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Bioenergy and Biological Invasions

Ecological, Agronomic, and Policy Perspectives on Minimizing Risk

EDITED BY **LAUREN D. QUINN, DAVID P. MATLAGA** AND **JACOB N. BARNEY**

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Edited by

LAUREN D. QUINN

Energy Biosciences Institute, University of Illinois, Urbana, Illinois, USA

DAVID P. MATLAGA

Department of Biology, Susquehanna University, Selinsgrove, Pennsylvania, USA

and

JACOB N. BARNEY

Department of Plant Pathology, Physiology, and Weed Science, Virginia Tech, Blacksburg, Virginia, USA

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CABI
Nosworthy Way
Wallingford
Oxfordshire OX10 8DE
UK

Tel: +44 (0)1491 832111
Fax: +44 (0)1491 833508
E-mail: cabi@cabi.org
Website: www.cabi.org

CABI
38 Chauncy Street
Suite 1002
Boston, MA 02111
USA

Tel: +1 800 552 3083 (toll free)
E-mail: cabi-nao@cabi.org

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CABI Invasive Series

Invasive species are plants, animals or microorganisms not native to an ecosystem, whose introduction has threatened biodiversity, food security, health or economic development. Many ecosystems are affected by invasive species and they pose one of the biggest threats to biodiversity worldwide. Globalization through increased trade, transport, travel and tourism will inevitably increase the intentional or accidental introduction of organisms to new environments, and it is widely predicted that climate change will further increase the threat posed by invasive species. To help control and mitigate the effects of invasive species, scientists need access to information that not only provides an overview of and background to the field, but also keeps them up to date with the latest research findings.

This series addresses all topics relating to invasive species, including biosecurity surveillance, mapping and modelling, economics of invasive species and species interactions in plant invasions. Aimed at researchers, upper-level students and policy makers, titles in the series provide international coverage of topics related to invasive species, including both a synthesis of facts and discussions of future research perspectives and possible solutions.

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Contributors

Jacob N. Barney, Department of Plant Pathology, Physiology and Weed Science, Virginia Tech, 435 Old Glade Road (0330), Blacksburg, Virginia 24061, USA. E-mail: jnbarney@vt.edu

Wan-Loy Chu, International Medical University, No. 126, Jalan Jalil Perkasa 19, Bukit Jalil, 57000 Kuala Lumpur, Malaysia. E-mail: wanloy_chu@imu.edu.my

Chuck D. Dowling, Department of Soil and Crop Sciences, Texas A&M University, College Station, Texas 77843, USA. E-mail: dowlicd@tamu.edu

A. Bryan Endres, Energy Biosciences Institute and Department of Agricultural and Consumer Economics, University of Illinois, Urbana, Illinois 61801, USA. E-mail: bendres@illinois.edu

Stephen F. Enloe, Department of Crop, Soil, and Environmental Sciences, Auburn University, 119 Extension Hall, Auburn, Alabama 36849, USA. E-mail: sfe0001@auburn.edu

Russel W. Jessup, Department of Soil and Crop Sciences, Texas A&M University, College Station, Texas 77843, USA. E-mail: rjessup@tamu.edu

Nancy J. Loewenstein, School of Forestry and Wildlife Sciences, 3301 Forestry Wildlife Building, Auburn University, Alabama 36849, USA. E-mail: loewenj@auburn.edu

Carol Mallory-Smith, Department of Crop and Soil Science, Oregon State University, Corvallis, Oregon 97331, USA. E-mail: carol.mallory-smith@oregonstate.edu

David P. Matlaga, Department of Biology, Susquehanna University, Selinsgrove, Pennsylvania 17870, USA. E-mail: matlaga@susqu.edu

Lloyd L. Nackley, South Africa National Biodiversity Institute, Cape Town, South Africa; UC Davis, Davis, California, USA. E-mail: nackley@ucdavis.edu

Siew-Moi Phang, Institute of Ocean and Earth Sciences, University of Malaya, 50603 Kuala Lumpur, Malaysia. E-mail: phang@um.edu.my

Lauren D. Quinn, Energy Biosciences Institute, 1206 W. Gregory Ave, University of Illinois, Urbana, Illinois 61801, USA. E-mail: ldquinn@illinois.edu

Caroline E. Ridley, US Environmental Protection Agency, 1200 Pennsylvania Ave, NW, William Jefferson Clinton Building, Mail code: 8623P, Washington, DC 20460, USA. E-mail: ridley.caroline@epa.gov

Larissa L. Smith, Department of Plant Pathology, Physiology and Weed Science, Virginia Tech, 435 Old Glade Road (0330), Blacksburg, Virginia 24061, USA. E-mail: lls14@vt.edu
Daniel R. Tekiela, Department of Plant Pathology, Physiology and Weed Science, Virginia Tech, 435 Old Glade Road (0330), Blacksburg, Virginia 24061, USA. E-mail: tekiela2@vt.edu

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Contents

1 The Bioenergy Landscape: Sustainable Resources or the Next Great Invasion?

Lauren D. Quinn,[1]* Jacob N. Barney,[2] and David P. Matlaga[3]

[1]*Energy Biosciences Institute, University of Illinois, Urbana, USA;* [2]*Virginia Tech, Blacksburg, USA;* [3]*Susquehanna University, Selinsgrove, USA*

Abstract

Government policies have spurred efforts to develop dedicated bioenergy crops that could avoid greenhouse gas emissions associated with fossil fuel combustion and the consequences of land use change associated with "first-generation" biofuels. Dedicated bioenergy crops, slated to be cultivated on marginal lands, have been the subject of debate regarding their potential for invasion outside of cultivation. Critics have cited the weedy life-history strategies and history of invasion for some dedicated bioenergy feedstocks. Evaluations of feedstock invasion potential must balance the potential for negative ecological impacts resulting from future invasions with potential economic losses associated with an overly cautious approach. This already difficult situation is complicated further by the uncertain nature of candidate species traits, which are continually "improved" through traditional breeding and genetic modification techniques. Preventing invasions will require re-evaluation of antiquated weed laws that focus primarily on taxa impacting agriculture, not "natural" areas. In addition, prediction and prevention of future invasions will require the initiation of multi-year and multi-site empirical studies quantifying the invasion potential of novel feedstocks within their production regions. We acknowledge that establishment of a robust framework to evaluate the invasive potential of bioenergy crops will not be developed and implemented overnight; however, this book highlights important factors to consider now, and as the industry develops.

1.1 A Bioenergy Renaissance: What's Old is New Again

Plant biomass has been used as a heating and energy source since the dawn of humankind, yet global demand for, and production of, crops grown as a dedicated feedstock for bioenergy—both liquid fuel and biopower—has increased sharply in recent years (Fernandes *et al.*, 2007). For example, between 2000 and 2009, global ethanol output grew from 16.9 to 72.0 bn l (Sorda *et al.*, 2010). This increase in biofuel production was driven by policies

* ldquinn@illinois.edu

recognizing the negative consequences of greenhouse gas emissions from fossil fuel combustion, dwindling global oil supplies, and increased demand for domestic energy security (Robertson *et al.*, 2008). Federal policies in the USA, Brazil, the European Union, and China have set ambitious goals for ramping up the production of bio-based energy in the coming decade (Sorda *et al.*, 2010; Chapter 6, this volume). Many of these policies mandate or support the development of alternative or second-generation (non-food) energy crops (i.e., dedicated feedstocks), not only to protect national food supplies, but also because corn-derived ethanol performs poorly in greenhouse gas life-cycle assessments (Sorda *et al.*, 2010). This growing global momentum towards development and deployment of novel energy crops presents many opportunities and challenges. One such challenge—the unintentional large-scale introduction of potentially invasive species as bioenergy crops—is the focus of this book.

1.2 Feedstock Selection

Government mandates will require dedicated energy crops to be cultivated across large areas (e.g., over 60 million ha in the USA alone (ISAC, 2009)). Because land scarcity is a major issue globally (Lambin and Meyfroidt, 2011), it will be of primary importance to select feedstocks that maximize biomass yield on a given (usually suboptimal) parcel of land. To achieve a favorable economic outcome for developers and producers, it will also be important to minimize chemical inputs (e.g., fertilizer and pesticides) and irrigation, meaning feedstocks will also be selected on the basis of their ability to thrive in low fertility and/or dry conditions. This combination of requirements has led to the agronomic development of plants with little or no history of domestication, many of which are non-native to the production region. Examples include *Arundo donax* L., *Camelina sativa* (L.) Crantz, *Eucalyptus* spp. L'Hér, *Jatropha curcas* L., *Miscanthus* × *giganteus* Greef & Deuter ex Hodkinson & Renvoize, *Panicum virgatum* L., *Pennisetum purpureum* Schumach., *Robinia pseudoacacia* L., and others.

The desire to achieve ever greater biomass yields in novel environments will undoubtedly lead to the application of genetic modification (GM) technologies to existing or new feedstock candidates. In fact, GM is likely to play a major role in bioenergy crop development as there is not sufficient time available to meet agronomic goals or policy mandates through traditional breeding (Xie and Peng, 2011). Furthermore, some of the more promising feedstocks, including the sterile *A. donax* and *M.* × *giganteus*, have limited genetic variation and may not be candidates for traditional crop improvement. Genetic modification has advanced agronomic development of row crops tremendously, primarily by enhancing pest protection (i.e., insects and weeds). Unlike row crops, however, genetic improvement of bioenergy crops will more likely be focused on enhanced stress tolerance (e.g., drought) or traits related to reproduction (e.g., late flowering or introduction of seeded varieties) (Vogel and Jung, 2001).

1.3 Raising the Spectre of Invasion

Although only 0.01% of introduced species are estimated to result in invasions (Williamson and Fitter, 1996), the consequences of some invasions can be severe enough to warrant apprehension about any introduction (Pimentel *et al.*, 2005; Pyšek *et al.*, 2012). This is why, despite the environmental, socioeconomic, and national security benefits of bioenergy production, there is concern about the fast pace and large scale of novel and non-native feedstock introductions. Traditional agronomic crops have been bred for and are cultivated under highly manipulated conditions, and their ability to survive outside of these conditions (e.g., without exogenous irrigation and/or fertilization) is generally low. In contrast, and as discussed above, bioenergy crops are selected for high yields, and for the ability to achieve those yields in suboptimal or "marginal" (Shortall, 2013) growing conditions. Below, we will discuss why the traits of an ideal bioenergy crop raise the spectre of invasion.

Although no single set of traits reliably predicts which plant species will establish weedy or invasive populations, several traits have been correlated with invasiveness in multiple analyses: (i) rapid growth; (ii) perenniality; (iii) asexual reproduction; and (iv) the ability to survive and reproduce in a wide range of environmental conditions (Baker, 1965, 1974; Mack, 1996; Rejmanek, 1996; Kolar and Lodge, 2001; Sutherland, 2004). All of these are desirable traits for bioenergy feedstocks grown on marginal land (Heaton *et al.*, 2010). Furthermore, several plant families contain a disproportionally high percentage of invasive species, including the *Poaceae* (grasses) (Daehler, 1998; Lambdon *et al.*, 2008), a family of particular interest to those developing dedicated feedstocks (Lewandowski *et al.*, 2003). The resemblance of desirable feedstock traits to those of the invasive plant ideotype is precisely what caused scientists to raise concern about invasion potential of non-native bioenergy crops (Raghu *et al.*, 2006). It has since been noted that some bioenergy candidates and their relatives are already regulated as noxious weeds or managed as invaders of natural areas in the USA (Barney and DiTomaso, 2008; Quinn *et al.*, 2013), giving credence to these concerns.

Despite the intuitive nature of utilizing traits as predictors of weediness, in reality, it is very difficult to predict invasion success with accuracy. Certainly, traits such as short generation times, prolific reproduction, and broad environmental tolerances increase the probability of success outside of cultivation, but a multitude of interacting factors (e.g., sufficient propagule pressure, compatibility with the abiotic and biotic environment) contribute to invasion success (Barney and Whitlow, 2008). A "goldilocks" combination of right species, right place, and right time ultimately determines the exotic winners and losers in all ecosystems. Although many sources of uncertainty exist, it is nevertheless worthwhile to assess the risk of invasion by bioenergy feedstocks prior to their introduction if it means that the industry and policy makers will be aware of and encouraged to select safer feedstocks.

1.4 What Do We Know About Invasion Risk?

To date, the majority of published articles addressing the invasive potential of bioenergy crops have been focused on expert opinions and trait-based risk assessments (e.g., Raghu *et al.*, 2006; Barney and DiTomaso, 2008; Cousens, 2008). Only recently have empirical and modeling studies become available for a limited number of feedstocks (see Quinn *et al.*, 2010, 2011, 2012a,b; Barney *et al.*, 2012; Matlaga *et al.*, 2012a,b; DiTomaso *et al.*, 2013; Matlaga and Davis, 2013; Dougherty *et al.*, 2014; Smith and Barney, 2014). This is understandable given that the renewable fuels industry is just getting off the ground in many regions. Many of the feedstocks with hypothesized invasion potential have not yet been introduced on commercial scales, or have been introduced so recently or on such small scales that escapes have yet to be realized. Thus, we have the unique opportunity to evaluate the invasive potential of a suite of new crops before large-scale commercialization, which is a historical rarity. In fact, most of invasion ecology is the study of existing invasions; here, we have the unique opportunity to study and mitigate invasions (potentially) in progress.

One major complicating factor as we evaluate the invasive potential of bioenergy crops is the decades-long lag time that many invasive species display before population growth rates increase and invasiveness is realized (Radosevich *et al.*, 2007). Lag times can be caused by a number of factors, including: (i) re-association with requisite mutualisms; (ii) previously unsuitable environments becoming suitable through disturbance, climate, or other regional or global change; or (iii) genetic changes that allow previously unsuitable genotypes to gain fitness advantages (Crooks and Soule, 1999). Given the difficulty of distinguishing non-invasive populations from populations undergoing a lag phase prior to rapid expansion, official policy often errs on the side of caution (i.e., the Precautionary Principle) and works to prevent introduction of non-native species. This caution has been expressed by governments in the creation of quarantine lists that ban import of known weeds (e.g., the US Federal Noxious Weeds List), or require a formal assessment of invasion risk prior to import (e.g., the Australian weed risk assessment (WRA) system (Pheloung *et al.*, 1999) or the US Animal and Plant Health Inspection Service (APHIS) WRA (Koop *et al.*, 2011)). Several authors have evaluated leading feedstocks through these formal risk assessment systems (Barney and DiTomaso, 2008; Cousens, 2008; Gordon *et al.*, 2008; Buddenhagen *et al.*, 2009; Gordon *et al.*, 2012; Chapter 5, this volume) and found that several species are at high risk for invasion if imported and widely planted.

Despite the wide acceptance of precautionary approaches, Marchant *et al.* (2013) recently argued that the Precautionary Principle has been used "recklessly" and "arbitrarily" due to inconsistencies in implementation, and warned of the economic damage that can result from "ill-advised" application. Certainly a cautiously balanced approach is warranted as we evaluate the pro and con ledger for bioenergy crops. For example, many have cried foul on supporting *A. donax* as a bioenergy crop due to its deserved reputation as a damaging invader in southern California and Texas. In fact, Virginia has historically listed *A. donax* as an invasive species. However, the Virginia Department of Conservation and Recreation is now considering removing it from the list as only two occurrences are known throughout the state (K. Heffernan, Virginia, 2013, personal communication). Additionally, the North Carolina Department of Agriculture and Consumer Services was petitioned to list *A. donax* as a noxious weed, which would have prevented interstate movement and commercialization. A similar situation played out in Oregon when Portland General Electric was planning to cultivate *A. donax* to be co-fired in a power plant. In both cases, it was decided to not regulate *A. donax* due to the economic benefits of cultivation, and the lack of empirical data demonstrating an eminent invasion in the local area (Southern Farm Network, 2014). The example of *A. donax* highlights an important if confounding element to the invasiveness issue in bioenergy feedstocks: economic benefits can trump the potential for environmental harm, especially where impact and/or spread data are lacking. Therefore, it is vitally important to investigate the dispersal behavior, escape and establishment rates, and impacts of feedstocks *in situ* over multiple growing seasons in order to provide an accurate assessment of local risk. Without this data, it is possible that the risk of invasion will be over- or underestimated, leading to potentially inappropriate decisions by regulators.

1.4.1 Economic impacts

We have discussed the economic factors that could lead to approval or denial of a particular feedstock, but we must consider these in a larger cost–benefit analysis that also accounts for potential environmental costs, including invasion. However, because the second-generation biomass industry is so new and any existing escapees have yet to be detected as invaders, we do not have data on the direct costs associated with feedstock invasion outside of cultivation. Therefore, we must discuss what is known about invasive species impacts in general, highlighting the impacts of those feedstocks that are already invasive in some portion of their introduced range. The most recent estimate of the economic impacts of invasive plants is now several years out of date, and relates to the US economy only. Keeping these limitations in mind, the almost $35 bn that the USA spends/loses annually as a result of invasion by non-native plants (Pimentel *et al.*, 2005) is not trivial.

The economic impacts of invasive plants include income loss (e.g., tourism) and navigation impediments (e.g., clogging shipping channels), but result primarily from eradication and control efforts. As Enloe and Loewenstein (Chapter 8, this volume) point out, the cost and success of eradicating an invasive population is proportional to the size of the population; thus, only small populations are practical to consider for eradication. Management costs for larger populations can be astronomical. For example, removing *A. donax* from riparian habitats in California and restoring native plant communities has been estimated at $25,000 acre^{-1} (0.4 ha) (Giessow *et al.*, 2011). This estimate is extremely high because of the severity of *A. donax* invasions in many Californian riparian systems, the tenacious and difficult-to-remove rhizome system of *A. donax*, and the difficulty in navigating heavy removal equipment in sensitive riparian areas. This estimate reflects costs common to all management projects associated with site accessibility, site remoteness, and proximity to sensitive species or habitat (Skurka Darin *et al.*, 2011). Large invasive *A. donax* populations are clearly very difficult and expensive to manage, and therefore may represent a worst-case scenario for costs associated with invasive plant management. Again, this example underscores the importance of detecting and eradicating small incipient populations.

It is important to note that the escape potential for bioenergy crops is not limited to cultivated field boundaries. Propagules can disperse great distances (e.g., Quinn *et al.*, 2011), but perhaps more importantly, natural dispersal distances may be greatly extended through transportation of feedstock material from production fields to storage sites or processing facilities. Transportation routes will likely traverse a diversity of habitats, each of which is likely to vary in its susceptibility to invasion (Dougherty *et al.*, 2014; Smith and Barney, 2014) and in the ease and costs of detection and control or eradication efforts. Because of the importance of early detection and eradication in controlling the progress of an incipient invasion and its associated costs, special attention must be paid to transportation routes. However, considering the scale at which some feedstocks may be grown, the costs of monitoring field margins and transportation routes may quickly add up.

1.4.2 Ecological impacts

Economic impacts are only part of the picture. The ecological damage from invasive plants is variable, but in worst-case scenarios can be staggering and permanent (Vilà *et al.*, 2011).

Invasive plants can directly reduce resident plant and animal species richness, abundance, and genetic diversity, disrupt mutualistic relationships and shift community dynamics, and lead to homogenization of biotic communities (Simberloff and Von Holle, 1999; Vilà *et al.*, 2000; Olden and Poff, 2003; Sax and Gaines, 2003; Traveset and Richardson, 2006; Pyšek *et al.*, 2012). They can also alter ecosystem dynamics and soil quality (Vilà *et al.*, 2011; Pyšek *et al.*, 2012). As Quinn reviews in Chapter 2 of this volume, several invasive feedstocks are known to exert strong ecological impacts on the habitats they invade. For example, *A. donax* can shift ecosystem processes from flood regulated to fire regulated (Spencer *et al.*, 2008; Coffman *et al.*, 2010), indirectly affecting flood-dependent resident species (Coffman *et al.*, 2010). The nitrogen-fixing legume *R. pseudoacacia* shifts community dynamics in resident vegetation to favor nitrophilous species (Von Holle *et al.*, 2006). These and other changes in ecosystem processes occur in conjunction with the direct effects of competitive interactions between invasive species and native residents, and are difficult to reverse through restoration efforts. Again, we cannot predict the impacts of escaped bioenergy feedstocks with accuracy, and the above examples were derived from long-standing invasive populations. Empirical studies are needed to estimate the impact of established feral bioenergy species on native populations, communities and ecosystem processes. Ideally, monitoring and control plans will be enforced to prevent escape, but the scale of introduction far exceeds that of most of our existing invasive plants, and introduces a great deal of uncertainty.

1.5 Future Sources of Uncertainty

We have discussed the potential risks of feedstocks that are of interest currently, but the future will bring greater uncertainty with the introduction of GM crops, fertile cultivars of sterile crops, algal cultivation, and other technologies not yet known. These advancements will likely have major agronomic and economic benefits, but their environmental consequences, including invasiveness, may be harder to predict. Unfortunately, it is no simple matter to assess the risk of invasion by GM feedstocks. As discussed by Barney *et al.* (Chapter 5, this volume), standard invasion risk assessment protocols are not necessarily appropriate for novel genotypes of known crops, and can introduce complexity and additional uncertainty that is difficult to adequately integrate into existing risk frameworks. It is important that assessments of risk be undertaken, however, because modified genotypes may incorporate traits that increase *or decrease* the likelihood of invasion relative to the parent species. Further complicating risk assessment is the fact that existing assessment methods focus primarily on the likelihood of invasion by the taxon in question, and do not account for the possibility of gene flow to and potential hybridization with wild relatives. As reviewed by Ridley and Mallory-Smith (Chapter 4, this volume), gene flow between crops and wild relatives has resulted in weedy hybrids that may benefit from GM traits. For example, gene flow from cultivated sunflowers (*Helianthus annuus* L.) modified with the *Bt* gene conferring herbivory resistance resulted in increased fitness and potential weediness of wild sunflower (Snow *et al.*, 2003). The likelihood of GM traits to appear in wild relatives of bioenergy crops remains unknown, but must be considered in the discussion of invasion potential by these crops.

An additional concern is the recent move towards development of fertile varieties of previously sterile bioenergy crops. Although sterility does not eliminate potential