Experimental approaches for evaluating the invasion risk of biofuel crops

S Luke Flory¹, Kimberly A Lorentz², Doria R Gordon³ and Lynn E Sollenberger¹

¹ Agronomy Department, University of Florida, PO Box 110500, Gainesville, FL 32611, USA
² Forest Resources and Conservation, University of Florida, Gainesville, FL 32611, USA
³ The Nature Conservancy, Department of Biology, University of Florida, Gainesville, FL 32611, USA

E-mail: flory@ufl.edu

Received 22 August 2012
Accepted for publication 11 October 2012
Published 6 November 2012
Online at stacks.iop.org/ERL/7/045904

Abstract
There is growing concern that non-native plants cultivated for bioenergy production might escape and result in harmful invasions in natural areas. Literature-derived assessment tools used to evaluate invasion risk are beneficial for screening, but cannot be used to assess novel cultivars or genotypes. Experimental approaches are needed to help quantify invasion risk but protocols for such tools are lacking. We review current methods for evaluating invasion risk and make recommendations for incremental tests from small-scale experiments to widespread, controlled introductions. First, local experiments should be performed to identify conditions that are favorable for germination, survival, and growth of candidate biofuel crops. Subsequently, experimental introductions in semi-natural areas can be used to assess factors important for establishment and performance such as disturbance, founder population size, and timing of introduction across variable habitats. Finally, to fully characterize invasion risk, experimental introductions should be conducted across the expected geographic range of cultivation over multiple years. Any field-based testing should be accompanied by safeguards and monitoring for early detection of spread. Despite the costs of conducting experimental tests of invasion risk, empirical screening will greatly improve our ability to determine if the benefits of a proposed biofuel species outweigh the projected risks of invasions.

Keywords: invasive, risk assessment, propagule pressure, disturbance, experiment, introduction, community

1. Introduction
Rising energy prices and the increasingly recognized role of fossil fuel consumption in climate change have driven the recent development of second-generation biofuels. However, concern is growing over the possibility of unintended environmental impacts from the hasty adoption of novel biofuel feedstock crops (Demirbas 2009). One of the primary concerns is that introduced biofuel crops will result in escapes into natural areas and widespread, ecologically damaging invasions (Raghu et al 2006, Richardson and Blanchard 2011). This concern is driven by the fact that many of the traits that maximize biofuel crop biomass yield are synonymous with the ecological traits of successful invasive species. Such traits include rapid accumulation of biomass, short generative time, perennial growth form, disease and pest resistance, and tolerance to drought, low soil fertility, and saline conditions (Raghu et al 2006, Barney and DiTomaso 2008, 2010, NISC 2009).

The desirability of these traits in bioenergy crops is apparent in the proposed cultivation of several fast growing species with a long history of invasive spread.
Biofuel feedstock candidates such as giant reed (*Arundo donax*), miscanthus (*Miscanthus sinensis*), reed canary grass (*Phalaris arundinacea*), and Chinese tallow (*Triadica sebifera*) commonly appear on invasive species lists, thus their development as biofuel crops could clash with current efforts to manage these species (Davis et al. 2010). In addition, selecting for certain traits in biofuel crop cultivars may increase the risk of biofuels becoming invasive. For example, while the sterility of *Miscanthus × giganteus* (triploid hybrid between the invasive *M. sinensis* and *M. saccharifloris*) has reduced concerns about invasiveness of this bioenergy crop (Barney and DiTomaso 2008), new efforts have produced a cultivar with viable seed that will be less expensive to propagate (Ross 2011). Furthermore, invasion risk for biofuel crops may be heightened by the sustained propagule pressure associated with large-scale cultivation (Davis et al. 2011, Mack 2008, Minton and Mack 2010). The amount of land required in order for second-generation biofuel crops to meet biofuel production targets is expected to be in the millions of acres (Dale et al. 2011), resulting in high potential for production and release of propagules. Biofuel feedstock may also be transported considerable distances to conversion facilities after harvest, further increasing the potential for release of propagules into natural areas (Barney and DiTomaso 2010).

Given the projected widespread planting of biofuel crops, distinguishing between species or taxa that are likely to become invasive and those with low risk of invasion will minimize the potential for invasions and promote the sustainability of energy production from second-generation biofuel crops (Barney and DiTomaso 2008, Cousens 2008, Gordon et al. 2011). Here we define an ‘invasive species’ as one that is both non-native to an ecosystem (i.e. would not have occurred without human action) and causes ecological or economic impacts (Lockwood et al. 2007). We define ‘invasion risk’ as the likelihood that a species will become invasive. In this paper we review the current methods used to evaluate the invasion risk of non-native species, describe how biofuels provide a unique invasion risk situation, and provide specific recommendations for conducting experimental tests of invasion risk. Such tests have frequently been called for (e.g. Mack 1996, Barney and DiTomaso 2010) but thus far little guidance has been offered.

2. Current approaches for evaluating invasion risk

Biological invasions are the result of a non-native species progressing through a series of steps from introduction to naturalization to having widespread ecological impacts. As such, to become invasive a species must overcome the barriers between stages in the invasion process, and most approaches for predicting invasion risk focus on a species’ ability to pass through specific barriers (figure 1). Tools to evaluate invasion

---

**Figure 1.** Tools to evaluate the invasion risk of biofuel crops presented on a gradient from qualitative to quantitative methods across the stages (shaded arrow boxes) and barriers (hatched bars) of the invasion process. Tools near the qualitative end of the spectrum are characterized by dependence on literature-derived information while quantitative tools are focused on empirical data, experimental tests, and statistical analyses. The gradient also corresponds to the three-sieve approach to invasion risk assessment described by Davis et al. (2010). Notes: 1 FAO (2004), 2 Gordon et al. (2011), 3 Daehler et al. (2004), 4 Richardson and Rejmánek (2004), 5 Rodda et al. (2007), 6 Davis et al. (2011), 7 Minton and Mack (2010), 8 da Silva et al. (2011).
risk range from qualitative tools such as expert evaluation to semi-quantitative tools, including weed risk assessments and climate matching, to quantitative, empirical tools that involve experimental tests in the field (figure 1).

The most basic of the existing invasion risk assessment tools is qualitative expert assessment, where experienced individuals use their knowledge to assess a species’ likely invasiveness (Hulme 2011). The simplest of these approaches relies on the question of whether the species is invasive elsewhere outside its native range. In support of this approach, history of invasiveness correctly predicts invasion probability in a new range 90% of the time (Panetta 1993, Gordon et al 2008b). However, the rapid increase in novel taxa (e.g. for biofuel crops) through hybridization, traditional crop breeding, and genetic modifications, means that the novel taxon may not have a sufficiently long introduction history elsewhere that can be used for predictive purposes. Additionally, the novel taxon may demonstrate such fundamental differences from the original or parent taxon that assessment of the original taxon is of limited value.

One of the most widely used risk evaluation tools is the Australian Weed Risk Assessment (WRA). The WRA is a semi-quantitative tool such that points associated with positive or negative answers to 49 questions about a species’ current weed status in other parts of the world, climate and environmental preferences, and biological attributes are summed, and the total score is used to assign a high or low risk of invasion or the need for further information (Pheloung et al 1999). The WRA is considered a semi-quantitative tool because there are scores associated with predictions that allow users to identify the probability of error associated with the different outcomes (Gordon et al 2012). Variations of the WRA have been successfully adapted for several climatic regions (e.g. Gordon et al 2008a, Buddenhagen et al 2009). Across geographies, the WRA can correctly identify major invaders and non-invaders 90% and 70% of the time, respectively (Gordon et al 2008a), and it can be performed quickly with relatively little expertise. Results are also relatively consistent across geographies of similar climate (Chong et al 2011).

Despite the utility and accuracy of the WRA, there are limitations. Where new taxa are involved, one has to assume that the only traits that might differ from the parent plant(s) or wild type are those that were the subject of manipulation (e.g. sterility, cold tolerance, etc). However, stochastic processes and local interactions with biotic and abiotic features of ecosystems in a new range can greatly influence the establishment and performance of taxa (Hulme 2011, Minton and Mack 2010). These complex processes and relationships are often nested, non-linear, and affected by temporal lags and positive feedbacks (Hulme 2011). Thus they are difficult to predict from the information used in the WRA. Additionally, the WRA does not always produce a conclusion about invasion risk. Even after implementation of a secondary screen (Daehler et al 2004) for species requiring further evaluation, on average 10% of species remain in that category (Gordon et al 2008a). Furthermore, concerns have arisen about WRA assessor subjectivity and inconsistency (Davis et al 2011, Hulme 2011). Finally, because there is no penalty for answering ‘unknown’ for questions that lack supporting evidence, and only ten questions need to be answered to draw a conclusion, it is possible for the WRA to incorrectly indicate low invasion risk for species whose basic biology is relatively undocumented (Barney and DiTomaso 2008).

There may be specific limitations of the WRA for evaluating the invasion risk of biofuel crop species (Cousens 2008). The interpretation of commonly used terms ‘cultivation’ or ‘domestication’ can become unclear in the context of biomass crops. For example, Question 1.01 in the assessment asks, ‘Is the species highly domesticated?’ Assessors are instructed to answer ‘yes’ if the taxon has been intentionally selected over several generations for a particular trait or suite of traits that likely reduces weediness. This decreases the final score by three points, making it more likely that the plant will be accepted for introduction. However, answering ‘no’ does not penalize the final score towards a ‘reject’ outcome. Crops that are cultivated for biofuel feedstock differ from annual species that are primarily cultivated for food production in that breeding for ideal biomass crops may increase typical invasive characteristics (Barney and DiTomaso 2008). This difference may result in underestimation of invasion risk for proposed biofuel crops that are close to the score cutoffs of invasion risk categories.

Weed risk assessment is sometimes conducted using other quantitative prediction tools that make use of demographic parameters derived from the literature or field studies in order to produce population dynamics models. In such demographic population models, invasion risk is determined by the population’s ability to reproduce faster than the mortality rate (i.e. net population growth rate, $\lambda$). If these models output a $\lambda > 1$, this would indicate the potential for naturalized populations to increase, and to potentially become invasive (figure 1, Davis et al 2011). However, such models are only applicable to the conditions and habitats evaluated in a particular study. Similarly, the application of discriminant functions derived from life history and biological characteristics (e.g. height, per cent germination, and minimum juvenile period) can be used to calculate a ‘Z-score’, which can be used to separate invaders from non-invaders based on their probability of becoming widespread (figure 1, Richardson and Rejmánek 2004). Invasion risk can also be assessed using climate data. Climate matching uses algorithms to identify locations that are at risk of being colonized by a non-native species on the basis of similarity to the temperature and rainfall parameters of the species’ native range (Rodda et al 2007). While climate characteristics and invasive potential do not always have a direct relationship, this tool gives a good indication of the potential for non-native species to colonize a new range (figure 1, Barney and DiTomaso 2011). Finally, a tool was recently developed to evaluate invasion risk based on biological traits but scaled to consider economic benefits (Schmidt et al 2012). These approaches are quite valuable; however, the same difficulties arise with these tools as with the WRA when few life-history details for a species or cultivar are known.
These limitations suggest the need for a more holistic approach to screening taxa of potential economic value, like biofuels, where a fully precautionary approach may be overly restrictive. To that end, Davis et al. (2010) proposed that new biofuels be subjected to screening with multiple sieves that might include all of the previously discussed tools, beginning with the WRA. If the WRA (sieve 1) is unable to produce an ‘accept’ or ‘reject’ outcome, quantitative predictive tools such as population dynamics models and climate matching (sieve 2) should be used. If the first two sieves conclude that a species is conditionally acceptable then they recommend that the proposed biofuel species should be further evaluated using experiments (sieve 3). Others have suggested that risk assessments should not be used for final conclusions on invasion risk and that crops should be further screened using in situ agronomic trials (Barney and DiTomaso 2008, 2010). Further, it has been suggested that assessment be performed for all candidate genotypes and cultivars because ecological interactions and growth characteristics (i.e. invasion potential) can vary widely within a species (Casler et al. 2004). Here we outline the advantages, limitations, and potential research methods for such experimental tests of invasion risk.

3. Experimental tests of invasion risk

Experiments that evaluate the invasion risk of biofuel crop species and taxa will increase confidence in predictions of that risk by providing an additional source of information for tools such as the WRA and may resolve recommendations for species that fall into the WRA ‘evaluate further’ category. Several previous studies have experimentally assessed factors contributing to invasion risk. For example, Myers (1983) used a combination of greenhouse experiments and seedling trials in different habitats to predict sites that were susceptible to invasion by the non-native tree Melaleuca quinquenervia in southern Florida. More recently, Minton and Mack (2010) conducted field trials to investigate how founder population size and the amount of cultivation influenced the invasion potential of four non-native species. Davis et al. (2011) expanded upon these approaches in an experiment to determine the role of disturbance and timing of introduction for the invasion success of the biofuel candidate Camelina sativa in rangeland ecosystems. While the value of experimental work is exemplified in these studies, a general framework for evaluating the invasion risk of biofuel crops is needed.

We draw upon the common threads of past experimental evaluations of invasion potential and make recommendations for future work. Because current invasion risk assessment methods poorly evaluate the ability of a species to spread locally and generate self-sustaining populations (figure 1), we focus on this barrier to invasion. Our recommendations include a series of incremental steps from small-scale experiments to determine a species’ basic biological requirements, to experimental introductions across broad geographic networks (figure 2). This stepwise approach should increase confidence in the evaluation of invasion risk of introduced biofuel crop species or taxon (hereafter ‘species’).

Figure 2. Recommended stages of experimental evaluation of potential biofuel crops on a gradient from mechanistic to realistic and from local to regional or national experiments. Arrows follow the suggested progression from local mechanistic experiments to trials in natural areas and eventually experimental introductions across broad geographic networks. The map shows USDA plant hardiness zones (http://planthardiness.ars.usda.gov) and points indicate Plant Materials Centers and Service Areas (http://ppplant-materials.nrcs.usda.gov/centers).

3.1. Greenhouse, growth chamber, and local field trials

The goal of small-scale, local experiments is to identify conditions that are favorable for germination, survival, and growth of proposed biofuel species. While experiments in such controlled environments cannot fully represent the more complicated invasion process, they can be valuable for informing subsequent experiments, which aim to identify habitats most susceptible to invasion. Further, when little is known about the basic biology and traits related to invasiveness of a species, contained experiments are an appropriate precautionary approach prior to field introductions. Preliminary common garden trials in a controlled outdoor setting may also be useful for determining requirements for establishment such as frost protection and insecticide application, which are difficult to approximate in a greenhouse (figure 2). Experimental treatments in growth chambers or greenhouses might include varying levels of moisture, nutrients, light, soil types, or herbivores and pathogens that are hypothesized to be important for determining establishment success.

Small-scale experiments have been used previously to better understand invasion risk of non-native species. For example, Myers (1983) evaluated how different water regimes affected time to germination, seedling height and biomass of M. quinquenervia. Treatments in their greenhouse experiment included seven different combinations of watering amount and frequency, and drainage frequency that corresponded to natural hydroperiod regimes found in different habitats in
nature. They found that seedlings could survive extended periods under water and thus determined that areas with periodic flooding should be included as sites for their experimental field introductions (Myers 1983). This work offers a useful model for initial experiments, but the approach taken for evaluating non-native biofuel candidates will need to be tailored to the species or plant functional group (e.g. grass, shrub, or tree) of interest. For example, germination and establishment requirements often vary widely among small-seeded grasses and larger-seeded trees, which differ greatly in stored resources that can be important for overcoming soil and litter barriers or immersion. In addition, propagule type (stem cuttings/fragments versus seed) may greatly influence when and where individuals might establish.

In general, the detail and extent of small-scale trials will vary among species and functional groups depending on how much is known about their biology. In addition, if multiple specific cultivars are proposed for introduction, each cultivar will need to be evaluated individually. General information about a species may accelerate this process by providing information about what factors are most important for establishment success, but we urge caution in applying results from one cultivar or genotype to other taxa. More broadly, information generated in small-scale experiments is vital for identifying habitats that are most susceptible to invasion, thereby increasing the efficiency of experimental introductions.

### 3.2. Experimental introductions

The next step in experimental evaluation is to assess the most important factors for establishment, survival, and reproduction in experiments that most closely simulate natural invasions (figure 2). Propagules including seeds, or stem fragments if the species reproduces vegetatively, should be scattered into test plots on the soil surface to mimic natural dispersal by wind or water, or disturbance treatments might be applied that result in propagules being buried by soil or leaf litter. We recommend collecting various performance measures include seedling germination and emergence, survival from emergence to maturity, and seed production. These measures can be used to calculate population growth rate ($\lambda$), which can be compared among species (Parker and Kareiva 1996), and provide a measure of a species’ ability to overcome reproductive limitations associated with barriers to naturalization and spread (figure 1).

Evaluation of individual life-history stages using sensitivity analysis (Koop and Horvitz 2006) might help to determine best management practices (BMPs) to control or prevent naturalization and spread. However, it may not be possible to measure fecundity in limited experimental time frames for certain species, particularly for shrubs and trees. More importantly, allowing a potential invasive species to flower and reproduce may not be advisable depending on the location and extent of experiments. Even if fecundity measures cannot be attained, measurement of response variables should be continued for a minimum of two years, although we suggest collecting up to four years of data to overcome the influence of stochastic weather conditions.

Evaluation of invasion risk needs to be based on both the attributes of introduced species and the specific environmental context; thus controlled introductions should occur at multiple sites that represent the range of land use types and natural communities that might be subjected to introductions (figure 2; Ewel et al. 1999, Parker and Kareiva 1996). Previous experimental work has demonstrated the value of repeating experiments in different environments. For example, Davis et al. (2011) employed two historically disturbed rangeland ecosystems that differed in soil characteristics and species richness and observed that the emergence of the introduced non-native species differed between sites. Likewise, *M. quinquenervia* introduced into various community types (e.g. burned transition, drained pond cypress, bald cypress-mixed hardwood, and mangrove) only survived for three years in certain habitats (Myers 1983). Thus, while limited introductions into a few sites may provide some insights, these results suggest that the full range of potentially susceptible habitats needs to be evaluated in order to determine when and where invasions might occur.

Experiments might first be located at only one location or at several locations spaced at latitudinal intervals, but would eventually need to occur in potentially susceptible environments across the full regional or national target range for biofuel planting and dispersal potential (figure 2). Testing across a broad geographic network is valuable not only because invasion potential would be determined relative to different and changing climates, but also because it can increase predictive power in a short time frame by increasing spatial diversity. One possibility is that US Department of Agriculture (USDA) Plant Materials Centers and Service Areas (figure 2, http://plant-materials.nrcs.usda.gov/centers) could provide the distributed field sites appropriate for these tests. Information gained from experiments conducted across the regional or national network could then be integrated in a Geographic Information System (GIS) framework to provide predictive maps of invasion risk (Lindgren 2012).

In addition to testing in different community and land use types, we also recommend that experiments consider the potentially important factors of disturbance, founder population size, and timing of introduction, by comparing these factors as treatments in split plot or block designs (Minton and Mack 2010, Davis et al. 2011, da Silva et al. 2011). Disturbances such as changes in grazing pressure, fire regime, soil scouring, or removal of vegetation are known to be important drivers of invasion (Elton 1958). Further, the type of disturbance and the habitat in which they occur (Burke and Grime 1996) can both affect invasion potential. In an experimental introduction, a disturbance treatment could be applied to individual plots (Davis et al. 2011) or by introducing seeds into plots at sites where the entire area has been disturbed naturally (Myers 1983). Using natural disturbances can accurately represent processes that occur in nature but it may prove difficult to find replicates and appropriate controls across a broad region.

Propagule pressure is also recognized as an important factor in facilitating invasion (Lockwood et al. 2005).
Experimental introductions should test different size founder populations in order to predict the level of propagule pressure needed to overcome stochastic processes and local circumstances that might affect establishment success (Minton and Mack 2010). The number of individuals introduced should reflect hypothesized maximum and intermediate levels that could occur naturally. The timing of introduction should also correspond to the periods of time when propagules are most likely to be spread, such as during seed production and harvest and planting events. Ideal experimental introductions to assess invasion risk might occur in both spring and fall (Davis et al 2011, Parker and Kareiva 1996) using seed and potentially other propagules, and would be repeatedly tested over multiple years.

The development of BMPs that reduce invasion risk, which could be voluntary or regulated, are another avenue for investigation that can be coupled with introduction trials. Some practices may be advisable regardless of the species involved. For example, creating a cleared buffer around cultivation sites would allow for initial monitoring of spread. Such cleared areas could be surrounded by similar buffer zones with dense vegetation (e.g. turfgrass). The width of these buffers would be dependent on the likely distance of vegetative growth or seed dispersal, but might be 10 m for herbaceous species and 30 m for woody species (Cremer 1977). Additional practices to reduce invasion risk would be dependent on more specific establishment traits of the species involved. One example of a BMP designed to reduce the probability of invasion has been developed by the University of Florida for five cultivars of Eucalyptus grandis. This BMP stipulates: (1) 75 ft planting distance from waterways, ditches, and wetlands; (2) planting in monoclonal blocks; (3) maintaining densely vegetated or bare soil perimeter buffers of 75 ft; (4) harvesting prior to seed maturation; and (5) monitoring for and eliminating seedlings within 200 ft of cultivation site (http://plants.ifas.ufl.edu/assessment/conclusions). Development of BMPs for other species and taxa could be accomplished by modifying this model using information derived from local trials and experimental introductions.

4. Limitations of experiments

Empirical methods will greatly increase our ability to assess the invasion potential of non-native bioenergy crops but there are limitations. Compared to non-empirical methods for assessing invasion risk, experiments require greater investments in time, money, labor, and space. As such, it has been suggested that experimental screening is not practical for all non-native or genetically engineered organisms proposed for introduction (Parker and Kareiva 1996). However, we believe that it is reasonable to suggest that experimental screening should be performed for the entire, relatively small, pool of proposed non-native biofuel crop taxa. Questions still remain about who will be responsible for the cost and oversight of experimental evaluations, but one scenario is that evaluations are required as part of a standardized permitting process at the state or preferably federal level. Alternatively, such testing could be promoted as a voluntary code of conduct similar to compliance to best management practices for pesticide and fertilizer use in forestry (Chimera et al 2010). The expense of conducting evaluations could be the responsibility of the importer or developer of the biofuel feedstock or others in the industry that will profit from the introduction. This approach is analogous to the testing of genetically modified organisms in the United States, which are regulated under the National Environmental Policy Act (Parker and Kareiva 1996).

One of the other primary concerns of experimental evaluation is that introductions might result in invasions of non-native species into natural areas. However, in locations with particularly sensitive natural areas, risk of escape can be reduced by placement of experiments within an agricultural or developed landscape distant from conservation areas and by adopting precautionary measures to prevent individuals from spreading outside of the experimental introduction sites. Such actions should include constructing silt fencing or other barriers around plots to reduce the movement of seed, vegetation buffers, monitoring surrounding areas for escaped individuals, and removal of all individuals at the conclusion of the experiment. Experimental work with species with long-lived seedbanks or long distance propagule dispersal mechanisms would require additional precautions. Regardless of the design, all experiments should include protocols for monitoring and responding to off-site colonization—both for assessment and control of incipient spread.

Finally, caution is required when drawing conclusions about invasion risk. It is not logistically possible to test all of the possible scenarios under which establishment and invasion might occur and inferences can only be made confidently for locations with similar biotic and abiotic features to the experimental sites. Additionally, experiments may not be able to capture relatively rare events that might influence invasion risk such as weather extremes or pest outbreaks. Researchers will need to balance what is possible to test with the certainty of their conclusions, keeping in mind that our intent is to improve the probability with which we assess risk, rather than identify definitive outcomes.

5. Conclusions

Current risk assessment systems offer a useful starting point for evaluating the invasion risk of biofuel crops but are limited in their utility due to unavoidable uncertainty. Thus, more experimental, repeatable, geographically distributed tests will improve our ability to evaluate invasion potential (Davis et al 2010). While we will not be able to guarantee that ‘acceptable’ biofuel crops will never become invasive, experimental screening increases our ability to predict invasiveness. If the risk is high, the challenge will be to assess whether the cost of cultivation of a species is likely to exceed the potential benefit. This level of risk assessment will require coordination among all stakeholders involved, including agronomists, ecologists, industry experts, and economists. Information on invasion risk will have to be integrated into a larger regulatory framework at the state or national level in order to maximize
economic benefits but minimize the risk of ecological damage. Through implementing experimental screening of invasion risk for non-native species or cultivars of biofuel crops, we can stimulate progress in the sustainable development of second-generation biofuels, and simultaneously promote practices that protect natural areas from potential invasions.

Acknowledgment

Publication of this letter was funded in part by the University of Florida Open-Access Publishing Fund.

References

Barney J N and DiTomaso J M 2008 Nonnative species and bioenergy: are we cultivating the next invader? Bioscience 58 1–7

Barney J N and DiTomaso J M 2010 Invasive species biology, ecology, management and risk assessment: evaluating and mitigating the invasion risk of biofuel crops Plant Biotechnology for Sustainable Production of Energy and Co-Products ed P N Mascia, J Scheffran and J M Widholm (Berlin: Springer).

Barney J N and DiTomaso J M 2011 Global climate niche estimates for bioenergy crops and invasive species of agronomic origin: potential problems and opportunities PLoS One 6 e17222

Buddenhagen C E, Chimera C and Clifford P 2009 Assessing biofuel crop invasiveness: a case study PLoS One e5261

Burke M J and Grime J P 1996 An experimental study of plant community invasibility Ecology 77 776–90

Casler M D, Vogel K P, Taliaferro C and Wynia R L 2004 Latitudinal adaptation of switchgrass populations Crop Sci. 44 293–303

Chimera C G, Buddenhagen C E and Clifford P M 2010 Biofuels: the risks and dangers of introducing invasive species Biofuels 1 785–96

Chong K Y, Corlett R T, Yeo D C J and Tan H T W 2011 Towards a global database of weed risk assessments: a test of transferability for the tropics Biol. Invasions 13 1571–7

Cousens R 2008 Risk assessment of potential biofuel species: an application for trait-based models for predicting weediness Weed Sci. 56 873–82

Cremer K W 1977 Distance of seed dispersal in eucalypts estimated from seed weights Aust. For. Res. 7 225–8

Daehler C C, Denslow J S, Ansari S and Kuo H C 2004 A Cremer K W 1977 Distance of seed dispersal in eucalypts estimated 2004 International Standards for Phytosanitary Measures Publication No. 11, Rev. 1; Pest Risk Analysis for Quarantine Pests Including Analysis of Environmental Risks (Rome: FAO)

Gordon D R, Gantz C A, Jerde C L, Chaddderton W L, Keller R P and Champion P D 2012 Weed risk assessment for aquatic plants: modification of a New Zealand system for the United States PLoS One 7 e40031

Gordon D R, Oderдорk D A, Fox A M and Stocker R K 2008a Accuracy of the Australian weed risk assessment system across varied geographies Diversity Distrib. 14 234–42

Gordon D R, Oderдорk D A, Fox A M, Stocker R K and Gantz C A 2008b Predicting invasive plants in Florida using the Australian Weed Risk Assessment Invasive Plant Sci. Manage. 1 178–95

Gordon D R, Tancig K J, Onderдорk D A and Gantz C A 2011 Assessing the invasive potential of biofuel species proposed for Florida and the United States using the Australian Weed Risk Assessment Biomass Bioenergy 35 74–9

Hulme P E 2011 Weed risk assessment: a way forward or a waste of time? J. Appl. Ecol. 49 10–9

Koop A L and Horvitz C C 2006 Population dynamics and invasion rate of an invasive tropical understory shrub 8th Int. Conf. on the Ecology and Management of Alien Plant Invasions (Raleigh: EMAP).

Lindgren C J 2012 Biosecurity policy and the use of geospatial predictive tools to address invasive plants: updating the risk analysis toolbox Risk Anal. 32 9–1

Lockwood J L, Casey P and Blackburn T 2005 The role of propagule pressure in explaining species invasions Trends Ecol. Evol. 20 223–8

Lockwood J L, Hoopes M F and Marchetti M P 2007 2011 Invasion Ecology (Malden: Blackwell)

Mack R N 1996 Predicting the identity and fate of plant invaders: emergent and emerging approaches Biol. Conserv. 78 107–21

Mack R N 2008 Evaluating the credits and debits of a proposed biofuel species: giant reed (Arundo donax) Weed Sci. 56 883–8

Minton M S and Mack R N 2010 Naturalization of plant populations: the role of cultivation and population size and density Oecologia 164 399–409

Myers R L 1983 Site susceptibility to invasion by the exotic tree Melaleuca quinquenervia in southern Florida J. Appl. Ecol. 20 645–58

NISC (National Invasive Species Council) 2009 Paper 11; Biofuels: Cultivating Energy, Not Invasive Species (Washington, DC: NISC)

Panetta F D 1993 A system for assessing proposed plant Pests Including Analysis of Environmental Risks (Rome: FAO)

Richardson D M and Blanchard R 2011 Learning from our mistakes: minimizing problems with invasive biofuel plants Curr. Opin. Environ. Sustain. 3 36–42

Richardson D M and Rejmánek M 2004 What attributes make some plant species more invasive? Ecology 77 1655–61

Rodd G H, Reed R N and Jarnevin C S 2007 Climate matching as a tool for predicting potential North American spread of brown tree snakes Proc. Managing Vertebrate Invasive Species ed G Witmer and K Fagerstone (Fort Collins, CO: National Wildlife Research Center)

Ross M 2011 New Miscanthus development possible biomass game-changer? FarmWeek 16 May p 9

Schmidt J P, Springborn M and Drake J M 2012 Bioeconomic forecasting of invasive species by ecological syndrome Ecosphere 3 46