Environmental Science & Technology Feature

Environ. Sci. Technol. **XXXX,** *xxx,* 000–000

Biofuel vs Bioinvasion: Seeding Policy Priorities

JOSEPH M. DITOMASO
University of California, Davis

JAMIE K. REASER
Congruence, LLC, C/O Ravens Ridge Farm, Stanardsville, Virginia

CHRISTOPHER P. DIONIGI
National Invasive Species Council, Washington, DC

OTTO C. DOERING
Purdue University, West Lafayette, Indiana

EARL CHILTON
Texas Parks and Wildlife Department, Austin

JEFFREY D. SCHARDT
Florida Fish and Wildlife Conservation Commission, Tallahassee

JACOB N. BARNEY
University of California, Davis (now at Virginia Polytechnic Institute and State University, Blacksburg)

Desirable biofuel crops may amount to mass cultivation of potentially invasive species—How should policy keep these agroecosystems in check?

To provide alternatives to petroleum-based energy, enhance global security, and reduce carbon emissions, the U.S. government has mandated a greater proportion of our energy portfolio be derived from plant-based fuels (i.e., 2007 Energy Independence and Security Act; EISA). However, the potential benefits of this nascent bioeconomy may be offset by damage to our biosecurity via land-use change, inappropriate agronomics, rapid adoption of novel crops, and/or lack of proper federal oversight (*1*). Of these potential externalities—the unintended and often negative effects or byproducts from an activity—little attention has been given to economic or ecological damage from invasive biofuel feedstocks. For example, many plant species proposed, and in some cases under development, for biofuel production in the U.S. are invasive species or have a high likelihood of escaping cultivation and becoming invasive (*2, 3*). The nature of invasive species is such that preventive actions will have to be taken both prior to and during cultivation of biofuel plants to ensure that damage from this externality does not occur (*4*). The federal government will be required to play a principal role in establishing many of these preventive actions, which we outline here.

SHUTTERSTOCK

This rapid increase in cellulosic energy production has seeded a policy dilemma: while biofuels offer great promise and will be subsidized and supported by the federal government (EISA, 2008 Farm Bill), the development and promotion of potentially invasive plants as biofuels could place federal agencies in direct conflict with 1999 U.S. Executive Order (EO) 13112 (*5, 6*), and other laws and policy directives. The National Invasive Species Management Plan (*7*) was created by the National Invasive Species Council (NISC) to guide Federal actions. NISC was established by EO 13122 and is cochaired by the Secretaries of Interior, Agriculture, and Commerce, and members work together to coordinate decision-making where invasive species are concerned. EO 13112 defines an invasive organism as a "[non-native] species whose introduction does or is likely to cause economic or environmental harm or harm to human health", and calls on federal agencies to work together and not take actions that are likely to introduce or spread invasive species. However, it also notes that the benefits of certain actions can outweigh the potential harm caused by invasive species. Therefore, in the case of biofuels, a comprehensive assessment of benefits (e.g., economic, energy balance, rural development, national security) weighed against potential environmental and economic consequences would reconcile bioenergy and invasive species policies.

Economic losses and the cost of control from invasive plants in the U.S. are estimated to be $34 billion annually—

10.1021/es100640y

FIGURE 1. ***Arundo donax*** **stand in Southern California.**

primarily agricultural losses (*8*). The environmental and economic costs of invasive plants to natural areas are also extensive—just 16 invasive plants infest over 51 million ha in the 48 contiguous states, where they alter ecosystem processes, change disturbance regimes, and crowd out native species (*9*). Although the benefits of biofuel production may be large, in some cases the socioeconomic and ecological costs of certain biofuel crops could ultimately exceed their benefits (*1*). The sustainability of the emerging biofuel industry depends upon coordination among many stakeholders, such as crop developers, researchers, farmers, energy companies, landowners, refinery operators, and governments (*10*). Fortunately, some stakeholders are self-organizing by creating and adopting guidelines to enhance sustainability (e.g., Council on Sustainable Biomass Production; *11*). Nevertheless, federal agencies must take coordinated action to avoid inadvertently facilitating the introduction (including cultivation escape) and spread of invasive species through their development, subsidization, funding for research, or other support of biofuels programs. Programs to produce biofuels, particularly from cellulosic feedstocks, will require large subsidies, especially in the early stages. If the public is to provide these subsidies, they must be assured that the materials developed and propagated for this purpose are not going to pose risks and do damage in the future, and by that incur additional public costs (*10*).

Invasive Species Risk

Although most of our food, fiber, and landscape plants are non-native, relatively few have proven invasive. However, those that are harmful have caused substantial socioeconomic and environmental impacts (*12*). The majority of the most harmful invasive species were introduced intentionally (*13*), some of which were introduced, and their plantings encouraged, by government actions. For example, johnsongrass (*Sorghum halepense*) was originally developed as a forage grass, but has become a yield-depressing weed that impacts corn, soybeans, and other crops (*14*). Over 85 million kudzu (*Pueraria montana*) seedlings were distributed by the U.S. government to encourage soil stabilization and as a forage in the early 20th century (*15*). Yet, kudzu now infests an estimated 40 million ha in the southeastern U.S. where it smothers native ecosystems, crowds out desirable species, and reduces land value (*15*). Ironically, kudzu is one of the species currently being considered for biofuel production within its invasive range due to its prolific biomass production (*16*). Other proposed terrestrial energy crops that are currently invasive in regions of the U.S. or elsewhere in the world include reed canarygrass (*Phalaris arundinacea*), giant reed (*Arundo donax*), and miscanthus (*Miscanthus sinensis*) (*5*). Additionally, some aquatic invasive species (e.g., *Eichhornia crassipes*) are under consideration as biofuel feedstocks, especially in developing nations (*17*).

Traits such as a perennial growth form; rapid and high aboveground biomass production; tolerance to drought, low fertility, or high salinity soils; competitiveness with other vegetation; and a lack of resident pathogen or insect pests that keep populations in check contribute to both a species' ability to yield biofuel and become invasive (*2, 5, 18*). In fact, many desirable agronomic biofuel feedstock characteristics are nearly identical to those found in damaging invasive species (*5*). Additionally, the three most robust predictors of invasiveness in an introduced range are climatic match, if the taxa is already a weed elsewhere, and propagule pressure (*19*). Considering the potential scale of biofuel cultivation, which is estimated at 1.5 billion ha by 2050 globally (*20*), there will be ample opportunity for biofuel crops to be introduced into environments in which they could persist and adversely interact with natural or managed ecosystems.

In addition to terrestrial and aquatic macrophyte species, the energy industry is evaluating algae for renewable production of starches for alcohols, lipids for diesel fuel surrogates, and H_2 for fuel cells (*21*). Algae have been shown to produce 250 times more oil than soybeans per unit area, and up to 31 times more oil per area than African oil palm (*Elaeis guineensis*) (*22*). However, a number of non-native algal species are being considered for biomass, but despite the potentially severe environmental risks, they have yet to be evaluated for their potential escape and impacts. For example, strains of freshwater cyanobacteria such as *Anabaena circinalis*, *Oscillatoria agardhii*, and *Cylindrospermopsis raciborskii* produce blooms known to cause serious illness or death to humans and animals. Open-water cultivation of non-native, or highly modified native algae, present an unknown risk to our waterways, drinking water reserves, and higher trophic level effects (e.g., fish that eat algae).

A coordinated strategic effort to develop and implement monitoring and mitigation procedures and policies is needed to reduce the risk of some biofuel crops escaping cultivation and causing substantial harm and public costs. The risks are particularly great where biofuel crops are cultivated or transported among sensitive ecosystems such as forest, prairie, desert, riparian, and wetland areas. Therefore, detailed risk assessment and cost-benefit analyses prior to adoption or rejection of biofuel crops must be conducted, and should be piloted and supported by relevant federal agencies.

FIGURE 2. Extensive ***Arundo donax*** **invasion, which is slated as a biofuel crop in the southeastern US.**

Roles and Responsibilities of Federal Agencies

Depending on their mission, federal agencies might engage in biofuel programs in a number of ways, such as (1) conducting biofuel research and development; (2) introducing and producing biofuel crops for experimentation and/or use; (3) subsidizing biofuel research, development, production, and marketing; (4) purchasing biofuels to supplement their energy demands; (5) establishing early detection and rapid response programs for escaped biofuel plants; (6) implementing long-term management of biofuel crops that become invasive; (7) restoring former biofuel production areas; and/or (8) regulating various aspects of production, use, and distribution of biofuels both domestically and internationally.

Specific agency directives for biofuel programs are emerging in federal legislation. For example, the 2007 EISA mandates the production of at least 60 billion liters of cellulosic-based fuels by 2022. This cannot be met with current agricultural, forestry, and municipal residues alone. It necessitates large-scale planting of dedicated energy crops, often referred to as "second generation" biofuel crops, that do not compete with food or feed (*23*). Various biofuel species and cultivars will have to be produced and promoted for experimentation and demonstration purposes. The U.S. Department of Agriculture's (USDA) research effort is therefore focused on identifying crops that will maximize yield while enabling cultivation on less productive, marginal lands with minimal agricultural inputs. The Food, Conservation, and Energy Act of 2008 (The Farm Bill; *24*) also directs USDA to provide subsidies for growers to encourage adoption of dedicated energy crops which currently have no market. The document goes on to state that the U.S. Environmental Protection Agency (EPA) in consultation with USDA and the Department of Energy (DOE), are to study the impact of the renewable fuel standard on environmental issues, including potentially invasive or noxious biofuel crop species.

Many federal agencies will be involved at various stages of biofuel crop development and adoption, agronomic production, harvest technology, and conversion to fuels and coproducts, as well as construction and financing of conversion facilities. Attenuating the development, promotion, and dissemination of a potentially invasive species in the name of energy security and economic development will require coordination across traditional federal jurisdictional boundaries.

FIGURE 3. Candidate biofuel feedstocks in a yield trial. Many of the desirable traits of biofuel crops are the same that characterize many invasive species.

Risk Mitigation and Recommendations

To minimize the risk of biofuel crop escape into surrounding environments and subsequently invasive, scientists and resource managers recommend that the U.S. government promote, fund, and employ ecological studies and scientific models that characterize the invasion risk of every biofuel crop within each target cropping region, and identify ecosystems most susceptible to invasion (*1, 2, 5, 13, 18, 25*). Science-based information generated from biofuel crop ecological studies, risk analyses, bioeconomic and niche modeling, and other methods can guide the government's risk mitigation plans. Depending on their respective authorities, federal agencies can take coordinated steps at appropriate points within biofuel research and development, crop selection and production, harvest and transportation, storage site selection, and conversion/refinery practices to minimize the risk of energy crops becoming invasive.

In response to this issue, in August 2009 the U.S. Invasive Species Advisory Committee (ISAC), a group of nonfederal experts and stakeholders chartered under the Federal Advisory Committee Act of 1972, adopted nine recommendations for the federal government's biofuel programs (Box 1). The recommendations comprehensively address biofuel production and use, as well as the necessity for agency and private sector stakeholder cooperation for effective implementation of the recommendations.

Box 1

Recommendations of the Invasive Species Advisory Committee, a subcommittee to the National Invasive Species Council, to the Secretaries and Administrators of 13 Federal departments and agencies (full document available at *7*).

1. Review/strengthen existing authorities
2. Reduce escape risks
3. Determine the most appropriate areas for cultivation
4. Identify plant traits that contribute to or avoid invasiveness
5. Prevent dispersal
6. Establish eradication protocols for rotational systems or abandoned populations
7. Develop and implement Early Detection and Rapid Response (EDRR) plans and rapid response funding
8. Minimize harvest disturbance
9. Engage stakeholders

As an initial step, all federal agencies with authorities relevant to biofuel production need to be identified, their likely responsibility on the invasiveness issue determined, and their ability to minimize the risk of biofuel escape and invasion strengthened as necessary. Secondarily, it is imperative that gaps and inconsistencies in authorities are identified and any potential conflicts be addressed in a timely manner. This is particularly important as EISA dictates huge volumes of biobased liquid fuels in the coming decade, with the second iteration of the Renewable Fuel Standard requiring 380 million liters in 2010. To reduce the risk of unintended biological invasion, the development of cooperative networks, memoranda of understanding, communication forums, and other forms of engagement and coordination among federal agencies and stakeholders, including state agencies, tribes, growers, and the private sector are critical. Similar successful cooperations have been developed related to invasive species that could serve as a model (e.g., Cooperative Weed Management Areas).

The federal government needs to take precautions to mitigate against the potential escape and invasion of biofuel crops into natural or managed systems, both in the context of its own programs and those it subsidizes or otherwise supports. For example, the 2008 Farm Bill will provide grower subsidies to encourage adoption of eligible biofuel crops (*24*).

As a first essential step, biofuel crops should be promoted that are not currently invasive or that pose a low risk of becoming invasive in the target region. Lists of noxious and invasive species are maintained at federal, state, and regional levels that should be consulted to identify species ineligible for further research and development. Identifying potentially invasive species will require a risk assessment protocol, which should be conducted for each candidate biofuel crop to assess its invasive potential in the proposed region of production (*2, 3, 26, 27*). Generic assessments at the species level across political rather than biogeographical regions will not be sufficient to identify actual invasion risk (e.g., *27*), and may cause unnecessary economic harm to this nascent industry by precluding cultivation of "safe" species. Existing risk assessment protocols are effective at identifying potentially invasive species that are important for horticulture and traditional agronomics before the target organism has been introduced (*28*). However, risk assessment protocols for biofuel crops should consider their current status—native, already introduced, or contemplating introduction—in the target region (e.g., ecoregion), and take account of economic, ecological, and unintended benefits and disadvantages (*2*). Therefore, the existing weed risk assessment protocols (*27*) may not be suitable for biofuel crops. For example, a forage-specific risk assessment was created in Australia to reflect the unique nature of forage crops (*29*). Federal adoption and requirement of a biofuel specific risk assessment would allow unbiased, science-based, and transparent accounting of biofuel crop adoption.

Ideally, biofuel crops should be propagated in containable systems (e.g., terrestrial fields or aquatic sites constructed specifically to cultivate biofuel crops), and best efforts made to develop cultivars unable to survive outside of cultivation. Through applied research and modeling, scientists can strive to identify the most appropriate production sites within a landscape for biofuel crop production, that is, sites least likely to impact sensitive habitat or create disturbances that facilitate invasion. A number of methods are available to identify which regions of the country would be most suitable for cultivation (i.e., require minimal inputs), while others are capable of discerning habitats most susceptible to invasion by the target crop. Several federal departments and agencies, particularly the USDA, have experience modeling species' ranges and predicting agronomic suitability and yield, and can extend this framework to include discerning invasible habitat within the agronomic region.

In concert with applied studies, fundamental research needs to be conducted and sponsored by relevant federal agencies to identify plant traits that contribute to or reduce the risk of biological invasion. Those traits which minimize the likelihood of invasiveness, such as sterility, reduced seed production, or an inability to regenerate by stem fragments, should be incorporated into biofuel varieties. On the other hand, traits that increase the probability of invasiveness, such as high competitiveness, tolerance to multiple environments, and prolific seed production, should be avoided or minimized in chosen varieties. Multidisciplinary collaborations among plant scientists, crop developers, growers, and refineries can be used to guide breeding, genetic engineering, and variety selection programs.

Most importantly, effective mitigation protocols need to be developed for precluding dispersal of plant propagules from the site of production, transportation corridors, storage loci, and/or processing facilities. These mitigation procedures need to be closely integrated with crop development, particularly with respect to the use of sterile cultivars, in combination with development of cultural techniques related to grower practices: harvest timing, maintaining clean equipment, using closed transport systems, or other methods to reduce propagule dispersal throughout the biofuel production cycle.

Finally, the development of multiyear eradication protocols based on integrated pest management (IPM) strategies needs to be in place *prior* to the release of a biofuel crop. These control methods are not only critical for preventing dispersal of biofuel crops from abandoned production sites, they can serve as an early detection and rapid response (EDRR) system for biofuel crop populations which escape active management. EDRR programs are key to a successful prevention program and, thus, a flexible funding source needs to be in place to support these efforts.

These recommendations require (1) improved coordination and cooperation among agencies and scientists, (2) research efforts to reduce the risk of invasion into natural environments or other cropping systems, and (3) field-to-process facility mitigation protocols that minimize the potential for crop escape. Although directed at the federal government, many of the recommendations are also relevant to state agencies, tribes, scientific institutions, and the private sector. Implementation of the recommendations proposed by the ISAC will help to ensure that the U.S. maximizes the benefits of its biofuel initiatives while minimizing the potential spread of invasive species.

Joseph M. DiTomaso is a Cooperative Extension Specialist at the University of California, Davis. He is a member of the Invasive Species Advisory Committee and his research focuses on understanding the biology and ecology of invasive plants and in developing effective management strategies. Jamie K. Reaser is an independent consultant focusing on environmental issues at the science—policy interface, and serves as the Vice Chair of the U.S. Invasive Species Advisory Committee. Chris Dionigi is the Acting Executive Director of the National Invasive Species Council and is primarily responsible for domestic policy development. Otto Doering is a Professor of Agricultural Economics and directs the Climate Change Research Center at Purdue University. He is a member of advisory boards for the National Academy of Sciences, the EPA, and serves on the Invasive Species Advisory Committee. Earl Chilton is Director of the Aquatic Habitat Enhancement Program with Texas Parks and Wildlife Department. He serves on the Invasive Species Advisory Committee and conducts research on invasive algae, plant—invertebrate—fish interactions, and the use of triploid grass carp for vegetation management. Jeffrey Schardt is an Environmental Administrator with the Invasive Plant Management Section of the Florida Fish and Wildlife Conservation Commission. He is a former member of the Invasive Species Advisory Committee and primarily works with invasive plants in aquatic systems. At the time of this writing, Jacob N. Barney was a Postdoctoral Scholar at the University of California, Davis, and is interested in invasive plant ecology, risk assessment, and biofuel crop ecology. Dr. Barney is now Assistant Professor of Invasive Plant Ecology at Virginia Tech, and is interested in invasive plant ecology, risk assessment, and biofuel crop ecology. Please address correspondence regarding this manuscript to him at jnbarney@vt.edu.

Literature Cited

(1) Meyerson, L. A. Biosecurity, biofuels, and biodiversity. *Front. Ecol. Environ.* **2008**, *6* (6), 291.

(2) Barney, J. N.; DiTomaso, J. M. Nonnative species and bioenergy: are we cultivating the next invader? *BioScience* **2008**, *58* (1), 64–70.

(3) Buddenhagen, C. E.; Chimera, C.; Clifford, P. Assessing biofuel crop invasiveness: a case study. *PLoS ONE* **2009**, *4* (4), doi: 10.1371/ journal.pone.0005261.

(4) Keller, R. P.; Lodge, D. M.; Finnoff, D. C. Risk assessment for invasive species produces net bioeconomic benefits. *Proc. Natl. Acad. Sci.* **2007**, *104* (1), 203–207.

(5) Raghu, S.; Anderson, R. C.; Daehler, C. C.; Davis, A. S.; Wiedenmann, R. N.; Simberloff, D.; Mack, R. N. Adding biofuels to the invasive species fire. *Science* **2006**, *313*, 1742.

(6) Beck, G. K.; Zimmerman, K.; Schardt, J. D.; Stone, J.; Lukens, R. R.; Reichard, S.; Randall, J.; Cangelosi, A. A.; Cooper, D.; Thompson, J. P. Invasive species defined in a policy context: Recommendations from the Federal Invasive Species Advisory Committee. *Invasive Plant Sci. Manage.* **2008**, *1* (4), 414–421.

(7) National Invasive Species Council homepage. Available at www.invasivespecies.gov.

(8) Pimentel, D.; Zuniga, R.; Morrison, D. Update on the economic and environmental costs associated with alien-invasive species in the United States. *Ecol. Econ.* **2005**, *52*, 273–288.
(9) Duncan, C. A.; Clark, J. K. *Invasive Plants of Range and Wildlands and Their Environmental, Economic, and Societal Impacts*; Weed Science Society of America: Lawrence, 2005; p 222.
(10) Schubert, R.; Blasch, J. Sustainability standards for bioenergy-A means to reduce climate change risks? *Energy Policy* **2010**; doi: 10.1016/j.enpol.2010.01.011.
(11) Council on Sustainable Biomass Production homepage. Available at www.csbp.org.
(12) Mack, R. N.; Simberloff, D.; Lonsdale, W. M.; Evans, H.; Clout, M.; Bazzaz, F. A. Biotic invasions: causes, epidemiology, global consequences, and control. *Ecol. Appl.* **2000**, *10* (3), 689–710.
(13) Simberloff, D. Invasion biologists and the biofuels boom: Cassandras or colleagues? *Weed Sci.* **2008**, *56*, 867–872.
(14) McWhorter, C. Introduction and spread of johnsongrass in the United States. *Weed Sci.* **1971**, *19* (5), 496–500.
(15) Forseth, I. N.; Innis, A. F. Kudzu (*Pueraria montana*): History, physiology, and ecology combine to make a major ecosystem threat. *Crit. Rev. Plant Sci.* **2004**, *23* (5), 401–413.
(16) Sage, R. F.; Coiner, H. A.; Way, D. A.; Runion, G. B.; Prior, S. A.; Torbert, H. A.; Sicher, R.; Ziska, L. Kudzu (*Pueraria montana* (Lour.) Merr. Variety *lobata*): A new source of carbohydrate for bioethanol production. *Biomass Bioenergy* **2009**, *33* (1), 57–61.
(17) United Nations Department of Economic and Social Affairs. *Small-Scale Production and Use of Liquid Biofuels in Sub-Saharan Africa: Perspectives for Sustainable Development*; New York, 2007.
(18) DiTomaso, J. M.; Barney, J. N.; Fox, A. *Biofuel Feedstocks: The Risk of Future Invasions*; QTA 2007-1; Council for Agricultural Science and Technology Commentary, 2007.
(19) Hayes, K. R.; Barry, S. C. Are there any consistent predictors of invasion success? *Biol. Invasions* **2008**, *10*, 483–506.
(20) Field, C. B.; Campbell, J. E.; Lobell, D. B. Biomass energy: the scale of the potential resource. *Trends Ecol. Evol.* **2008**, *23* (2), 65–72.
(21) Beer, L.; Boyd, E.; Peters, J.; Posewitz, M. Engineering algae for biohydrogen and biofuel production. *Curr. Opin. Biotechnol.* **2009**, *20* (3), 264–271.
(22) Hossain, A.; Salleh, A.; Boyce, A.; Chowdhury, P.; Naqiuddin, M. Biodiesel fuel production from algae as renewable energy. *Am. J. Biochem. Biotechnol.* **2008**, *4* (3), 250–254.
(23) Robertson, G. P.; Dale, V. H.; Doering, O. C.; Hamburg, S. P.; Melillo, J. M.; Wander, M. M.; Parton, W. J.; Adler, P. R.; Barney, J. N.; Cruse, R. M.; Duke, C. S.; Fearnside, P. M.; Follett, R. F.; Gibbs, H. K.; Goldemberg, J.; Mladenoff, D. J.; Ojima, D.; Palmer, M. W.; Sharpley, A.; Wallace, L.; Weathers, K. C.; Wiens, J. A.; Wilhelm, W. W. Sustainable biofuels redux. *Science* **2008**, *322* (5898), 49–50.
(24) U.S. Food, Conservation, and Energy Act of 2008. Public Law 110-234, 2008; http://farmcreditmidsouth.aghost.net/images/E0037001/2008_Farm_Bill_Booklet.pdf.
(25) Tilman, D.; Socolow, R.; Foley, J. A.; Hill, J.; Larson, E.; Lynd, L.; Pacala, S.; Reilly, J.; Searchinger, T.; Somerville, C.; Williams, R. Beneficial biofuels-The food, energy, and environment trilemma. *Science* **2009**, *325*, 270–271.
(26) Cousens, R. Risk assessment of potential biofuel species: an application for trait-based models for predicting weediness. *Weed Sci.* **2008**, *56*, 873–882.
(27) Pheloung, P. C.; Williams, P. A.; Halloy, S. R. A weed risk assessment model for use as a biosecurity tool evaluating plant introductions. *J. Environ. Manage.* **1999**, *57*, 239–251.
(28) Gordon, D. R.; Onderdonk, D. A.; Fox, A. M.; Stocker, R. K. Consistent accuracy of the Australian weed risk assessment system across varied geographies. *Divers. Distrib.* **2008**, *14*, 234–242.
(29) Stone, L. M.; Byrne, M.; Virtue, J. G. An environmental weed risk assessment model for Australian forage improvement programs. *Aust. J. Exp. Agric.* **2008**, *48* (4), 568–574.

ES100640Y