CAST
CAST Commentary
QTA2016-1 February 2016

A Life-cycle Approach to Low-invasion Potential Bioenergy Production

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Introduction

Elements of a Strategy for Noninvasive Bioenergy Crop Production

Bioenergy, or biomass-based energy production, is being pursued globally to decrease greenhouse gas emissions and provide a reliable energy source.

Invasive species are among the top five threats to global biodiversity, imposing a variety of adverse impacts on native ecosystems, and they are extremely taxing on local to federal economies.

Bioenergy, or biomass-based energy production, is being pursued globally to decrease greenhouse gas emissions and provide a reliable energy source. Dedicated bioenergy crops are being selected, bred, and deployed to maximize biomass (or seed for biofuel production) with minimal inputs, and they are ideally to be grown on marginal lands to lessen conflicts with existing food/feed production. The biological traits to achieve these production goals include crops with rapid growth rates, tolerance of poor growing conditions, and broad climate tolerance, as well as those that require minimal inputs (Lewandowski et al. 2003). These traits are shared by many ecologically damaging invasive plants (Raghu et al. 2006); thus many are concerned that new invasive species may be introduced as bioenergy crops.

Invasive species are among the top five threats to global biodiversity, imposing a variety of adverse impacts on native ecosystems (Vilà et al. 2011), and they are extremely taxing on local to federal economies (Pimentel, Zuniga, and Morrison 2005). Ecological impacts from invasive plants include reductions in native plant diversity, alterations to nutrient and hydrological cycles, and effects on pollinators (Jeschke et al. 2014). Importantly, the majority of the most damaging invasive plants were intentionally introduced for forage, as ornamentals, or for forestry (Mack 2000). For example, the southeastern United States continues to experience the consequences of widespread planting of kudzu (*Pueraria* *montana* var. *lobata*), which was subsidized by the government for soil erosion protection and feeding of livestock, though now it is a major invader.

Unfortunately, once established, invasive plant eradication is difficult and expensive except in very small areas (Rejmánek and Pitcairn 2002), making prevention the best strategy to mitigate future invasions (Keller, Lodge, and Finnoff 2007). Invasions can most effectively be prevented through a life-cycle approach that adopts appropriate scientific and policy tools at each step in the production process, from crop selection to field production, feedstock transport and storage, and decommissioning. Importantly, even with appropriate prevention tools and policies, unforeseen mistakes and a volatile economy will mean that appropriate policy must cover potential liabilities and plan for responding to escapes. This approach will require collaboration and strategic interactions among plant breeders, ecologists, agronomists, farmers, energy companies, land managers, and other stakeholders (Simberloff 2008) and, if successful, can enable broad-based support for an emerging bioenergy industry without simultaneously providing incentives for new invasions.

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Why a Life-cycle Strategy?

Invasions result from complex interactions among the new species with the resident plant and animal community as well as local climate and soils, and they depend on a source of propagules (seeds or vegetative tissues that propagate a plant)—all of which can vary in time and space (Barney and Whitlow 2008). Thus predicting where and which species will become invasive is difficult and could be viewed as "the right plant, in the right place, at the right time." Therefore, invasion mitigation cannot be limited simply to choosing the right species and planting it. Just as the viability of bioenergy production requires analyzing the carbon balance across the life cycle—from field to fuel (Davis, Anderson-Teixeira, and Delucia 2009)—mitigating the invasion risk of bioenergy crops will require a strategy that considers the entire life cycle (Barney 2014).

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Invasion Risk Mitigation: Cultivar Selection

Weed Risk Assessment

Davis and colleagues (2010) recommend a "nested sieve" approach with three stages for estimating the invasive possibility of a potential biofuel feedstock. The first stage, to which all proposed feedstocks would be subjected, is a relatively "quick-and-dirty" questionnaire, a weed risk assessment (WRA). A WRA is a recent and fast-developing tool for assessing the invasion risk associated with a plant—be it a species, hybrid, cultivar, or variety. These tools allow users to identify plants that pose a high risk of establishing and causing impacts to the economy and environment. Because these tools were initially developed to support government agency decisions, they are well suited to a screening process that identifies and avoids high-risk plants—or, conversely, seeks out low-risk plants (Quinn et al. 2015).

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The WRA tool of this sort currently employed most widely is the Australian Weed Risk Assessment (AWRA). The Australian Department of Agriculture and Water Resources uses the AWRA to determine whether or not any plants proposed for introduction (not just biofuel feedstocks) should be permitted entry based on an estimate of invasive potential (Pheloung, Williams, and Halloy 1999). The AWRA consists of 49 questions about the species proposed for introduction, divided into eight sections (Table 1), and most questions call for a "yes," "no," or "unknown" answer that is scored. Scores are summed, and the total score results in a regulatory outcome: <1 = recommend permit import; >6 = recommend forbid import; and 1 to 6 = recommend forbid import pending further study. The threshold scores for these three outcomes are set by regulators according to the degree of invasion risk they are willing to accept. The AWRA system has been adapted for, and in some cases adopted for regulatory use in, other countries and regions such as New Zealand, Italy, Japan, Hawaii, and Florida (Lewis and Porter 2014).

In tests applying the AWRA to nonnative species already introduced to Australia and several other locations, the AWRA successfully identified 82 to 100% of species that became major invaders (Gordon et al. 2008). The AWRA, however, would have rejected for importation several species that turned out not to be invasive. Smith, Lonsdale, and Fortune

(1999) point out that estimating the cost of such an error relative to the cost of failing to identify a species that subsequently becomes invasive is a matter outside the scope of duties of those implementing AWRA and similar instruments, but it should strongly influence policymakers' and regulators' assignment of thresholds. Keller, Lodge, and Finnoff (2007), however, determined that use of the AWRA system in Australia and New Zealand has resulted in substantial net bioeconomic benefits.

Table 1. Categories of questions making up the Australian Weed Risk Assessment, with examples in each category

Category	Question
1. Domestication/Cultivation	Has the species become naturalized in any region to which it has been introduced?
2. Climate and distribution	Is the species suited to Australian climates?
3. Weed elsewhere	Is the species a weed of agriculture, forestry, or horticulture anywhere where it has been introduced?
4. Undesirable traits	Is the species a host for recognized pests or pathogens? Does the species grow on infertile soils?
5. Plant type	Is the species a grass? Is the species a nitrogen fixer?
6. Reproduction	Can the species self-fertilize? Can the species hybridize with other species?
7. Dispersal mechanisms	Are propagules likely to be dispersed unintentionally?
8. Persistence attributes	Does the species produce seeds prolifically? Is the species well controlled by herbicides?

The USDA uses the Plant Protection and Quarantine (PPQ) WRA as a decision-support tool, but it is not directly used to make regulatory decisions.

The Plant Protection and Quarantine (PPQ) program of the U.S. Department of Agriculture (USDA) developed an improved WRA model based on the AWRA that decreases rejection of species that are unlikely to be invasive (false positives) and incorporates evaluation of the likelihood of major impact if a species is established in addition to the likelihood of establishment, as well as geographic potential and entry potential (Koop et al. 2012). The USDA uses the resulting risk assessment instrument, the PPQ WRA, as a decision-support tool, but it is not directly used to make regulatory decisions. The PPQ WRA consists of 23 questions that aim to estimate the risk of establishment and another 18 questions used to estimate the risk of major impact if establishment occurs. Tests on a large group of species show that the PPQ WRA indeed lowers the frequency of false positives without increasing the probability of false negatives (invasive species that are scored as low risk). Both the AWRA and the PPQ WRA, however, need to be used at the appropriate taxonomic level to accurately evaluate risks associated with particular biofuel feedstocks (Quinn et al. 2015).

Both the Australian WRA and the PPQ WRA need to be used at the appropriate cultivar variety-specific assessment.

Importantly, Cousens (2008) demonstrated that different assessors using the same data scored a given plant species differently, suggesting that, like all assessments using human judgment, WRAs have a degree of subjectivity. There is also the matter of data quality. To mitigate these concerns, the PPQ WRA includes an explicit treatment of uncertainty associated with the answers to the various questions (USDA–APHIS–PPQ 2015). For each question, risk analysts qualitatively report uncertainty as negligible, low, moderate, high, or maximum, and these scores are reported along with the resulting overall level of uncertainty associated with the estimate of risk of establishment and the estimate of risk of major impact (USDA–APHIS–PPQ 2015).

Other risk assessment procedures for species introductions share many features with the AWRA and PPQ WRA.

Other risk assessment procedures for species introductions share many features with the AWRA and PPQ WRA. For instance, the Non-native Species Secretariat (NNSS) Risk Assessment Scheme for Great Britain (NAPRA Network 2010) uses both expert judgment and objective information to answer a series of questions about the species proposed for introduction. The NNSS scheme also addresses the type and cost of potential environmental and economic impacts. The NNSS questions tend to require more judgment than those in the AWRA and PPQ WRA. Thus, whereas most AWRA or PPQ WRA questions will have a clear yes/no answer (e.g., Is the species a nitrogen fixer?), NNSS questions often demand guesswork (e.g., How likely is it that establishment will occur despite predators, parasites, or pathogens already present?). The NNSS scheme clearly separates the risk of establishment (naturalization) from the risk of impact if naturalization occurs, as does the PPQ WRA, and it also explicitly acknowledges to regulators that expert knowledge can be fallible, listing the degree of confidence in the answers to each question, also in line with the PPQ WRA.

Environmental Niche Models of Likely Degree of Spread

A feedstock may be found inappropriate for introduction. A second possibility is conditional acceptance. The third possible outcome is a requirement for further study.

In the latter case, environmental niche modeling (ENM) or species distribution modeling—the second sieve in the Davis and colleagues approach—comes into play.

These statistical tools seek to forecast where a nonnative species will ultimately spread from points of introduction.

Depending on the WRA score of a proposed feedstock, and on the thresholds set by regulators or policymakers, a feedstock may be found inappropriate for introduction. A second possibility is conditional acceptance. The third possible outcome is a requirement for further study. In the latter case, environmental niche modeling (ENM) or species distribution modeling—the second sieve in the Davis and colleagues (2010) approach—comes into play. These statistical tools seek to forecast where a nonnative species will ultimately spread from points of introduction, based on information on the physical environment (especially climate) in the native range (and sometimes also in the invaded range) (Elith, Kearney, and Phillips 2010).

There is substantial debate about the accuracy of predictions derived from ENM tools.

There is substantial debate about the accuracy of predictions derived from ENM tools (Fitzpatrick et al. 2007) based primarily on three issues. First, input data for ENM methods are usually presence-only data; rarely are data available showing that a species is not present at a site. This lack of absence data does not preclude use of ENM tools, but their results should be viewed with these limitations in mind. Second, these models use abiotic data only, but species' ranges are sometimes partly determined by which other species are present—predators, pathogens, parasites, mutualists. Certain ENM models can be modified to accommodate presence or absence of particular other species, but among the multitude of other species with which a newly introduced nonnative will interact, it is often not obvious which might be crucial to its spread or limitation. Third, these models do not account for evolution and assume that physical tolerances of a species change very slowly; yet all species evolve, and evolution is sometimes rapid.

Finally, global climate change will surely affect the geographic range of all plants, introduced as well as native, and some weeds will become far more widespread (Bradley et al. 2010). Climate change is taken into account in many risk assessment tools only indirectly. For example, the PPQ WRA produces predictive range maps that are based on changing hardiness and precipitation data sets (USDA–APHIS–PPQ 2015). Other recently developed risk assessment schemes, such as Belgium's Harmonia+, also directly require consideration of how introduction, establishment, spread, and impacts will change as a result of climate change (D'hondt et al. 2014). It is noteworthy that the nonnative species risk assessment template suggested by the British NNSS for the European Union includes a set of three questions specifically asking how the risk might change because of climate change.

Mechanistic Models of Risk of Establishment

If the ENM does not indicate high likelihood for spread, a third sieve comes into play—"mechanistic modeling" of a species' likely trajectory if introduced, accomplished by experiments.

If the result from a risk assessment is a requirement for further study, and if the second sieve—an ENM—suggests high likelihood for spread, decision makers should reject this feedstock. If, however, the ENM does not indicate high likelihood for spread, a third sieve comes into play—"mechanistic modeling" of a species' likely trajectory if introduced, accomplished by experiments. Davis and colleagues (2010) suggest that such research could be carried out in situ in the region targeted for introduction in quarantined field experiments. The risk of escape would have to be minimized, which is a major challenge. Some such experiments can be conducted in a laboratory or greenhouse setting, thus lessening risk, but the multitude of factors in the field that could affect whether or not an introduced species becomes invasive suggests that, ultimately, field experiments will be required to yield cogent estimates of invasion likelihood. Designing such experiments taxes the ingenuity of researchers. Whereas it is straightforward to determine empirically if a plant is a nitrogen fixer, a substantial research program is required to determine the probable impact of herbivores, parasites, or pathogens on a nonnative plant proposed for introduction.

The multitude of factors in the field that could affect whether or not an introduced species becomes invasive suggests that field experiments will be required to yield cogent estimates of invasion likelihood.

Flory and colleagues (2012) outline how such a program might progress for proposed biofuel feedstocks with a sequence of local experiments (perhaps in a laboratory or greenhouse) to identify conditions favorable for germination, survival, and growth followed by experimental introductions in semi-natural areas to assess factors controlling establishment and performance (e.g., disturbance, founder population size, and timing of introduction across a range of habitats) leading to experimental introductions, monitored for multiple years, across the expected geographic range of cultivation. They emphasize the rigor and cost of such a program but convincingly argue that such research is needed to estimate with confidence whether or not benefits of a proposed biofuel feedstock outweigh the projected risks of invasion.

Mechanistic models have become routine for proposed insect introductions for biological control.

Field tests of varied length and complexity have been performed for 30 years on genetically modified crop plants, mostly to assess how genes for insect resistance and herbicide tolerance affect various aspects of the environment, including the likelihood of spread outside designated fields (Sanvido, Romeis, and Bigler 2007). Mechanistic models have become routine for proposed insect introductions for biological control (Simberloff 2012), with more or less comprehensive laboratory trials to see which nontarget organisms a proposed control agent will eat or infect and can complete reproduction on, sometimes followed by field tests. Refinement of this approach has substantially lessened the risk of nontarget impacts by phytophagous control agents (Simberloff 2012). Escape from such tests for both genetically engineered (GE) crops and biocontrol insects has been an abiding challenge, and further work is needed to identify means of preventing escapes.

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Invasion Risk Mitigation: Production

Preintroduction germplasm selection and screening is the most critical step for decreasing bioenergy crop invasion risk, but it is unlikely to succeed by itself. A new set of invasion risk factors associated with the production environment must be considered after a crop species or particular cultivar is chosen for production. Agricultural cultivation of a plant species increases risk potential by creating many plant populations at landscape to regional scales that are protected from negative environmental conditions, thereby increasing the number of chances each population has to sample surrounding environments for establishment opportunities (Mack 2000).

No single prescription exists for decreasing invasion risk associated with bioenergy crop production. Anticipation and management of the risks inherent in various aspects of production are necessities, however, including siting of plantations, plantation layout, planting, harvest, storage, transportation, and extirpation (IUCN 2009). Also, prevention and containment strategies should be informed by likely invasion pathways—including dispersal, establishment, and spread—for a particular crop cultivar (Hulme et al. 2008). Those strategies should also minimize proximity of plantations to highly sensitive natural areas in case an escape should happen.

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Take *Miscanthus* × *giganteus* as an example for relating plant ecology and agronomy to best management practices (BMPs). The broad environmental tolerances and prodigious biomass production of *M.* × *giganteus* have made it a leading bioenergy feedstock candidate (Heaton, Dohleman, and Long 2008). The USDA Biomass Crop Assistance Program (BCAP) has provided support for scaled-up production of particular varieties of this plant, with pilot project areas of 20,250 hectares (50,000 acres) in the Midwest and Southeast (USDA–FSA 2015a).

The BMPs for *M.* × *giganteus* depend upon the cultivar chosen. The "Illinois" clone of *M.* × *giganteus* is a sterile triploid that produces no viable seeds and spreads slowly (0.1 to

0.4 meters year^{-1} [m yr^{-1}]) from rhizomes (Matlaga, Schutte, and Davis 2012). Rhizome fragments remain viable for one or more years, are buoyant, and sprout readily to form new clones (Mann et al. 2013). The green tillers of this cultivar are also capable of sprouting and establishing viable plants from the culms (aerial stems) (Mann et al. 2013; West, Matlaga, and Davis 2014a).

These traits indicate that the most likely long-distance dispersal routes for this cultivar are through riparian environments. Therefore, proper siting of plantations for the Illinois clone should avoid environments with potential for rhizome fragmentation and spread, including close proximity to riparian areas and steep slopes with highly erodible soil. Field margin buffers for this cultivar should be at least 8 m (USDA–FSA 2011, 2012), a figure arrived at by multiplying the maximum observed spread rate under field conditions of 0.4 m yr^{-1} by a 20-yr production period. The buffer width was designed to accommodate a situation in which no monitoring occurred; proper buffer width with annual monitoring and extirpation as necessary should permit production of the Illinois clone with minimal escape risk (West, Matlaga, and Davis 2014b). Harvest and transportation of the mature biomass of this cultivar should be designed to decrease risk of culm dispersal. Although the green culms of this cultivar (when harvested in early fall) can disperse and establish effectively, fully mature, dry culms harvested in late fall or winter pose little dispersal risk (Mann et al. 2013). Because planting the Illinois clone currently involves harvesting and preparing 10 centimeter-long rhizome fragments from “mother fields,” the rhizome harvesting and transportation process should also be sited and monitored to prevent escapes.

Lack of planning for bioenergy plantations may result in biological invasions that then become a public responsibility. Bioenergy plantation transitions with the potential to foster invasions, beyond inadequate determination of risk mitigation measures, include plantation closure, transfer of ownership, and noncompliance with best management practices.

In contrast to the sterile, vegetatively reproducing Illinois clone of *M.* × *giganteus*, a precommercial cultivar engineered for fertile seed (hereafter referred to as FSC) is more challenging. While WRA tools suggest that the Illinois clone presents a low risk of invasion, the same methods suggest that seed-bearing varieties are high risk (Smith, Tekiela, and Barney 2015). If introduced, the seeds of the *Miscanthus* species, including *M.* × *giganteus*, can easily travel distances of 0.5 kilometer by wind (Quinn et al. 2011). A simulation model of the spatial population dynamics of *M.* × *giganteus* based on data from field experiments (Matlaga and Davis 2013) demonstrated that seed viability and germinability at levels observed for FSC increase the spread rate of this species on the landscape by several orders of magnitude as compared to the Illinois clone. Visits to the preproduction nurseries for FSC confirmed this prediction (West, Matlaga, and Davis 2014a), with numerous visible escapes dotting the surrounding environment (Davis, A. S. Personal observation). Minimizing invasion potential for this cultivar, if it was used contrary to risk prevention principles, would likely require situating it within a very large corn production area that would serve as a managed buffer (Pitman et al. 2015).

Invasion Risk Mitigation: Closure

Much as abandoned or noncompliant industrial operations can threaten human and environmental health and become an economic burden on communities (e.g., Superfund sites), lack of planning for bioenergy plantations may result in biological invasions that then become a public responsibility. Bioenergy plantation transitions with the potential to foster invasions, beyond inadequate determination of risk mitigation measures, include plantation closure, transfer of ownership, and noncompliance with BMPs. For each of these situations, a successful plan will be built around risk mitigation information and a clear chain of responsibility.

Closing a bioenergy plantation in a way that minimizes invasion risk will involve developing and implementing a plan that clearly identifies the parties responsible for extirpation (complete removal). For a species such as *M.* × *giganteus*, for which the extirpation process is lengthy, the plan may need to involve a third party to complete the process even after the plantation has closed or ownership has been transferred, or if follow-up treatments are necessary. New owners of the property should be made aware of the possibility that the former bioenergy crop will continue to reemerge for some time, requiring continued management. They should also be apprised of—and required to follow—applicable BMPs for preventing and containing escapes of this species.

Closing a bioenergy plantation in a way that minimizes invasion risk will involve developing and implementing a plan that clearly identifies the parties responsible for extirpation (complete removal).

Not all such transitions will be orderly, and a former bioenergy plantation may then become a strong source for invasive spread into surrounding areas. Land abandonment or owner noncompliance with BMPs for mitigating invasion potential are certainly possibilities. If culpability is assigned to the growers, this could lead to difficulty in determining the source of an escaped population, depending on the number of plantations in the nearby landscape. Thus, contracts and the assignment of responsibility could ultimately affect the ability to extirpate escapes.

Extirpation can be an intensive, time-consuming process.

Extirpation can be an intensive, time-consuming process. Although grass and broad-spectrum herbicides can kill the shoots of many bioenergy species and translocate to rhizomes, causing considerable damage, single herbicide treatments are unlikely to result in complete elimination and may not be possible where the species has escaped beyond the cultivation site (Anderson et al. 2010). Extirpation should thus be planned well in advance to ensure completion of the process.

Invasion Risk Mitigation: Policy Tools

Laws and regulations can require or provide incentives for all bioenergy producers to mitigate invasion risk throughout the production life cycle; however, bioenergy programs currently address invasion risk only inconsistently.

Approaches to invasion risk mitigation in cultivar selection, production, and closure are implemented through voluntary efforts and mandatory, regulatory requirements. Standards and certification schemes provide tools to support and guide users in voluntary mitigation of invasion risk throughout the production life cycle. Laws and regulations can require or provide incentives for all bioenergy producers to mitigate invasion risk throughout the production life cycle; however, bioenergy programs currently address invasion risk only inconsistently.

Voluntary guidance and standards have been developed by nongovernmental organizations.

Voluntary guidance and standards have been developed by nongovernmental organizations with the intention of building on practices identified in the scientific literature to provide independent standards for the types of practices that should be considered by governments and growers (Lewis and Porter 2014). The International Union for the Conservation of Nature (IUCN) has produced guidelines for governments and developers for mitigating invasion risk in the bioenergy supply chain (IUCN 2009). The guidelines include feedstock selection (including WRA and environmental impact assessment) and production and processing (including environmental monitoring plans with certain listed management practices to prevent and respond to escapes), but they do not include specific guidelines for closure. These guidelines are general and require specification for effective implementation in particular locations for particular feedstocks. The Roundtable on Sustainable Biomaterials (RSB) requires that certified producers conduct WRA using its own modified AWRA template (RSB 2011). Producers certified by the RSB also must implement the IUCN guidelines (RSB 2011), but RSB guidance does not assist in identifying specific practices needed to implement the IUCN guidelines for a particular location or feedstock or in evaluating whether or not the selected measures are likely to be effective in practice.

Although voluntary provisions reflect a broad awareness that invasion risk mitigation practices are necessary for responsible bioenergy production, widely available tools are incomplete in scope and are not specific enough to ensure effective implementation.

In limited contexts, laws and regulations in the United States require invasion risk mitigation either as a condition of a production permit or to qualify for an incentive program.

Although voluntary provisions reflect a broad awareness that invasion risk mitigation practices are necessary for responsible bioenergy production, widely available tools are incomplete in scope and are not specific enough to ensure effective implementation. Government programs can fill these gaps and require that all producers comply. In limited contexts, laws and regulations in the United States require invasion risk mitigation either as a condition of a production permit or to qualify for an incentive program. Although permits are not required to cultivate most crops, a federal permit is required to introduce a GE energy crop (Office of Science and Technology Policy 1986), and a few states (including Florida, Mississippi, and Idaho) require a permit to introduce a new nonnative energy crop.

Federal permits may be issued after environmental assessment, provided that they incorporate specific measures that permittees must take to prevent escape and establishment of species, submit field test reports to the agency, and notify the agency of any releases (USDA–APHIS 2012). Although not incorporating WRA per se, consideration of escape risk associated with both the particular plant and proposed field test or environmental release is central to these assessments and resulting permit conditions.

State bioenergy permitting provisions may incorporate invasion risk mitigation covering cultivar selection, production, and closure.

State bioenergy permitting provisions may incorporate invasion risk mitigation covering cultivar selection, production, and closure. Although no state currently requires the use of particular cultivar selection techniques such as WRA, agencies can and do use WRA and other assessment methods in their permitting process (Porter, R. Personal communication). State laws more explicitly address identification and use of mandatory management practices. For example, applications for a permit to introduce an “Energy Crop Invasive Species” in Idaho (a category that includes any nonnative crop used for bioenergy) must include a “detailed confinement plan” as well as detailed plans for surveys and control of escapes (State of Idaho 2010). The resulting permits may include “any necessary conditions to prevent release or escape.” Florida regulations similarly require that agency staff “visit the proposed growing location and determine if feasible measures are available to prevent the spread of the plant into neighboring ecosystems,” and permits must include four minimum requirements to decrease the risk of spread (State of Florida 2014). Florida and Mississippi permittees must also provide a bond or certificate of deposit to cover potential control costs that devolve to the state and are legally barred from abandoning plots (State of Florida 2014; State of Mississippi 2015).

Government grant and incentive programs can encourage use of mandatory risk mitigation practices throughout the product life cycle without requiring all growers to comply.

Government grant and incentive programs can encourage use of mandatory risk mitigation practices throughout the product life cycle without requiring all growers to comply. Eligibility for USDA’s BCAP is conditioned on the use of noninvasive feedstocks and requires development of and adherence to a conservation or stewardship plan (USDA–APHIS 2011). Approved BCAP projects require environmental assessment, and the USDA has conducted both a programmatic environmental impact statement and project-specific environmental assessments for two strains of sterile *M.* × *giganteus* (Lewis and Porter 2014). Each assessment identifies specific management practices for specific crops, which are to be incorporated into contracts and/or conservation plans so they are binding on project participants. The USDA, however, recently indicated its intent to conduct a preliminary environmental impact assessment for the program that will include consideration not only of lower-risk crops such as the Illinois clone, but also of the high-risk seeded clone and other high-risk species, including *Arundo donax*, “jatropha,” and pennycress (*Thlaspi arvense*) (USDA–FSA 2015b). The Farm Service Agency is using this process, rather than simple consideration of the PPQ WRA, to evaluate whether or not these crops are eligible for the program (Porter, R. Personal communication).

The Renewable Fuel Standard also now incorporates management measures to mitigate escape risks associated with plants posing a high risk of invasion.

The Renewable Fuel Standard (RFS)—the primary federal program providing indirect incentives for production of qualifying feedstocks—also now incorporates management measures to mitigate escape risks associated with plants posing a high risk of invasion because such plants may result in indirect land use change affecting the life-cycle carbon emissions associated with energy production. Although feedstock approval is not conditioned on invasion risk, production of approved species with a high risk—to date, only *Arundo donax* and *Pennisetum purpureum*—must comply with an Environmental Protection Agency (EPA)-approved risk management plan that demonstrates that the growth of the plants “will not pose a significant likelihood of spread beyond the planting area of the feedstock” (USEPA 2012).

Risk management plans must identify and incorporate management measures throughout the bioenergy life cycle, including for production, transportation, processing, and closure.

Risk management plans must identify and incorporate management measures throughout the bioenergy life cycle, including for production, transportation, processing, and closure. These measures should both include accepted mitigation practices such as field buffers and incorporate traits (such as sterility) that may decrease escape risk and adopt an early detection and rapid response approach. Plans must also include closure arrangements providing for removal and destruction of the cultivated crop at the end of operations and provide for independent, third-party monitoring and reporting to the EPA (USEPA 2012). The EPA requires a letter from the USDA agreeing that the planting does not pose a significant likelihood of spread and recommending whether or not financial mechanisms are appropriate to ensure that control costs will be available in case of escapes (USEPA 2012).

Plans must also include closure arrangements providing for removal and destruction of the cultivated crop at the end of operations.

In sum, the RFS regulations for these two species provide the most specific and robust requirements for development and implementation of risk mitigation practices that have been included in U.S. law to date, albeit because of the acceptance that the program is providing financial incentives to produce crops posing a high risk of invasion. The novelty of this program, however, means that no approved risk mitigation plans are available, such that it is impossible to evaluate how effective they will be in practice or how tailored they may be to the site and crop—as well as if they will effectively address monitoring and control over an area sufficient to identify and eradicate escapes that do occur.

Consideration of existing bioenergy policies and programs in the United States suggests a partial adoption of a life-cycle approach. Cultivar selection is primarily left to the producer; WRA is not required, but some agencies use it as a decision support tool during permitting. Environmental niche modeling and other risk assessment techniques may also be used without a specific legal linkage (with the exception of GE crop permitting, which may be conducted in part to enable mechanistic modeling). Management measures are commonly used in the rare case in which a permit is required, and they are determined by the agency such that their efficacy will be based on both the agency's experience and its understanding of the specific risks of producing, transporting, and processing the crop in a given location. In practice, therefore, the management plans and other actions taken to mitigate invasion risk during production will differ from grower to grower and are unlikely to be consistently effective (Low, Booth, and Sheppard 2011). Finally, closure requirements are included in some but not all current policies, primarily through financial assurance mechanisms like surety bonds that can be executed if a permittee abandons or fails to control a plant. These provisions may not, however, fully compensate for the costs of responding to escape or abandonment, particularly when the source of an escape is uncertain or when producers have limited liability by contract.

Consideration of existing bioenergy policies and programs in the United States suggests a partial adoption of a life-cycle approach.

Exit Strategy

Legal Mechanisms to Deter Abandonment and Cover Costs

Several regulatory strategies can encourage producers to internalize costs at the plantation and project levels and decrease risk to the public. Policymakers have deployed a range of financial responsibility mechanisms in other contexts in which future cleanup is a concern, including oil spill prevention, hazardous chemical releases, mine remediation, wetlands mitigation site performance evaluation, and nuclear facility safety (Porter and Diamond 2009). Mechanisms used in these contexts include financial assurance (surety bonds); reserve funds; mandatory penalties for noncompliance; permit bars; mandatory liability insurance; strict, joint, and several liability; and monitoring and response fees (Porter and Diamond 2009). Financial assurance bonding requirements have already been applied to bioenergy feedstock production, whereas others, such as conditions in permits and incentive programs, could be used to mitigate the potential for escapes to occur and to ensure that adequate funds are available to eradicate escapes resulting from bioenergy production, transportation, or processing.

Several regulatory strategies can encourage producers to internalize costs at the plantation and project levels and decrease risk to the public.

Several U.S. states that require permits for cultivation of commercial-scale bioenergy crops currently require financial assurance as part of their permitting processes. In Florida, for example, prospective growers must provide "proof that the applicant has obtained, on a form approved by the department, a bond issued by a surety company admitted to do business in this state or a certificate of deposit, or other type of security adopted by rule of the department, which provides a financial assurance of cost recovery for the removal of a planting" (State of Florida 2014). This assurance guarantees that money will be available to eradicate the cultivated crop from the project area if that area is abandoned or the grower otherwise violates its compliance obligations. The amount of the bond will be based on the anticipated costs of eradication on the cultivated acreage. The minimum required amounts have been set at 150% of the estimated removal costs, with a $5,000 per acre maximum, with reduction or removal of the bonding requirement if the grower can demonstrate a low risk of invasion through field experience or science-based evidence (State of Florida 2015). Mississippi also requires a bond of not less than 150% of the estimated cost of removing and destroying the plant, capped at $5,000 per acre (State of Mississippi 2012).

Several U.S. states that require permits for cultivation of commercial-scale bioenergy crops currently require financial assurance as part of their permitting processes.

Financial assurance is a useful, but limited, disincentive to abandonment of bioenergy plantations. Assurance requirements consistently undercompensate the public for actual costs (Boyd 2001), whether as a result of inadequate surety amounts, difficulty recovering costs, inability to afford recovery costs *ex ante*, or other reasons. At the same time, industries—including bioenergy producers—consistently argue that assurance requirements will be insurmountable barriers to financial success; however, these fears in other contexts have largely proved to be unfounded (Boyd 2001). Current bioenergy assurance requirements are limited in two additional ways. First, they apply only to plants cultivated on the site—not those that escape— and by their terms they are unlikely to support eradication efforts on

Financial assurance is a useful, but limited, disincentive to abandonment of bioenergy plantations.

neighboring, uncultivated lands or other locations in the event of escapes. Second, even if assurance was available for escaped plants, it would require connection of the escaped plants to a particular plantation.

Although revision of bonding requirements could ensure that assurance funds can be used off the cultivated acreage to address escapes, issues of liability allocation will persist.

Although revision of bonding requirements could ensure that assurance funds can be used off the cultivated acreage to address escapes, issues of liability allocation will persist. Additional legal tools can increase the likelihood that funds both are available to eradicate escaped bioenergy feedstock plants and can be linked to the responsible party. These tools include conditions in operating permits and liability provisions extending fault for escapes throughout the production life cycle. Without such tools, it may be difficult or impossible to allocate responsibility for escapes on a landscape scale, as noted earlier, particularly for species that disperse long distances. This issue may be compounded for instances in which energy producers divest liability associated with plantation escapes through their contracts with growers (Davis, A. S. Personal communication).

The centralized structure of bioenergy production offers a solution that may resolve issues of liability.

The centralized structure of bioenergy production offers a solution that may resolve issues of liability. The economics of bioenergy production—and particularly the costs of transporting feedstocks—require that production be centered in a limited radius around a refinery facility; moreover, production contracts are needed to guarantee adequate supply. Because refiners have substantial control over grower practices through their contracts, inclusion of such presumptions and limitations on liability avoidance are likely to be the most reasonable and effective mechanisms for connecting escapes to the responsible party, and such presumptions would provide incentives for the bioenergy industry to implement BMPs that prevent such escapes throughout the bioenergy production life cycle.

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