. 2010; also see footnote 4). In all, 64 species identified by researchers to be under consideration as biofuel feedstock crops have been evaluated at least once using the Australian WRA framework, but very few have been analyzed with the other tools to date; therefore, this synthesis focuses on evaluations using the Australian WRA. The categorizations, accept, reject, and evaluate, are shown for each species in Fig. 1. The studies incorporated into Fig. 1 cover a variety of geographic regions, including the United States as a whole, Hawaii and the Pacific Islands, Florida, Italy, and Japan, as previous studies have suggested that Australian WRA evaluations are accurate among regions with similar climates (Gordon et al. 2008a, Chong et al. 2011).

Assessment resulted in reject in at least one instance for 44 of the 64 considered species, while 15 species had at least one accept evaluation (including species conditionally accepted following an initial assessment of evaluate; Fig. 1 lists the original evaluate score for these species). The assessments differ on specific scoring decisions, but rarely on outcomes. For eight species, assessors disagree on the appropriate outcome; all of these disagreements entail evaluate outcomes contrasting with outright reject or accept outcomes. For one species, *Panicum virgatum* (switchgrass), assessments result in reject and conditional accept after evaluation. Of the potential biofuel feedstock species considered herein, 69% have at least one reject score, which is consistent with Buddenhagen et al. (2009), who compared WRA scores of 40 potential biofuel feedstock species and 40 other, randomly selected introduced species and found that the biofuel feedstock species scored significantly higher (statistically more likely to be invasive) than the other introduced species. These results demonstrate the invasion potential of a wide range of biomass feedstocks and the need to assess risk of invasiveness.



FIG. 1. Results of Australian Weed Risk Assessment (WRA) application to various biofuel feedstocks. Blue lines indicate the transition between categories (≤ 0 means accept, 1–6 means evaluate, >6 means reject). For HPWRA, see footnote 5.

POSTINTRODUCTION SPECIES ESCAPE AND SPREAD

Even with the use of WRA to screen potential bioenergy feedstock crops, it is impossible to totally eliminate the risk of introducing a problematic invasive species. The postintroduction risk of invasion involves the combined probability of escape, spread, and resulting harm (Hails and Timms-Wilson 2007).

Once a feedstock species has been selected and introduced to a new location for cultivation, escape from cultivation can occur as a result of normal seed dispersal or pollen outcrossing or as a result of specific

cultivation activities. For example, the transport of intact seeds or regenerative plant fragments from the point of harvest to the point of processing may unintentionally result in dispersal to new locations along the transport route or at the point of unloading at the processing facility. Furthermore, the movement of vehicles to and from the area of cultivation may result in inadvertent transport of plant propagules in mud on vehicle tire treads or other unintended mechanisms. Other human-related sources of accidental transport include hitchhiking (Stohlgren et al. 2011), such as on worker clothing or domesticated animals.

Vegetative propagule dispersal can result from damage to plants capable of regenerating from fragments of root or stem (e.g., *Arundo donax*) or, for example, underground or surface spreading of clonal species that are able to resprout outside cultivated areas (e.g., *Populus* species and many grasses). In addition, the spread of genetic material from an introduced species can occur via pollen dispersal and successful hybridization with related species in the surrounding environment, although the associated likelihood of resulting invasion is related to the frequency and fitness of hybrids (Hails and Timms-Wilson 2007).

These escape routes can result in the establishment of naturalized populations of the plant that can form the nucleus for spread into other areas. Each of these mechanisms for escape poses concerns that can be at least partially mitigated through active risk management. In the biofuel context, seedlings of some biofuel feedstock candidates with high scores on WRA assessments have been observed to have escaped from bioenergy planting areas in Hawaii, leading the authors to recommend implementation of mitigation practices to minimize invasion risk associated with cultivation of these species (Daehler et al. 2012).

Once escape occurs, the next phase of invasion is spread from the initial point of establishment. Many species experience a delay, or lag phase, between introduction and invasion (Nuzzo 1993, Kowarik 1995, Mack et al. 2000). This delay may represent a period of cryptic (undetected) spread of the species (Carey 1996) or may reflect when suitable conditions become available for spread (Mack et al. 2000). During this lag phase, detecting incipient invasions is difficult because the escape may be comprised of a few, small individuals in a few suitable locations (Carey 1996). Once the lag phase ends, invasion tends to occur in a stream along paths of suitable habitat rather than uniform spread outward from a single or several points (Carey 1996). Knowledge of pathways for dispersal and spread can inform best management practices to minimize likelihood of dispersal and improve monitoring and containment efforts.

MANAGING INVASION RISKS THROUGH VOLUNTARY BEST PRACTICES

Many industries use voluntary best practices to minimize risk of environmental damage, and there are many sources for identifying best management practices (BMPs) to reduce the risks of selecting or cultivating a species at high risk of becoming invasive. IUCN has created BMPs for feedstock species selection and cultivation that apply to both governments and growers, and include the use of WRA (IUCN 2009). The United States has included many of the IUCN's government-related BMPs in the National Invasive Species Management Plan (NISMP).

Preventing the introduction of invasive species is the easiest and most cost-effective strategy for reducing the

environmental and economic impacts of invasive species (NISC 2008). Prevention can occur in the biofuel context by screening potential nonnative feedstock species for invasion risk prior to introduction and excluding those that present a high risk. The IUCN BMPs provide guidance for governmental management of biofuel feedstock species risks, including strategic guidance on species selection and regulatory requirements for nonnative species introductions. For growers, the BMPs involve prospective analysis of potential environmental impacts of the introduced species (Environmental Impact Assessment or EIA), including a detailed WRA of the proposed feedstock species. Both the WRA and the EIA can identify potential sources of harm from the species under consideration or assure the producer, regulators, and potential fuel purchasers that the feedstock species is low risk. The IUCN best practices relevant to pre-importation decision making for nonnative species are summarized in Box 1.

NISMP recommendations also include incorporation of WRA into screening processes and enhancement of quarantine and phytosanitary measures in accordance with the IPPC, the North American Plant Protection Organization, and other programs (NISC 2008). The NISMP also recommends the development of additional BMPs by stakeholders, thereby suggesting the use of BMPs created by IUCN or other groups within the United States (NISC 2008). These NISMP elements indicate the intention to enhance consistency between U.S. policy and internationally recognized BMPs.

WRA is also incorporated into other voluntary management systems, including the sustainability criteria created by the Roundtable on Sustainable Biofuels (RSB; Roundtable on Sustainable Biofuels 2010). RSB's sustainability criterion 7.e requires that "biofuel operations shall prevent invasive species from invading areas outside the operation site." Strategies proposed by RSB for fulfilling this criterion include not selecting known invaders as feedstock crops, using WRA during the selection of a new feedstock species without invasion history, and following monitoring, containment, and mitigation best practices consistent with those put forth by the IUCN.

The use of WRA to identify and select low risk species may help feedstock producers to minimize reliance on other BMPs to prevent invasion during cultivation and processing. Species categorized as evaluate further by the WRA or that are introduced despite conclusions of reject or high risk need to be monitored to ensure that they do not escape and spread, and even some species that are scored as accept may warrant further evaluation after introduction (Davis et al. 2010). Postintroduction management practices and related policy interventions may provide additional protection to enable early detection and to prevent the spread of crops that prove invasive after introduction.

Early detection and rapid response practices have been defined to reduce the risks of invasive species

Box 1. Summary of IUCN Best Management Practices (BMPs)[†]

Pre-importation prevention BMPs

Government-related practices

- Strategic environmental assessment to plan regional/national biofuel feedstock strategy.
- Robust quarantine requirements in effect and enforced.
- Monitor biofuel industry for compliance with relevant importation regulations.
- Cost benefit analysis for species introduction, including potential costs of invasion, introduction of pests/diseases.

Feedstock-producer-related practices

- Perform weed risk assessment (WRA), considering ecological boundaries, as well as political ones.
- Environmental Impact Assessment document that includes potential costs of control, WRA.
- Support and comply with mandatory and voluntary quarantine and importation best practices.
- Possible certification for WRA and selection of noninvasive species (e.g., sustainability criteria from Roundtable on Sustainable Biofuels).

Cultivation BMPs

Government-related practices

- Promote projects with local conversion of feedstocks.
- Monitor movement of high-risk feedstocks within country.
- Develop communication and education programs for transporters and other supply chain participants to promote monitoring and awareness.

Feedstock-producer-related practices

- Produce third-party-audited Environmental Management Plan to outline use of BMPs.
- Develop and implement monitoring system to check for escape, pests, and pathogens.
- Utilize buffer zones and wildlife corridors.
- Utilize zero-till planting to reduce disturbance and open soil.
- Plant indicator species that may warn of pest problems.
- Maintain soil health through crop rotation or mixed cropping.
- Use fencing and other barriers to prevent animal vectoring of seed, propagules, pests, etc.
- Consider use of biological control agents to reduce spread.
- Harvest cellulosic biomass prior to seed/fruit set.
- Use sterile or low-fertility varieties.
- Find, identify, and control escapees.
- Convert feedstocks on or near production site.
- Site nurseries near plantations.
- Monitoring plan for vehicles to prevent spread of seed, propagules, pests, etc.
- Monitor transport corridors for escape and spread of species.
- Regular monitoring, cleaning of harvest/transport vehicles.
- Utilize polluter pays strategy.[‡]
- Surety bonding (financial assurance requirements) for eradication/clean up.[†]

[†] IUCN 2009.

[‡] These practices address eradication, containment, management, or restoration. All other cultivation BMPs address monitoring and/or on-site prevention.

escape and spread (e.g., NISC 2003), as have BMPs for crop cultivation and management. Voluntary measures have been ineffective in other contexts in the absence of legal requirements, and commentators have argued that voluntary BMPs alone are unlikely to prevent biofuel-mediated invasions, as BMPs impose costs, and the likelihood of financial penalties for the source of an escaped species is low (Low et al. 2011). However, some legal provisions mandate the use of BMPs, which may increase their adoption, effective implementation, and industry-wide acceptance.

The IUCN best practices (IUCN 2009) include BMPs for cultivation of bioenergy crops in order to reduce the likelihood of escape and spread. Many of these practices are also incorporated into the RSB Sustainability Criterion 7.e and are recommended by research studies (Barney and DiTomaso 2008, Davis et al. 2010, Byrne and Stone 2011, Lonsdale and Fitzgibbon 2011). Best practices for prevention of escape focus on seed/propagule production and dispersal. Several authors recommend the use of quarantined field trials similar to those used for transgenic crops (Barney and DiTomaso 2008, Davis et al. 2010, Lonsdale and Fitzgibbon 2011),

and some suggest using trials to develop management guidance for each species (Barney and DiTomaso 2008, Byrne and Stone 2011). Lonsdale and Fitzgibbon (2011) suggest more specific management measures that include slowly scaling up plantings of novel species, monitoring, preventing reproduction, and requiring the use of buffer zones around plantings, with additional monitoring beyond the buffer zones. Buffer zones around crop plantings inhibit seed dispersal and facilitate the detection of escaped crop offspring or associated pests (through the use of indicator species; IUCN 2009, Lonsdale and Fitzgibbon 2011). Other IUCN strategies for limiting invasive species establishment and spread include low-/no-till cultivation and fencing and other barriers to reduce seed/propagule dispersal (IUCN 2009; see Box 1). Similar management measures are likely to be included in any management plan calling for site hygiene (e.g., Byrne and Stone 2011). Because natural seed dispersal may be difficult to control once seeds mature (as in wind-dispersed grass species, such as *Miscanthus*), harvesting prior to seed set is considered a best practice for cellulosic biomass crops to prevent escape from cultivation (IUCN 2009); however, this best practice cannot be applied to oilseed crops for which the mature seed is the feedstock source. For such crops, IUCN best practices call for minimizing transport of intact seeds (e.g., from oilseed crops) or other potentially regenerative propagules, including transport routes as well as cultivation sites, in monitoring plans and maintaining and cleaning vehicles to prevent accidental dispersal of propagules (IUCN 2009).

Rapid response to escaped organisms requires proactive detection techniques. Although monitoring may require resources, the investment is likely to be worthwhile, as early detection of escape can substantially reduce eradication costs (Rejmánek and Pitcairn 2002). A model monitoring program encompasses the entire zone of intact propagule use, including nurseries, fields, transport routes, and initial processing sites. Early detection best practices promote the use of both active and passive detection networks (by responsible parties and by organizations or individuals that may fortuitously detect escaped organisms, respectively) and robust knowledge management techniques (e.g., data sharing, training for monitoring and detection, and learning from past experiences; NISC 2003). Carey suggested that detection of new invasions is hindered by the assumption of random dispersal/concentric spread (Carey 1996). Using knowledge of ecological compatibility may enable a feedstock producer to better focus its own monitoring efforts toward likely habitats for establishment of escaped individuals near the sites of crop activities. Monitoring efforts should take into account habitat specificity as well as dispersal pathways.

Upon detection of an escape from cultivation into the environment, a response strategy is needed. Rapid assessment of the extent of spread, selection among potential actions, and rapid response, supported by

advance preparation such as personnel training and availability, response manuals and action plans, and funding availability, are critical to the success of postescape control efforts, as elaborated in the National Invasive Species Council (NISC) guidelines for EDRR (NISC 2003). Immediate eradication is the most effective action to prevent establishment or spread, particularly when the area the species initially colonized is small (Rejmánek and Pitcairn 2002). Barney and DiTomaso (2008) suggest requiring proactive management plans to provide for complete eradication of feedstock species should they prove invasive. However, once spread has begun, containment and mitigation may be the only options to manage the potential harm caused by an incipient invader (Rejmánek and Pitcairn 2002). The main best practice (and incentive for other BMP use) is to establish a contingency fund to cover costs associated with any mitigation or control efforts resulting from cultivation of the bioenergy crop (IUCN 2009).

REGULATIONS, POLICIES, AND INCENTIVES RELATING TO THE POTENTIAL INTRODUCTION OF NOVEL FEEDSTOCK SPECIES AND RISK OF INVASION

While voluntary measures are important, regulatory systems also play an important role in preventing harm from invasive species. We review key elements of the complex and interwoven system of federal and state laws, as well as regulations governing and providing incentives for bioenergy cultivation, to identify where and how they restrict the importation or cultivation of invasive or potentially invasive species.

Federal agencies are required to consider and avoid the introduction and spread of invasive species in the United States. Executive Order 13112 requires agencies to manage how their actions may affect the introduction and spread of invasive species, regardless of taxon, habitat, or type of impacts. To comply with the Order, federal agencies must identify actions that “may affect the status of invasive species,” and they cannot authorize, fund, or carry out discretionary actions likely to cause or promote the introduction or spread of invasive species without first determining that the benefits clearly outweigh the potential harm and taking “all feasible and prudent measures” to minimize the risks, with exceptions for national security (Executive Order 13112 1999).

The NISC (established by Executive Order 13112) and its associated Invasive Species Advisory Committee (ISAC) have identified biofuel feedstock species screening as an important agency responsibility. The most recent NISMP calls for the development of screening processes to evaluate the invasiveness of plants moving in international trade (NISC 2008). ISAC’s 2009 white paper (ISAC 2009) identified actions specifically related to biofuels that may “cause or promote the introduction or spread of invasive species,” and it calls upon agencies to evaluate biofuel feedstock species invasiveness and to use and promote genotypes and cultivars that are

unlikely to escape from cultivation, become established in the environment, or become invasive (ISAC 2009). Development and implementation of the new USDA WRA tool is a substantial step forward to meeting the goal set out in the NISMP and for enabling agencies, including but not limited to USDA, to assess feedstock species invasion risk and promote low-risk feedstock species. Regarding postintroduction invasion and spread, some agencies, such as the Federal Highway Administration, have created guidance to enhance detection of invasive species and limit their spread (Federal Highway Administration 2006); however, no federal agencies have created guidance to date specifically to address the invasion risks associated with biofuel feedstock crop cultivation.

Regulation of harmful plant species

Federal and state agriculture and weed laws are the most applicable to biofuel cultivation, as these laws limit plant importation, transportation, and cultivation, including for biofuel feedstock species. The Department of Agriculture (USDA) primarily regulates harmful plants under two laws that authorize regulation of noxious weed species. The Plant Protection Act (PPA; Plant Protection Act 2011) authorizes USDA to prohibit or restrict importation, exportation, and interstate movement of plants, plant products, certain biological control organisms, noxious weeds, and plant pests if necessary to prevent the introduction into the United States or the dissemination of a plant pest or noxious weed within the United States. The Federal Seed Act (FSA; Federal Seed Act 2011) authorizes USDA to regulate import of and trade in seeds and prohibits the transportation of noxious weed seeds in interstate commerce.

Together, the PPA and FSA restrict the importation, transportation, and cultivation of federally listed noxious weed and weed seed species. Like the definition of invasive species under Executive Order 13112, a species must cause harm to be added to the federal noxious weed list: under the PPA, a plant species must cause harm to agriculture, irrigation, navigation, natural resources, public health, or the environment (Plant Protection Act 2011: § 7702). USDA's Animal and Plant Health Inspection Service (APHIS) evaluates whether species meet this definition and may add potentially harmful species to the list. The FSA defines a noxious weed as any plant recognized as noxious by USDA or a state (Federal Seed Act 2011: § 1562). USDA and each state have established lists of prohibited and restricted noxious weed seeds.

The FSA prohibits seed shipments (i.e., transport or sale of seed) that exceed tolerances for the presence of noxious weed seeds (zero for prohibited noxious weed seeds and a maximum tolerance for restricted weed seeds; Federal Seed Act 2011: § 1571) and prohibits any import of agricultural or vegetable seeds containing noxious weed seeds (Federal Seed Act 2011: § 1581).

Under the PPA, a permit is required to import, trade, transport, or release any noxious weed into the environment (USDA Regulations 2011: § 360.100). APHIS will not issue a permit that would result in dissemination if the weed's destructive potential outweighs its probable benefits or for other reasons (USDA Regulations 2011: § 360.304). Permits for the release of noxious weeds into the environment must include conditions necessary to prevent dissemination into the environment (USDA Regulations 2011: § 360.303). These conditions are developed on a case-by-case basis and may include inspections to determine "whether the facilities are adequate to prevent noxious weed dissemination" and to ensure compliance with permit conditions (USDA Regulations 2011: § 360.303). A biofuel producer that allows a listed noxious feedstock species to escape from cultivation into the environment would be subject to civil and criminal penalties (Plant Protection Act 2011: § 7734) and could be required to destroy its crops (USDA Regulations 2011: § 360.305). In addition, APHIS may hold, treat, or destroy an article imported into or moving in interstate commerce if necessary to prevent the dissemination of a noxious weed that is new to or not prevalent and widely distributed in the United States (Plant Protection Act 2011: § 7714). APHIS is also authorized to take remedial and emergency action to control and eradicate noxious weeds and plant pests after they are released into the environment or may require owners to do so at their own cost (Plant Protection Act 2011: § 7714-15, USDA Regulations 2011: § 360.106).

Species are not subject to these restrictions under either the PPA or FSA unless they are listed as a noxious weed or weed seed. In recent years, APHIS has used its PRA tool as the basis for its noxious weed listing decisions (APHIS 2004, 2010) and will likely use the new WRA tool in the future, as indicated in recent assessment documents (APHIS 2009b). As a result, future noxious weed and weed seed listing decisions, at least those under the PPA, are likely to be strongly influenced by the USDA WRA outcomes, among other factors, such as presence and economic importance. As weediness is only one of several considerations in the listing process, the federal noxious weed list is not a comprehensive listing of weedy species, and many species with high WRA scores will not be listed.

In practice, current noxious weed and weed seed lists include few biofuel species with high scores under the Australian WRA methodology (Table 2). As a result, most potential biofuel species are not currently subject to related prohibitions on importation, commerce, or release into the environment, regardless of potential invasiveness. APHIS may add potentially invasive feedstock candidates to the noxious weed lists in the future as species evaluations proceed, either as a result of requests for review or in reaction to proposals for cultivation, particularly for species listed as noxious by one or more states.

TABLE 2. Noxious weed and weed seed status of selected candidate bioenergy feedstocks.

Scientific name	Common name	Noxious weed listings by state	Weed seed listings by state
<i>Arundo donax</i>	giant reed	CA, NV, NM, TX	NV
<i>Camelina sativa</i>	gold-of-pleasure	none	
<i>Jatropha curcas</i>	Barbados nut	none	
<i>Miscanthus sinensis</i>	miscanthus	CT, NH	
<i>Panicum virgatum</i>	switchgrass	none	
<i>Paulownia tomentosa</i>	princess tree	CT, WI	
<i>Pennisetum purpureum</i>	elephant grass	none	
<i>Phalaris arundinacea</i>	reed canarygrass	CT, MA, NH, WA	
<i>Pueraria montana</i> var. <i>lobata</i>	kudzu	CT, FL, IL, KS, KY, MA, MS, MO, NH, OH, OR, PA, TX, WA, WV, WI	KS, PA
<i>Salicornia bigelovii</i>	dwarf saltwort	no noxious or invasive listings; listed as threatened/special concern in ME, NH, NY	
<i>Triadica sebifera</i>	Chinese tallow	FL, LA, MS, TX	
Various spp.	native prairie grasses	requires compliance with seed purity laws	

Notes: State abbreviations are CA, California; NV, Nevada; NM, New Mexico; TX, Texas; CT, Connecticut; NH, New Hampshire; WI, Wisconsin; MA, Massachusetts; WA, Washington; FL, Florida; IL, Illinois; KS, Kansas; KY, Kentucky; MS, Mississippi; MO, Missouri; OH, Ohio; OR, Oregon; PA, Pennsylvania; WV, West Virginia; ME, Maine; NY, New York; LA, Louisiana.

Recognizing that potentially noxious, but unlisted, plants are eligible for import but not yet present in the United States, APHIS recently used its PPA authority to proactively use WRA to identify and prevent the importation of nursery stock. Any species listed as Not Authorized Pending Pest Risk Analysis (NAPPRA; APHIS 2011b) cannot be imported. Species can be petitioned for removal from the list, in which case APHIS will conduct a risk analysis and thereafter allow (subject to general or specific restrictions) or prohibit importation. Depending on the results of the risk assessment, APHIS could also list the species on the federal noxious weed list. A species is added to the NAPPRA list if APHIS determines, based on scientific evidence, that it is host to a plant pest or is “a plant pest or noxious weed that is of potential economic importance to the United States and not yet present in the United States, or present but not widely distributed and being officially controlled” (USDA Regulations 2011: § 319.37-1). In practice, data to support listing will be captured on a short data sheet, and WRA is not required for NAPPRA listing. Further guidance on this process, some of which may be forthcoming (APHIS 2011b), and practical experience with implementation will clarify the operation of this program.

Unlike general noxious weed listing, which does not consider native status, NAPPRA listing is limited to potentially harmful plants that are not present or not widespread in the United States. NAPPRA thus echoes the elements of the federal (and international) definition of a quarantine pest, but also that of an invasive species. However, many potential biofuel feedstock species are native to all or part of the United States (e.g., *Panicum virgatum*) or already present in the United States (e.g., *Camelina sativa*), so it is not surprising that the initial list of NAPPRA species does not include any species currently under consideration as a biofuel feedstock

crop. As a result, NAPPRA is likely to be most applicable to nonnative species that are identified as feedstock candidates in the future. For example, the potential cellulosic biomass feedstock species *Acacia saligna* is not on the NAPPRA list (APHIS 2011c), but its congeneric *Acacia hockii* is listed. If *A. hockii* had compatible biofuel characteristics and was considered for biofuel use in the future, a WRA and a PRA would be required before it could be imported. Species that are hosts for plant pests may also be listed and subject to PRA before importation; for example, potential biofuel feedstock *Psidium* spp. is on the NAPPRA list because it is a host plant for *Anoplophora chinensis*, a quarantine pest (APHIS 2011a). The associated PRA will focus on the risk of introducing the pest rather than whether the species is itself harmful, and therefore will not rely on the WRA tools discussed here.

State noxious weed and invasive plant laws.—States have enacted laws analogous to the PPA and FSA, generally administered by state agriculture departments. Every state has its own seed laws and most states have enacted noxious weed laws. Some states have also enacted species-specific laws, independent of or in addition to existing noxious weed lists, to address harmful plants of particular concern.

State seed laws closely follow the structure of the FSA by limiting the commercial sale of seed containing listed species of prohibited and restricted weed seeds (USDA 2010). Similarly, while specific provisions differ by location, state noxious weed laws follow the federal structure and are based on lists of noxious weeds. Both seed and weed laws prohibit or restrict the import, introduction, purchase, sale, transportation, propagation, or other uses of listed species. State noxious weed laws also go beyond the PPA by imposing direct burdens on landowners to control noxious weeds (Environmental Law Institute 2004).

State species lists differ greatly in both form and content. Some states, including Alabama, North Carolina, South Carolina, and Vermont, incorporate the federal noxious weed list by reference and supplement it with additional species of local concern; other states have developed their own unique lists that may or may not include species that are on the federal list. State lists may be extremely short; for example, Delaware lists only four species (Delaware Department of Agriculture 2011). Other states have lengthy lists of species in multiple categories associated with specific management goals. Montana classifies its listed weeds into five categories, each of which corresponds to a management outcome. Priority 1A species are subject to statewide eradication, education, and prevention efforts, while Priority 2B species are widespread and management must be undertaken by local weed districts for eradication or containment where not abundant (Montana Department of Agriculture 2010).

Species are most likely to be listed in locations where they are likely to thrive (and are therefore likely to become invasive). *Triadica sebifera* (Chinese tallow), a candidate bioenergy crop in the southern United States (Breitenbeck 2008), is a listed noxious species in several southern states where it grows most quickly, but is not listed elsewhere. Likewise, *Arundo donax* (giant reed) is listed as a noxious weed in several arid states in the Southwest (see Table 2). Some state legislatures have supplemented noxious weed lists by creating species-specific restrictions that apply to species of particular concern. For example, Louisiana has enacted a law declaring *T. sebifera* to be a noxious plant that may be destroyed wherever found (Louisiana Statutes 2013: § 1791).

Some states have additionally enacted laws restricting the release of invasive species. Such laws are unique to the state level, as no federal laws directly restrict the use, transport, and cultivation of invasive plants in the private sector. Like noxious weed laws, many state invasive species laws restrict importation, transportation, and propagation only of listed species. However, some state invasive species laws use a clean list approach that bars the importation or release of nonnative species unless and until specifically authorized by the responsible state agency. These invasive species laws may be administered by state departments of environmental protection or by natural resource agencies rather than by departments of agriculture and may focus more on species affecting natural areas than on agricultural weeds. If so, invasive species lists may contain different species than noxious weed lists, which historically have focused on agricultural weeds (Quinn et al. 2013).

Florida enacted a law to address invasion risk associated with bioenergy development in response to a 2005 proposal to produce giant reed (*Arundo donax*) as a bioenergy crop. The law adopts a clean list approach that restricts the cultivation of any nonnative plants for “fuel production or purposes other than agriculture”

(Florida Statutes 2011: § 581.083). The law requires a special permit from the Florida Department of Agriculture and Consumer Services (FDACS) to plant more than two contiguous acres of nonnative or genetically engineered plants, unless FDACS has determined that the species is not invasive. Permits require the use of biosecurity measures and include financial incentives to prevent escape into the environment during or after production. FDACS issues permits only if it determines that feasible measures can be taken to prevent the spread of the plant into neighboring ecosystems. Permits must include conditions for project design and operation that include but are not limited to traps to prevent escape through ditches or drainage, measures to prevent spread by seed, a fallow area to prevent spread into adjacent areas, and cleaning requirements of equipment used on the site (FDACS regulations 2013: § 5B-57.011). If a special permit expires or if the permit holder ceases to meet permit conditions, the permit holder is required to immediately remove and destroy the plants subject to the permit and to notify FDACS within 10 days (Florida Statutes 2011: § 581.083). This law also incorporates special financial conditions to address the risk of abandonment and ensure that escapes of nonnative species can be eradicated or controlled, regardless of listing status. Permit applications must indicate the cost of removing and destroying the planting. Unless exempted by FDACS, permit holders must maintain a bond or certificate of deposit of at least 150 percent of the cost estimate but not more than \$5000 per acre unless necessary to protect public health, safety, and welfare (FDACS regulations 2013: § 57.011, Florida Statutes 2011: § 581.083). The bond is held by the state and can be used to fund removal of the plants in the event of abandonment or if the permit holder violates other permit conditions (FDACS regulations 2013: § 57.011).

Determination of potential invasiveness is crucial to effective implementation of noxious weed and invasive species restrictions under both federal and state law. For clean list systems like the Florida biomass law, the state must determine whether a species can be allowed entry and what, if any, restrictions may be required to minimize the possibility of escape. For traditional noxious weed laws and other laws based on a dirty list, the state must proactively identify potential invaders for which listing is justified. The manner in which state agencies consider and implement WRA tools thus plays a substantial role in determining the efficacy of these regulatory programs. Statutes and regulations rarely require WRA tools to be used or provide guidance for their deployment. As a result, implementation of WRA at the state level, like the sophistication of noxious weed lists, differs from state to state. However, little specific information is available on whether and how such tools are used in the regulatory context, and most state-specific WRA information comes from nonregulatory sources (e.g., Gordon et al. 2008b, 2010, 2011). In

addition to uncertainty over WRA implementation, the substantial differences from state to state in the restrictions associated with listing mean that a case-by-case determination is required to determine the potential applicability of state noxious and invasive species laws to a given biofuel candidate species.

Crops produced via genetic engineering

There is a great deal of interest in optimizing biofuel production through development of genetically engineered feedstocks (e.g., Xie and Peng 2011). APHIS's Biotechnology Regulatory Services (a different branch of APHIS than Plant Protection and Quarantine, which manages noxious weeds) is the primary regulator of environmental releases of GE plants (Office of Science and Technology Policy 1986). APHIS biotechnology regulations "govern the introduction (importation, interstate movement, and release into the environment) of certain GE organisms termed regulated articles. Regulated articles are essentially GE organisms which might pose a risk as a plant pest" (APHIS 2008). Regulated articles include organisms altered or produced through GE that are or may be plant pests or that incorporate material from listed species of donors, recipients, or vector agents that are plant pests (USDA regulations 2011: § 340.1). Parasitic plants are the only plant species currently included in the list of organisms that are or contain plant pests, but donor or vector material from listed species could be used in the biofuel context.

In 2008, APHIS proposed a rule to substantially revise the biotechnology regulations to address potential noxious weed risk of GE organisms, as well as plant pest concerns, by enabling review, risk assessment, and regulation of these organisms (APHIS 2008). This proposed change would clarify that GE plants would be subject to APHIS regulation due to concerns about their invasiveness and ensure that weed risk is considered under these regulations. After receiving comments from the public, APHIS has not finalized the proposed regulatory changes, and potential timeframe and revisions are uncertain (APHIS 2009a). Pending final action on this or other revisions of the regulation, GE bioenergy crops that meet the definition of a regulated article are regulated under the current APHIS biotechnology regulations. In practice, potential GE bioenergy crops including GE eucalyptus have been subject to APHIS oversight (ArborGen 2011).

Movement or release of regulated articles into or within the United States requires APHIS authorization in the form of notification or a permit (USDA regulations 2011: § 340.0–1). Regulated articles can be introduced through notification if they are nonweedy plants with a stable genome that do not include genetic material that causes production of infectious agents, viruses, toxic substances, or products for industrial use. Neither noxious weeds nor plants that APHIS determines are weedy in the location proposed for introduc-

tion can be introduced by notification. Regulated articles introduced by notification must meet performance standards, which provide protection against escape as a result of shipment, mixing with other plant materials, vectors, or persistence after completion of field trials (USDA regulations 2011: § 340.3).

Regulated articles that do not meet the criteria for notification may be eligible for permits to allow importation, movement, or release (USDA regulations 2011: § 340.4). Importation and movement permits for GE crops contain permit conditions that producers must follow to minimize the possibility of escape into the environment, and accidental releases must be reported to APHIS. Applications for environmental release permits must describe the procedures, processes, and safeguards proposed to prevent escape and dissemination of the regulated article, among other elements. APHIS may carry out environmental assessment as required by the National Environmental Policy Act (NEPA) when determining whether to issue some permits for environmental release. If approved, environmental release permits for production of GE biofuel crops will contain measures permittees must take to prevent escape and establishment of species in the environment. Permits for environmental releases also require the submission of field test reports and notification to APHIS upon accidental or unauthorized release, or upon discovery that the organism has different characteristics from those listed in the permit (USDA regulations 2011: § 340.4). APHIS can take remedial measures, such as quarantining or destroying the regulated articles, upon failure to follow the requirements for introduction (USDA regulations 2011: § 340.1).

GE plant permitting and notification requirements do not explicitly incorporate WRA tools or outcomes, except insofar as noxious weeds are ineligible for notification. This is unsurprising given that genetic engineering is not a consistent predictor of invasion or incorporated into any WRA tool, as discussed previously. More detailed, case-by-case assessment may be merited to determine the potential weediness of GE plants (Koop et al. 2012). In practice, environmental assessments carried out for environmental release permits consider weediness and invasion risk; for example, environmental assessments carried out during GE eucalyptus permitting have considered invasion risks associated with eucalyptus generally and as genetically modified (ArborGen 2011). Moreover, the GE regulations provide for performance requirements and permit conditions to mitigate associated invasion risks. Thus, while WRA tools may not be incorporated explicitly into the GE regulations, APHIS biotechnology assessment and approval requirements are proactive and likely to ensure assessment of invasion risk for GE bioenergy feedstocks that are regulated articles.

The GE permitting requirements, like those for noxious weed release, substantially overlap with moni-

toring and management recommendations identified in the scientific literature and in voluntary BMPs. While the application of GE permitting requirements to advanced feedstock crop cultivation is currently limited, these regulations may become more relevant in the future as genetic engineering is increasingly applied to feedstock crops other than corn and soybeans.

Incentives and subsidies for bioenergy production

Federal and state governments have established a variety of programs to increase the production of energy from nontraditional sources, including bioenergy production. These programs provide incentives to increase propagation by providing markets for biofuels or subsidies for bioenergy production. Many biofuel-related programs, such as the blenders' credits for the use of ethanol, biodiesel, and alternative fuels (U.S. Code 2011a), focus on the final fuel product and are silent on crop selection and management. However, access to other programs is conditioned on the use (or avoidance) of certain species. These programs may directly influence feedstock species selection, and WRA tools and outcomes may be incorporated into these programs to ensure that they do not inadvertently promote the use of high-risk species. We focus on programs that are likely to influence the use of particular species or categories of biofuel feedstocks for advanced biofuels.

Renewable Fuel Standard.—The National Renewable Fuel Standard Program (RFS), administered by the Environmental Protection Agency (EPA), requires refiners, importers, and other obligated parties to blend four specified categories of renewable fuels into gasoline and diesel transportation fuels (EPA Regulations 2011: § 80.1406). Renewable fuels must be produced from renewable biomass, which includes planted crops, trees, crop and tree residues, slash and precommercial thinning, algae, and other materials. Crop residues include invasive species biomass removed for invasive species control, and precommercial thinning includes vegetative material removed to promote tree growth, including invasive species (EPA Regulations 2011: § 80.1401). Unless otherwise exempt, renewable fuels also must have life-cycle greenhouse gas emissions 20% or more below baseline emissions, with particular requirements depending on the type of renewable fuel (EPA Regulations 2011: § 80.1401). A fuel only qualifies as renewable if EPA has determined that the feedstock and processing pathway used to create it meets or exceeds this threshold (EPA Regulations 2011: § 80.1416, 1425). Species that are not approved for RFS qualification can still be used to produce fuels, but the resulting fuel does not provide a credit toward meeting RFS requirements. Therefore, RFS provides incentives for the production of fuels from species with approved production pathways without preventing use of non-approved species.

The application of the expanded RFS program (RFS2) to existing invasive species biomass could benefit

invasive species control efforts, but the primary impact of the RFS2 program on invasive species will likely arise from intentional cultivation for biofuel production. To date, EPA has evaluated and approved fuel pathways arising from various species and categories of renewable biomass, including corn, soybeans, sugarcane, switchgrass and miscanthus, *Camelina sativa*, *Arundo donax*, *Pennisetum purpureum*, and other specific species and generic feedstocks, including certain categories of wastes and residues, each of which can be processed to produce several types of renewable fuels. Feedstock species that are not currently covered by existing, qualified pathways, such as *Jatropha*, could be evaluated and considered for approval in the future through a petition process (EPA Regulations 2011: § 80.1416) should the evaluations demonstrate they meet the minimum GHG threshold. EPA has already approved several new pathways through the petition process and others have been proposed or are under review (EPA 2011b).

The Energy Independence and Security Act (EISA), which authorized the RFS2 Program, does not require the use of WRA in the implementation of the RFS2 program. However, Section 204 of EISA requires consideration of invasiveness as part of EPA's periodic evaluations of the program. EPA has done so in its initial triennial report to Congress (EPA 2011a). Regulatory programs maintained by other agencies may limit the cultivation of potentially invasive feedstocks that can be used to generate renewable fuels. For example, it would be unlawful to cultivate a species on the federal noxious weed list in the United States even if the feedstock met the minimum life cycle GHG threshold qualifying it under the RFS2 program. Furthermore, EPA has suggested that WRA tools be used and that BMPs be incorporated into selection and cultivation plans to address invasion risks, particularly in the case of perennial grasses and woody crops (EPA 2011a).

EPA required the implementation of BMPs in its recent approval of a pathway for production of elephant or napier grass (*P. purpureum*) and giant reed (*A. donax*). Unless fuel producers or importers can demonstrate that there is no significant likelihood that their plants will spread beyond the planting area, they must obtain EPA approval of a Risk Management Plan (RMP) that incorporates BMPs throughout feedstock production, management, transport, collection, monitoring, and processing (EPA 2013). The BMPs should, inter alia, include provisions to mitigate risks of escape and dispersal, including incorporation of traits that reduce invasion risk (e.g., seed sterility), as well as a closure plan that includes early detection and rapid response and that provides for destruction and removal of the feedstock from the growing area (EPA 2013, EPA 2014: § 80.1450(b)(1)(x)(A)). In addition to the RMP, producers or importers also must meet other criteria, including obtaining a letter from USDA with conclusions about whether the proposal presents a significant

likelihood of spread beyond the planting area and whether financial mechanisms are recommended to cover potential remediation costs should the plants escape from the intended planting areas (EPA 2013, EPA 2014: § 80.1450(b)(1)(x)(A)).

Biomass Crop Assistance Program.—The Biomass Crop Assistance Program (BCAP) is a voluntary program that provides financial incentives to farmers and forest landowners within a designated project area to assist in the establishment, maintenance, cultivation, and transportation of biomass for conversion into energy or biobased products. Project areas are established based on proposals submitted to USDA by either a group of producers or a facility that converts the biomass into heat, power, a biobased product, or a liquid biofuel. USDA preapproval of the project area is required for producers to receive establishment or annual payments. Among other limitations, known or potentially invasive or noxious species (USDA Regulations 2011: § 1450.2) are explicitly ineligible for establishment or maintenance payments (U.S. Code 2011*b*: § 8111, USDA Regulations 2011: § 1450.2) but are eligible for matching payments, subject to the limitations in federal, state, or local law, and consistent with Executive Order 13 112 (USDA Regulations 2011: § 1450.103(a)(iii)).

For BCAP purposes, the Farm Service Agency (FSA), with the Natural Resources Conservation Service, the Agriculture Research Service, and the Animal Plant Health Inspection Service (all agencies within USDA), reviews the feedstock species proposed by BCAP project area applicants and determines invasiveness and noxiousness, in consultation with other appropriate federal or state departments and agencies, federal and state noxious weed and invasive plant lists, and NEPA analyses. Although the FSA has not yet systematically incorporated WRA tools to date to determine actual and potential invasiveness and noxiousness, the 2014 Farm Bill revised BCAP's definition of eligible crop to exclude "species or varieties of plants that credible risk assessment tools or other credible sources determine are potentially invasive" (Agricultural Act of 2014, Pub. L. 113-79, s. 9011(a)(4)). If enacted, this revision would directly approve the use of WRA tools to assess biofuel feedstock species invasiveness for this program.

The Commodity Credit Corporation and FSA have finalized a Programmatic Environmental Impact Statement (PEIS) for BCAP (USDA Farm Service Agency 2010) as well as project-specific Environmental Assessments (EAs; USDA Farm Service Agency 2011, 2012). These analyses consider a range of impacts of program implementation, including invasion risk as informed by published WRA studies, and impose a variety of mitigation and monitoring requirements, such as producer education, site-specific conservation plans, and buffers, to minimize negative impacts to biological resources. BCAP project proposals associated with planting species considered in the PEIS, including

perennial switchgrass, forage sorghum, and hybrid poplar and willow, generally will not require additional review, while proposals to use other feedstock species require site-specific EA. To date, FSA has issued two EAs for *Miscanthus* × *giganteus* production (USDA Farm Service Agency 2011, 2012), each of which requires the establishment and maintenance of a minimum 25 feet (1 foot = 0.3048 m) of setback or border around a giant *Miscanthus* stand and prohibits planting giant *Miscanthus* within approximately 1300 feet of any known *Miscanthus sinensis* or *Miscanthus sacchariflorus* to limit the potential for cross-pollination resulting in viable seed. One of the EAs requires the use of only the sterile Illinois clone variety of giant *Miscanthus* within the proposed project areas, approval of all cultivars through the Ohio Seed Improvement Association's Quality Assurance program, and a seed sampling program to determine the ongoing sterility of seeds produced from the acres within the project areas (USDA Farm Service Agency 2011). The other EA requires the use of only the sterile variety of giant *Miscanthus* known as Freedom giant *Miscanthus* within the proposed project area, with all rhizomes appropriately tagged and meeting the certification conditions of the Georgia Crop Improvement Association minimum standards for *Miscanthus* (USDA Farm Service Agency 2012).

To date, USDA has approved 11 project areas to support a variety of biomass crops, including mixtures of perennial native grasses and forbs, such as switchgrass, big bluestem, Illinois bundleflower and purple prairie clover (in Kansas, Missouri, and Oklahoma), the sterile Illinois clone of *Miscanthus* × *giganteus* (in Arkansas, Missouri, Ohio, and Pennsylvania), *Camelina* (in Oregon, Washington, California, and Montana), and hybrid poplar trees (in Oregon; USDA 2011*a*).

Based on the project areas approved to date and the rules in place for collection and harvesting of eligible materials, it appears that the BCAP program is and will remain limited to native and low-risk species. The recently enacted congressional text supports this perspective by explicitly providing that WRA tools can be used to assess potential invasiveness, but given the detailed assessments carried out during the NEPA process for BCAP project proposals to date, their incorporation may offer limited additional value, except in the context of species for which such analyses are not available in the literature or about which little is known.

USDA crop insurance.—The development of crop insurance is a key source of risk reduction for farmers. In 2011, USDA Risk Management Agency's Federal Crop Insurance Corporation insured 265 million acres of crops for a total value of \$US114.1 billion (USDA/RMA 2012). Recently, USDA announced a new pilot program for Actual Production History crop insurance for *Camelina sativa* in selected counties in Montana and North Dakota (Federal Crop Insurance Act 2011: § 1523, USDA 2011*b*). Under the program, a grower's

yield is insured against loss due to adverse weather, fire, insect and plant diseases, and some natural disasters. Growers under contract with a biofuels processor are eligible for the program. If this pilot program becomes permanent and other crop insurance programs are established for dedicated bioenergy crops, the availability of such insurance would likely provide incentives for growers to switch to new crops. The current regulation does not address potential invasiveness in defining eligibility, nor are WRAs currently used to determine the development of insurance tools for bioenergy crops. However, it is conceivable that insurers would consider invasion risk as a financial concern, particularly in cases where financial bonds are required to mitigate risk.

Regional and state subsidies and incentives.—States have established biofuel incentive and benefit programs that are analogous to those in federal law. Examples of these programs include the California low-carbon fuel standard (LCFS) and Oregon biofuel subsidies, which are silent on invasive or nonnative status, and Reinvest in Minnesota—Clean Energy (RIM-CE) and the Regional Greenhouse Gas Initiative (RGGI), which contain limits on eligibility of nonnative species.

The LCFS is analogous to RFS2 and seeks reductions in the carbon intensity of transportation fuels in California (California Executive Order S-1-07 2007, California Air Resources Board regulations 2011). It requires regulated parties to meet yearly average carbon intensity requirements for their fuels (California Air Resources Board regulations 2011: § 95482(a), 95484). The table of fuel carbon intensities currently only includes biofuels derived from corn, soybeans, and sugarcane (California Air Resources Board regulations 2011: § 95486), but the regulations do not limit the LCFS based on biological criteria, and regulated parties can propose new fuel pathways based on life-cycle carbon intensity values. Pathway evaluation under the LCFS does not incorporate invasiveness assessment.

Oregon is one of many states that have created financial benefits for bioenergy production without incorporating limitations based on invasion risk. In 2007, it enacted a package of biofuel subsidy programs, including a tax credit for producers and collectors of biofuel raw materials, a property tax exemption for biofuel production facilities, demand drivers including requirements for the state to use biofuels, an RFS2-like program, and other provisions (Oregon Legislative Assembly 2007). These programs are intended in part to stimulate the cultivation of oilseed crops for biodiesel, but none requires the use of native or noninvasive feedstock species.

On the other hand, Minnesota's RIM-CE law conditions qualification for bioenergy subsidies on the use of native species. RIM-CE offers payments in exchange for long-term guarantees, via easements, that agricultural land will be used to produce native bioenergy crops. Among other requirements, easements must limit agricultural crop production to native

perennial bioenergy crops and may allow for nonnative perennial prairie or pasture established by 1 September 2007 that meets other objectives of the RIM-CE program (Reinvest in Minnesota Clean Energy Program 2011: subdivision 5). RIM-CE payments to landowners are tiered to provide the highest per-acre value for diverse native prairie and perennials (Reinvest in Minnesota Clean Energy Program 2011: subdivision 7). The base-level payment for planting one native perennial grass or woody species is 80% of estimated market value; payments increase with the planting of additional species and for plantings that address specific local environmental benefits (Minnesota Board of Water and Soil Resources 2008). Thus, RIM-CE conditions benefits explicitly on native status and biodiversity, thereby ensuring that the state will not financially support the cultivation of invasive species and rendering WRA unnecessary.

Carbon offset projects may provide funding for biomass production, and one regional effort has limited the use of invasive species for this purpose. RGGI caps and gradually reduces the allowable carbon dioxide emissions from fossil fuel-fired electrical generating units in participating states. Among other methods, regulated power plants can meet part of their compliance obligations by sponsoring afforestation projects (i.e., creating new forest lands) to sequester carbon outside of the electricity sector (RGGI 2005), including through biomass projects based on woody species. A qualifying afforestation project uses “mainly native species and avoids the introduction of invasive nonnative species” (RGGI 2008). Determination of which species are considered native or invasive nonnative in a particular state, and whether proactive WRA is required prior to cultivation, depends on that state's implementation of other laws and programs, most notably, state invasive and noxious plant laws.

DISCUSSION

Bioenergy feedstock species could be selected for characteristics that would also increase the risk of invasiveness; these characteristics include rapid growth, high seed production, broad ecological tolerances including tolerance of marginal growing conditions, or escape from or resistance to pests. Existing studies using the Australian WRA to evaluate bioenergy feedstock species under consideration for introduction to various countries indicate that biofuel feedstock species are more likely, when compared to nonfeedstock species, to have a relatively high risk for invasion, thus potentially harming the economy and environment.

A variety of interdependent restrictions and incentive programs affect feedstock species selection. Direct restrictions on the importation, trade, and cultivation of species are primarily a function of federal and state noxious weed provisions, GE crop cultivation restrictions, and other state laws. These laws generally apply to

TABLE 3. Invasion history, weed risk assessment (WRA) scores, and potential legal and policy relevance for a selection of biofuel feedstock candidates.

Species	Feedstock type	Native to United States?	Present in United States?	Known invader or weed elsewhere	Existing WRA score(s)
<i>Arundo donax</i>	cellulosic biomass	no	widespread	yes	reject
<i>Camelina sativa</i>	oilseed	no	widespread	yes	reject
<i>Jatropha curcas</i>	oilseed	no	FL, HI, PR, VI	yes	reject
<i>Panicum virgatum</i>	cellulosic biomass	yes	widespread	yes	conditional accept/reject
<i>Miscanthus sinensis</i>	cellulosic biomass	no	widespread	yes	reject
<i>Miscanthus</i> × <i>giganteus</i> (sterile)	cellulosic biomass	no	unknown	no	accept/evaluate further
<i>Salicornia bigelovii</i>	oilseed	yes	widespread	no	none found

Note: Abbreviations are PPA, Plant Protection Act; NAPPRA, Not Authorized Pending Pest Risk Analysis; RFS2, the expanded National Renewable Fuel Standard Program; RIM-CE, Reinvest in Minnesota–Clean Energy.

† Based on native status in Florida.

‡ Based on native status in Minnesota.

agricultural cultivation rather than to bioenergy production in particular.

Despite consistent suggestions from the scientific literature and warnings from NISC's advisory committee (ISAC 2009), the federal government and the states have yet to comprehensively integrate WRA tools or approaches into regulations and policies focused on or affecting biofuel selection or cultivation. In a few cases, including GE crop production, importation of species on the NAPPRA list, and cultivation in the few states that use a clean list approach to nonnative plant regulation, risk assessment may be required prior to importation or cultivation of nonnative species. WRA is not proactively required prior to importation or cultivation in the remaining programs, although many of these programs incorporate some form of WRA to determine whether listing and associated restrictions are warranted.

In practice, USDA has published few evaluations of biofuel feedstock candidates conducted under either its old or new risk assessment tools, and many nonnative bioenergy feedstock candidates are not listed as noxious weeds at either federal or state levels despite Australian WRA scores indicating substantial invasion potential (Table 3). Further, many potential feedstock species are ineligible for NAPPRA listing due to their widespread presence in the United States. As a result, many nonnative feedstock species with high WRA scores currently can be imported and cultivated without limitations. The NISMP (NISC 2008), EPA (EPA 2014), and multiple NGOs (e.g., IUCN 2009, Roundtable on Sustainable Biofuels 2010) recommend the proactive use of WRA analysis to assess nonnative feedstock candidates and to reduce potential environmental harm resulting from biofuel development by avoiding the importation and cultivation of candidate species that present a high risk of economic or environmental harm.

All direct biofuel incentive programs rely upon noxious weed listings and other restrictions on importation and cultivation to avoid inadvertently supporting the cultivation of potentially invasive bioenergy feed-

stock species, and this reliance is crucial for incentive programs without independent eligibility criteria. The current set of interlocking regulatory programs depends on the cooperation of multiple agency actors to effectively prevent invasion; for example, to determine eligibility for RGGI afforestation offsets, a state might consult its noxious weed and invasive plant lists or request a WRA from USDA or another expert authority rather than carry out an independent risk analysis. While agencies need to work together to prevent invasion (as outlined in the NISMP), programs have disparate direction and priorities and therefore may not reach identical conclusions on the appropriate regulation of a given species. For example, while it would be inappropriate to provide incentives for cultivation of a harmful species that is widespread in part, but not all, of the United States, that species would be ineligible for inclusion on the NAPPRA list, which is limited by USDA regulation to species "not yet present in the United States, or present but not widely distributed and being officially controlled." Thus, regulatory determinations under one regulatory program may not necessarily generate restrictions that are appropriate to others.

Some, but not all, bioenergy incentive programs restrict eligibility based on invasive or native status. For example, approval of a BCAP project requires environmental assessment that includes consideration of species- and/or cultivar-specific invasion risk based in part on WRA or PRA outcomes, thereby limiting eligibility for establishment or maintenance payments to native or noninvasive species, cultivars, and hybrids. Recently adopted language in the 2014 Farm Bill further strengthens consideration of invasion potential by endorsing WRA for determining potential invasiveness under this program. This marks the first time Congress, rather than an agency, has explicitly supported the use of WRA as a decision support mechanism. When incentive programs (such as BCAP) incorporate independent assessments of invasion potential based on WRA outcomes, they reduce the risk of inadvertently providing incentives to cultivate potentially invasive

TABLE 3. Extended.

Listed under PPA or state analog?	Listed as NAPPRA?	Approved RFS2 Pathway?	Permit required in FL?†	Eligible for RIM-CE?‡
CA, NV, NM, TX	no	yes, with RMP	yes	no
no	no	yes	yes	no
no	no	under review	yes	no
no	no	yes	no	yes
CT, NH	no	yes	yes	no
no	no	yes	yes	no
no	no	no	no	no

species that are not otherwise regulated by noxious weed lists or other importation and cultivation restrictions.

Applying this information

We show that there are a variety of relevant legal frameworks in place that may govern and affect feedstock species selection, but these frameworks do not comprehensively restrict the importation or cultivation of potential invasive species. As a result, the use of best practices to reduce invasion risk associated with cultivation is crucial to effectively avoid the introduction and spread of invasive species in the United States as a result of biofuel development. In some instances, such as for noxious weed permits, GE crop permits, or nonnative species releases in states with clean list laws regarding bioenergy or species introductions, the use of best management practices may be required by federal or state law. Elsewhere, however, application of best practices such as those outlined by the IUCN and in the NISMP to facilitate EDRR and reduce the risk of a detrimental invasion by a new plant species is mostly voluntary (e.g., as part of the RSB sustainability criteria). Therefore, most of the responsibility for feedstock species selection and BMP implementation lies with feedstock producers and processors.

The patchwork of requirements and opportunities can make it seem as if the selection process and pursuit of best practices to reduce invasion risk is complicated. However, explicit consideration of a few key decision points can reduce the risks of introducing or cultivating a potential invasive species and can also lead to qualification for incentive programs that can facilitate producer activities.

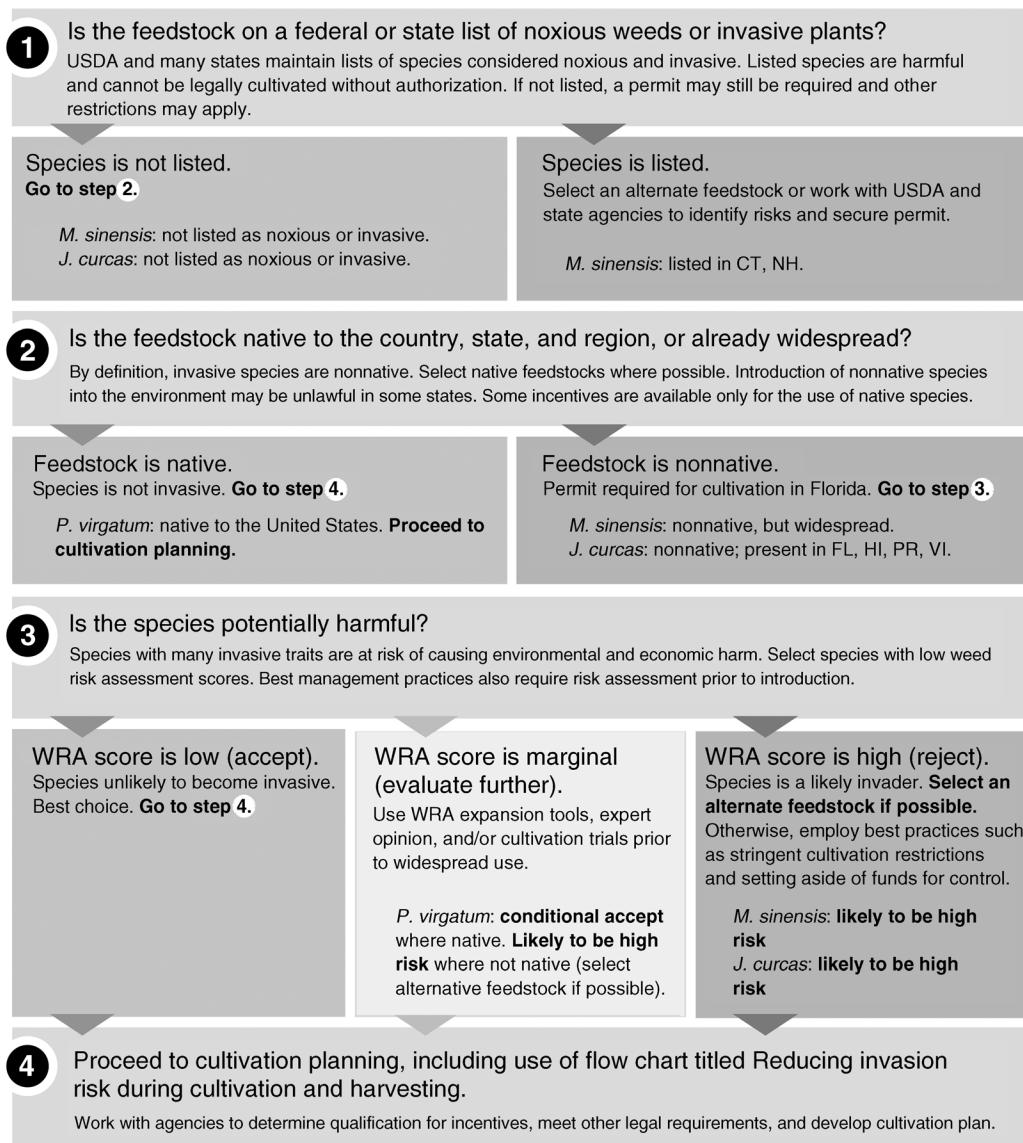
While we do not provide new tools for assessing invasiveness, we highlight the existing tools and approaches for assessing invasion risk and avoiding the introduction and spread of invasive species as a result of biofuel feedstock cultivation. To facilitate the use of this information, we have synthesized the information from this study into two flow charts (Figs. 2 and 3) that integrate the information on pre- and postintroduction invasion risk management and outline the steps involved in selecting or cultivating a low-risk biofuel feedstock species based on weed risk assessment, species regulation, and recommended best practices. The

flow charts use three bioenergy feedstock candidates, *Miscanthus sinensis*, *Jatropha curcas*, and *Panicum virgatum*, as examples; however, these charts are not intended to imply any universal recommendations about the use of specific species. These flow charts are intended to provide the basic outlines of a procedure for feedstock selection and implementation of best practices but are not exhaustive and should not be construed as legal advice. These charts provide some guidance to help biofuel feedstock producers understand how to effectively comply with existing legal restrictions and incorporate the best practices and emerging scientific understanding to minimize invasion risk.

CONCLUSION

As society pursues advanced renewable energy sources, such as the alternative drop-in transportation fuels desired by the aviation community, novel bioenergy crops are likely be introduced and/or cultivated as biofuel feedstocks. These crops will likely express characteristics such as high growth rates, tolerance of marginal conditions, and other traits predictive of high invasion risk, and this risk needs to be managed. Examination of how the U.S. legal systems consider and address biofuel invasion risks reveals a complex patchwork of partially interlocking restrictions on, and incentives for, bioenergy production. Under existing restrictions, only listed species and categories of high-risk feedstock candidates, such as GE crops, are subject to comprehensive regulation or WRA prior to introduction; however, some programs consider invasiveness proactively for particular purposes. Where invasion risk is not comprehensively managed by laws and regulations prior to introduction, as in the United States, the use of voluntary BMPs created by IUCN and other groups (which uniformly call for incorporation and use of WRA) and implementation of EDRR programs are crucial to drive selection of low-risk feedstock species and to reduce the risk of introducing or allowing escape and spread of new invasive species. The NISMP recognizes the importance of these initiatives; it outlines joint agency efforts to expand monitoring, evaluation, and control efforts (including identification of gaps in management and control strategies, treatment of invaded areas, and

Noninvasive biofuel feedstock selection process

Example species: *Miscanthus sinensis*, *Jatropha curcas*, and *Panicum virgatum*

Examples used here do not constitute legal advice. Check with responsible federal and state agencies to ensure compliance with permitting and other legal requirements.

FIG. 2. Flow chart describing the steps for a feedstock producer to select a low-risk biofuel feedstock, using the examples of Chinese silvergrass (*Miscanthus sinensis*), jatropha (*Jatropha curcas*), and switchgrass (*Panicum virgatum*) based on regulatory listing, native status, and weed risk assessment. Abbreviations are WRA, weed risk assessment; CT, Connecticut; NH, New Hampshire; FL, Florida; HI, Hawaii; PR, Puerto Rico; VI, Virgin Islands.

increased cleaning programs) to reduce invasive species impacts in the United States. Such coordination on EDRR programs and associated implementation of proactive WRA in existing regulatory frameworks may promote selection of native and noninvasive feedstock species and improve cultivation methods. A well-coordinated combination of species restrictions, biosecurity requirements, and incentives for selection of less risky biofuel crops, consistent with the approach

outlined for all nonnative species by the NISMP, may effectively balance the desire for increased biofuel production while minimizing invasion risk.

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Reducing invasion risk during cultivation and processing

Example species: *Miscanthus sinensis*, *Jatropha curcas*, and *Panicum virgatum*

To be followed after step 4 of Noninvasive biofuel feedstock selection process.

5 Are incentives or subsidies available?
 Federal and state incentives and subsidies benefit feedstock producers or processors. Some programs are limited to noninvasive species, e.g., Biomass Crop Assistance Program (BCAP), Reinvest in Minnesota–Clean Energy (RIM–CE), or approved pathways, e.g., Renewable Fuel Standard (RFS).

Incentives or subsidies available.
 Utilize available benefits for the feedstock and proceed with cultivation.

P. virgatum:
 Native species: eligible for RIM–CE and BCAP.
 Approved RFS pathway.

M. sinensis:
 Approved RFS pathway.

Incentives or subsidies unavailable.
 Proceed with cultivation under plan if economically feasible. If appropriate, work with agencies to qualify feedstock for benefits in the future.

J. curcas:
 RFS pathway approval under review.
 May be ineligible for BCAP due to high invasion risk.

M. sinensis:
 May be ineligible for BCAP due to high invasion risk.

6 Is a permit required to cultivate or transport the feedstock? What conditions apply?
 Permits are required to import or cultivate federal or state noxious species, species not native to Florida (for cultivation in the state, and new crops produced through genetic engineering [GE]) or other states with similar laws. Permits are conditioned on the use of biosafety protocols such as field monitoring, use of buffer zones, test plots, and posting of financial assurance bonds. Escape can result in seizure and/or destruction of crops and forfeiture of bonds.

No permit required.
 Move ahead with production under cultivation plan and best practices.

P. virgatum: native, not noxious or GE crop; no permit required from USDA, FL, or other states.

Permit required.
 Work with USDA and state agencies to identify risks and secure permit. Comply with all permit conditions.

J. curcas:
 Nonnative; permit required in FL.
 Not noxious and not GE; no USDA permit required.

M. sinensis:
 Nonnative; permit required in FL.
 Listed as noxious in CT and NH; permit required.
 Not GE crop; no USDA permit required.

7 What best practices are needed to reduce the risk of escape?
 Implement required conditions based on cultivation plan. Where no permit is required, follow best practices.

Permit conditions require mitigation.
 Implement required conditions based on cultivation plan. In states where no permit is required, follow voluntary best practices.

J. curcas: Follow permit conditions in FL.

M. sinensis: Follow permit conditions in FL, CT, NH.

Voluntary best practices needed.
 Follow IUCN, RSB, or other guidelines to prevent dispersal, monitor escape, and fund potential response capability.

P. virgatum: No permit conditions required. Develop cultivation plan.

J. curcas, M. sinensis: Where no permit required, develop cultivation plan.

Examples used here do not constitute legal advice. Check with responsible federal and state agencies to ensure compliance with permitting and other legal requirements.

FIG. 3. Flow chart describing the steps for a feedstock producer to reduce risk of invasion following introduction and potential eligibility for incentives/subsidies using the examples of Chinese silvergrass (*Miscanthus sinensis*), jatropha (*Jatropha curcas*), and switchgrass (*Panicum virgatum*), based on permitting requirements, best practices, and regulations.

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PLATE 1. Sample harvest of *Camelina sativa*, Montana, 2009. Photo credit: K. C. Lewis.

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