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Research Article

Assessing the Invasion Risk of *Eucalyptus* in the United States Using the Australian Weed Risk Assessment

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Many agricultural species have undergone selection for traits that are consistent with those that increase the probability that a species will become invasive. However, the risk of invasion may be accurately predicted for the majority of plant species tested using the Australian Weed Risk Assessment (WRA). This system has been tested in multiple climates and geographies and, on average, correctly identifies 90% of the major plant invaders as having high invasion risk, and 70% of the noninvaders as having low risk. We used this tool to evaluate the invasion risk of 38 *Eucalyptus* taxa currently being tested and cultivated in the USA for pulp, biofuel, and other purposes. We predict 15 taxa to have low risk of invasion, 14 taxa to have high risk, and 9 taxa to require further information. In addition to a history of naturalization and invasiveness elsewhere, the traits that significantly contribute to a high invasion risk conclusion include having prolific seed production and a short generation time. Selection against these traits should reduce the probability that eucalypts cultivated in the USA will become invasive threats to natural areas and agricultural systems.

1. Introduction

Global travel and trade have resulted in unprecedented introductions of nonnative species [1, 2]. Furthermore, many agronomic and silvicultural species are being selected and bred for rapid growth, high fecundity, and tolerance to a wide range of climatic and environmental conditions [3, 4]. These traits are the same as those of many invasive species, thus there is increasing concern that cultivated species may become invasive [5]. Because biological invasions can have considerable ecological and economic costs [5, 6], accurately predicting which introduced species are likely to become invasive can have significant benefits.

As the majority of the ecological and economic impacts are caused by a relatively small proportion of nonnative species that become harmful invaders [4, 7], tools that differentiate this group from the non-invasive majority are critical. One such tool, the Australian Weed Risk Assessment (hereafter WRA) [8], was developed in Australia and has been used for regulatory purposes for over a decade. This system has now been tested in temperate, tropical, island, and continental geographies and appears to have comparable accuracy across regions [9]. On average across these tests, the WRA correctly identified 90% of the harmful plant invaders as of high invasion risk and 70% of the noninvaders as having low risk [9]. Roughly 10% of each of the noninvaders and the harmful invaders were misclassified, with the remainder requiring further evaluation. This WRA discriminates between invaders and noninvaders independently of the proportion of species in either category, which is important because the true proportions are unknown but are clearly dominated by noninvaders [9, 10]. While concerns about this base-rate, misclassifications and bias have been raised about the WRA and other predictive tools [11], the ecological and economic value of prevention supports the implementation of a proactive approach [12]. The cost savings for Australia associated with implementation of the WRA were conservatively estimated to save up to US$1.67 billion over 50 years [13].

Eucalyptus species (Myrtaceae) are widely cultivated in subtropical and tropical regions for reforestation, production of timber, pulp, and other forest products, and increasingly, as potential bioenergy feedstocks [14, 15]. Several species, hybrids, and genotypes (hereafter "taxa") of eucalypts show rapid growth across a wide range of environments [16]. Selection and genetic modification are increasing that range, focused on a potential need for 20 million tons/year from *Eucalyptus* for pulp and biofuel production in the Southern USA alone by 2022 [17]. As a result, 5,000 to 10,000 ha/year may be converted to commercial *Eucalyptus* plantations in this region [17].

More than 200 *Eucalyptus* taxa have been screened for cultivation outside their native range over the last 180 years [18]. Only a few of these have become harmful invaders, including *E. globulus* [15, 19], *E. megacornuta* [20], *E. camaldulensis* [21, 22], *E. grandis* [21, 22], *E. conferruminata* [15, 22], *E. robusta* [15], and *E. diversicolor* [22]. *Corymbia citriodora* (*C. maculata*), *E. cinerea, E. cladocalyx, E. tereticornis*, and *E. saligna* have also been identified as invasive [15, 22].

The relatively small proportion of eucalypts introduced that has become invasive (~5%) may reflect the frequency and extent of cultivation, number of propagules introduced, or geographic range of introduction (propagule pressure *sensu* [27]), rather than increased likelihood of invasion risk of these taxa [15]. Three of the species identified as invaders above are among the four species (*E. camaldulensis, E. globulus, E. grandis,* and *E. urophylla*) and their hybrids that represent 80% of global *Eucalyptus* plantations [14]. The majority of taxa that have become invasive belong to the subgenus *Symphyomyrtus* [15], so there may be specific biological traits that influence invasion risk. As cultivation of eucalypts is anticipated to increase in the USA, predicting and avoiding those taxa that are likely to become expensive and damaging invasive species would be beneficial.

Given the increasing focus on eucalypts for pulp and bioenergy crop production in both the USA and elsewhere [14, 16], we have selected a suite of *Eucalyptus* taxa for evaluation using the WRA. As these taxa have already been introduced into the USA and received some testing for forestry production, they do not represent a random sample within this genus. Despite their intended use for forest products and biomass, we hypothesized that high and low risk taxa may be identified using the WRA. Assuming that some of these taxa are likely to be cultivated despite the potential for substantial external costs associated with unintended escape and invasion, we identified the traits that were most closely associated with the high risk invasion group. We suggest that selection against those traits could reduce invasion risk as cultivation of eucalypts in the USA increases.

2. Methods

We selected 38 *Eucalyptus* taxa (Table 1) that had previously been evaluated using the WRA in Hawaii, the Pacific, or Florida for which the results are available online (http://www.hear.org/pier/, http://plants.ifas.ufl.edu/assessment/predictive_response_forms.html). Inclusion in previous assessments likely indicates current or historic interest in those taxa for cultivation. These assessments were conducted at the regional scale across limited environmental conditions, but they provided an initial source of the literature and data for each taxon. Furthermore, we found more recent data to address several of the questions than were available when the original assessments were completed.

We followed the published guidance available for use of the WRA [28], which was modified for application in the USA [29]. Like the original WRA, this system has 49 questions that address historical, biogeographical, and biological traits of the species. Responses to the questions result in points ranging from −3 to 5, with the majority ranging from −1 for negative responses to 1 for positive responses [8]. At least 10 questions from the three categories of questions with specified distribution must be addressed for completion of the WRA. The points are summed for a total score with the corresponding conclusions: scores below one indicate that the species has a low risk of being invasive; scores of one through six indicate that further evaluation is necessary before risk level may be concluded; scores above six indicate the species has a high risk of becoming invasive [8]. We used the secondary screen for species requiring further evaluation [23] to resolve the risk level where possible.

Sources of information included primary literature from forestry, biological and invasive species references, floras and websites for different regions of the world, and the U.S. Department of Agriculture (USDA) Germplasm Resources Information Network [30] and USDA PLANTS [31] databases. Natural distribution of eucalypts was determined from Australian floras [32, 33]. All data, including evidence and references used to develop scores, are archived and available (http://plants.ifas.ufl.edu/assessment/predictive_response_forms.html).

We assumed that any published information for a species or hybrid applied to the taxon of that name. Unless we had specific information about seed dispersal, we assumed that all taxa had negligible wind dispersal, but could be water dispersed [15]. Additionally, we assumed that seeds are not dispersed through animal ingestion because *Eucalyptus* seed does not survive the alimentary canal [34]. We also answered negatively about presence of a persistent propagule bank [15] for all taxa. Responses to all other questions were based on taxon-specific data; questions were left blank if no data were available.

The WRA results allowed us to identify *Eucalyptus* taxa with the lowest and the highest risk for invasion. We used regression analyses (Proc REG, SAS Enterprise, 2010) to investigate whether the total WRA score was dependent on the number of questions answered for each taxon independently and all taxa combined. We also identified the questions that differentiated taxa with low and evaluate further conclusions (scores ≤ 6) from high risk taxa (scores > 6) using Welch's t-tests for samples with unequal variances (Proc t-test, SAS Enterprise, 2010).

3. Results

We were able to complete the WRA for all taxa, answering an average of 28 questions (range: 23–35). The scores varied from –3 to 18 across taxa (Figure 1). Out of the 38 taxa,

Table 1: Taxa assessed using the Weed Risk Assessment (WRA) modified for the USA [22], with WRA results from other assessments for comparison.

No.[a]	Species	Subgenus	USA score	Other published score(s)	Risk level
1	*Eucalyptus dorrigoensis*	*Symphyomyrtus*	−3	—	Low
2	*Eucalyptus dunnii*	*Symphyomyrtus*	−2	0[b]	Low
3	*Eucalyptus salubris*	*Symphyomyrtus*	−1	−3[b], −2[c]	Low
4	*Eucalyptus amplifolia*	*Symphyomyrtus*	0	2[d]	Low
5	*Eucalyptus benthamii*	*Symphyomyrtus*	0	—	Low
6	*Eucalyptus stoatei*	*Symphyomyrtus*	0	−2[b]	Low
7	*Eucalyptus cloeziana*	*Idiogenes*	1	−1[b]	Low[e]
8	*Eucalyptus nitens*	*Symphyomyrtus*	1	—	Low[e]
9	*Eucalyptus smithii*	*Symphyomyrtus*	1	—	Low[e]
10	*Eucalyptus caesia*	*Symphyomyrtus*	1	0[b]	Evaluate
11	*Eucalyptus gardneri*	*Symphyomyrtus*	2	0[b]	Low[e]
12	*Eucalyptus gunnii*	*Symphyomyrtus*	2	—	Low[e]
13	*Eucalyptus erythrocorys*	*Eudesmia*	2	6[b]	Evaluate
14	*Eucalyptus platypus*	*Symphyomyrtus*	2	0[b]	Evaluate
15	*Eucalyptus pellita*	*Symphyomyrtus*	3	3[b]	Evaluate
16	*Eucalyptus kruseana*	*Symphyomyrtus*	4	0[b]	Low[e]
17	*Eucalyptus macrocarpa*	*Symphyomyrtus*	4	3[b]	Low[e]
18	*Eucalyptus urograndis (=E. grandis X E. urophylla)*	*Symphyomyrtus*	4	—	Evaluate
19	*Eucalyptus microcorys*	*Alveolata*	5	1[b], 0[c]	Low[e]
20	*Eucalyptus torquata*	*Symphyomyrtus*	5	−1[b]	Low[e]
21	*Eucalyptus intermedia (=Corymbia intermedia)*	*Corymbia*	5	1[b]	Evaluate
22	*Eucalyptus yarraensis*	*Symphyomyrtus*	5	1[b]	Evaluate
23	*Eucalyptus crebra*	*Symphyomyrtus*	6	−1[b], −1[c]	Evaluate
24	*Eucalyptus macarthurii*	*Symphyomyrtus*	6	—	Evaluate
25	*Eucalyptus cinerea*	*Symphyomyrtus*	7	4[b]	High
26	*Eucalyptus paniculata*	*Symphyomyrtus*	7	11[b], 6[c]	High
27	*Eucalyptus sideroxylon*	*Symphyomyrtus*	7	2[b]	High
28	*Eucalyptus urophylla*	*Symphyomyrtus*	7	4[b]	High
29	*Eucalyptus deglupta*	*Symphyomyrtus*	8	2[b]	High
30	*Eucalyptus saligna*	*Symphyomyrtus*	9	7[b]	High
31	*Eucalyptus grandis*	*Symphyomyrtus*	10	11[b], 8[d]	High
32	*Eucalyptus tereticornis*	*Symphyomyrtus*	10	5[b]	High
33	*Eucalyptus viminalis*	*Symphyomyrtus*	10	—	High
34	*Eucalyptus robusta*	*Symphyomyrtus*	11	3[b], −1[c]	High
35	*Eucalyptus citriodora (=Corymbia citriodora)*	*Corymbia*	12	9[b], 6[c]	High
36	*Eucalyptus torelliana (=Corymbia torelliana)*	*Corymbia*	13	4[b]	High
37	*Eucalyptus camaldulensis*	*Symphyomyrtus*	18	12[d]	High
38	*Eucalyptus globulus*	*Symphyomyrtus*	18	10[b]	High

[a]The taxon number corresponds to the number on the bars in Figure 1.
[b][23, 24]: Hawaii and Pacific.
[c][25]: Tanzania.
[d][26]: U.S.
[e]Outcome determined after use of the secondary screen [23].

15 (39%) were determined to have a low probability of invasion, 14 (37%) were predicted to have high probability of invasion, and 9 (24%) required further information (Table 1), even after use of the secondary screen. Several of our predictions (33%) were different from WRA results found previously for the USA and other regions (Table 1), reflecting both the availability of new published data and differences in how the WRA was implemented. All our scores were higher than those found by earlier assessments. In several cases, we found new evidence that a taxon has naturalized beyond its native range (e.g., for *E. robusta, E. deglupta, and E. tereticornis*), explaining a difference of 2 to 4 points. Other authors also responded negatively (incurring negative points) to some questions when they found no

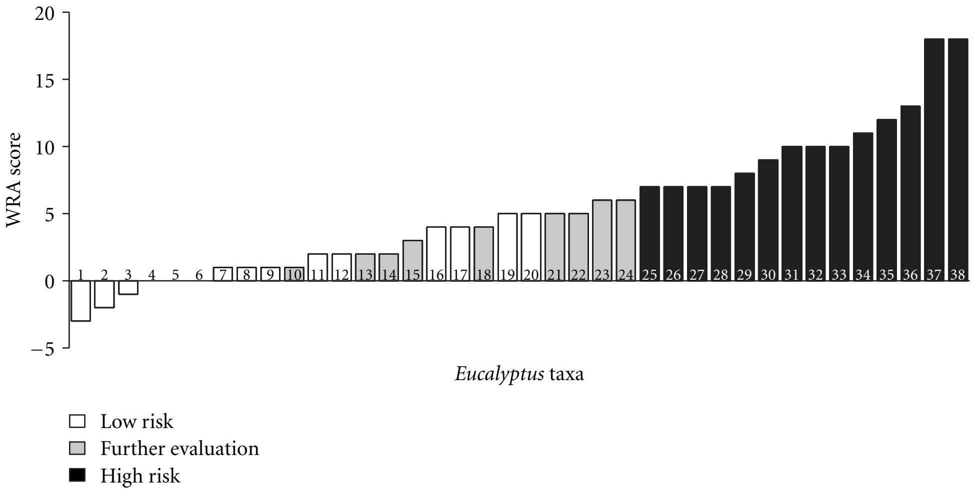

Figure 1: Distribution of Weed Risk Assessment (WRA) scores of 38 *Eucalyptus* taxa evaluated for the USA. Scores < 1 suggest that the taxon is a low risk for invasion; scores of 1–6 indicate that the taxon requires further evaluation unless a secondary screen [23] allowed resolution to a risk outcome; scores > 6 suggest that the taxon is a high risk for invasion [8]. See Table 1 for identification of the taxon associated with each score. Numbers within bars correspond to numbers in the first column of Table 1.

affirmative data. In this case, we were more likely to leave the question unanswered (0 points) following the WRA guidance [28]. We have not presented Florida WRA results in this comparison (http://plants.ifas.ufl.edu/assessment/) as our group conducted those regional analyses.

Across all taxa, total scores were dependent on the number of questions answered ($n = 38$, $P = 0.03$, $r^2 = 0.13$; Figure 2). However, this relationship was not found for taxa predicted to be of high risk ($n = 14$, $P = 0.10$, $r^2 = 0.20$) or for those needing further evaluation or low risk for invasion ($n = 24$, $P = 0.21$, $r^2 = 0.07$). Taxa for which we could answer high numbers of questions but were designated as low risk included *E. dunnii* (31 questions answered), *E. macarthurii* (31), *E. nitens* (32), *E. benthamii* (34), and *E. gunnii* (34).

Not surprisingly, traits associated with whether the taxon has been introduced and invasive elsewhere (naturalized beyond its native range, invasive in disturbed, agricultural, or natural areas) were disproportionately ($P < 0.0001$, $P = 0.0009$, $P = 0.04$, and $P = 0.02$, resp.) associated with high risk taxa (Figure 3). Other traits contributing to the invasive conclusion included short generation time ($df = 16$, $t = 2.13$, $P = 0.045$) and prolific seed production ($df = 5$, $t = 3.16$, $P = 0.025$) (Figure 3). Absence of a specific pollinator requirement ($P = 0.08$) and seed dispersal by animals (invertebrates; seed not ingested) ($P = 0.08$) also contributed to prediction of high risk for invasion.

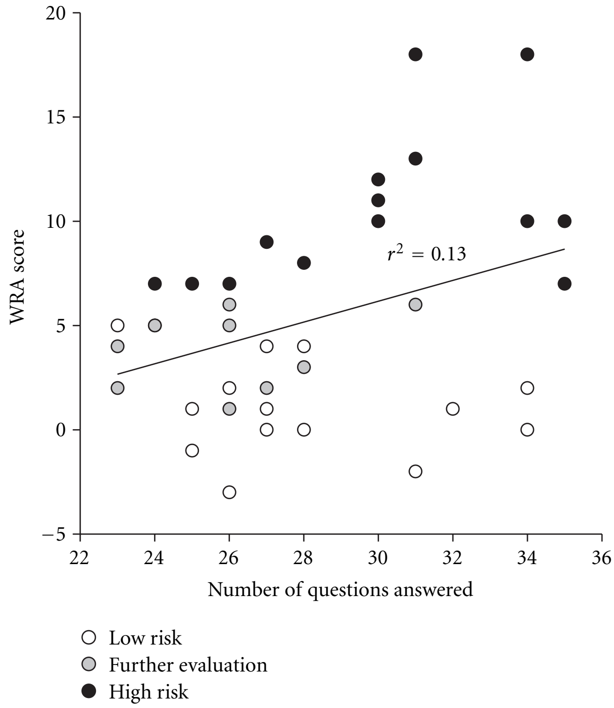

Figure 2: Relationship between the number of questions answered and the WRA score for *Eucalyptus* taxa assessed.

4. Discussion

The majority of eucalypts assessed was determined to present a low risk for invasion or required further evaluation (collectively, 63%). Conversely, over a third of the taxa (37%) were predicted to pose a high invasion risk. While this percentage would be unexpectedly high if the taxa had been randomly selected from all possible eucalypts [7], higher proportions are not unusual for forestry species cultivated over large areas. For example, 24% of the species introduced to Australia for forestry have naturalized, and 17% have become harmful invaders [35]. Forestry species represent 13% and 24% of the invasive species flora in North America and Europe, respectively [4]. Twenty percent (22/110) of *Pinus* species are invasive outside their native ranges [4]. Overall, tree species with multiple uses are disproportionately likely to be invasive [4].

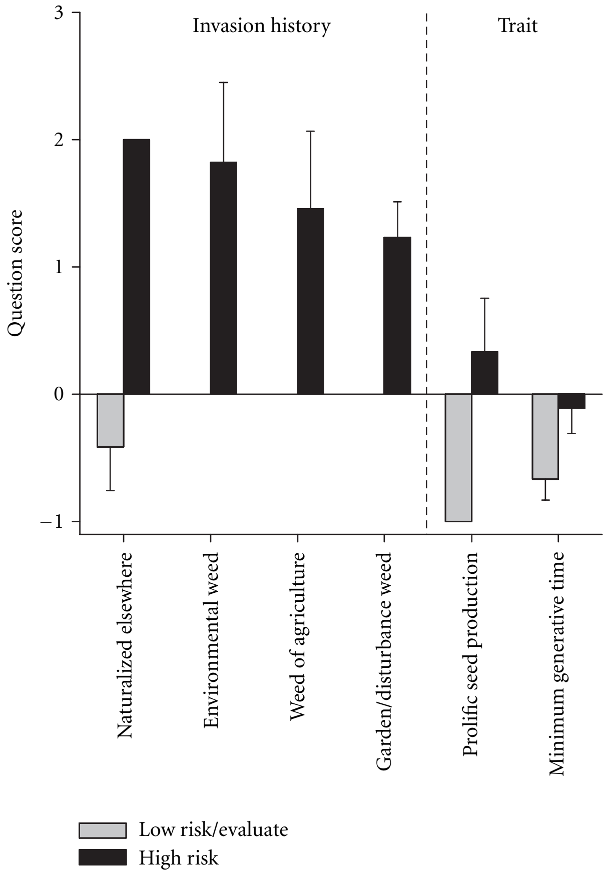

Figure 3: WRA questions on invasion history elsewhere or specific traits with responses (mean ± SE) that significantly ($P < 0.05$) differentiated taxa that scored ≤6 (low risk or requiring further evaluation) from >6 (high risk).

Of the *Eucalyptus* taxa we evaluated, more were predicted to have a high risk of invasion than are currently recognized as harmful invaders. This result may be due to the lag time often observed with invasion [36]. The only study that has quantified the lag time in invasive tree species found that it takes an average of 170 years from the time of their introduction to identification as invasive [37]. That lag can result from several factors, from intrinsic rates of population growth, to selection for tolerance to the new environment, to changes in climate or other environmental or biotic characteristics [37]. Propagule pressure has been demonstrated to influence the lag time and the probability of invasion as more genotypes are introduced into more environments, increasing the opportunity for taxa to encounter a situation favorable for population growth [27, 38].

Invasion by eucalypts has been contrasted with that by pines as likely resulting more from propagule pressure than from biological traits [15]. While the four globally most extensively cultivated taxa: *E. globulus, E. camaldulensis, E. grandis*, and *E. tereticornis* [15, 17] had high risk outcomes, so did a number of other taxa. *Eucalyptus urograndis*, the other most frequently cultivated taxon [17], requires further evaluation before risk can be assessed. Significant reliance of the WRA on whether the taxon is invasive outside its native range (Figure 3) supports the contribution of propagule pressure to invasion risk. However, traits of specific taxa and characteristics of introduction sites may also be critical.

While our evaluation was conducted at the national scale because eucalypts are cultivated in multiple states and territories, the majority of new cultivation is likely to be across the southeastern states [17]. Thus, as discussed previously, a more regional assessment may provide greater resolution of these outcomes for different species (Florida WRA results by region at http://plants.ifas.ufl.edu/assessment/). Differences in phenology, age at reproductive maturity, seed viability, and cold tolerance will certainly impact the potential invasiveness of species and genotypes. As the acreage planted in *Eucalyptus* increases, the potential for spread from plantations will be better understood. Moreover, the active selection for genotypes that are cold tolerant and have desirable growth and wood characteristics (e.g., [14]) means that although some species have been introduced for many years, novel genotypes with unknown invasiveness are being propagated. As a result, the list of *Eucalyptus* taxa currently considered invasive in the USA may not be indicative of the long-term invasion risks from this genus.

The differences in WRA outcomes between our work and earlier assessments (Table 1) contrast with reports of the generality of WRA predictions across geographies with similar climates [39]. Although we sought to conservatively interpret the literature and answered questions only when we found specific evidence, our scores are consistently higher than those from other efforts. However, several recent publications (e.g., [4, 15, 16]) provided data not available to earlier studies. Additionally, the greater range of environments in the US versus a more regional scale effort increased the potential habitat suitability for some taxa. Improvements in both of the available data and guidance for application of the WRA and the secondary screen should reduce discrepancies in scoring and the probability of cognitive bias [11], increasing the reliability of the WRA results. We found only a weak correlation between WRA score and the number of questions answered when data for all conclusions were combined (Figure 2), indicating that risk prediction is largely independent of the amount of data available on taxa (see also [23]).

The hypothesis that taxa in the subgenus *Symphyomyrtus* are likely to be more invasive than taxa in other subgenera [15] is not supported by our data. While we had insufficient numbers of taxa in other subgenera to specifically test this hypothesis, taxa in this subgenus spanned the range of low to high risk results (Table 1). This suite of species suggests that *Symphyomyrtus* taxa are more likely to be cultivated than taxa from other subgenera (see also [15]).

Of the eucalypts that are currently most likely to be cultivated in the Southern USA [40], four (*E. amplifolia, E. benthamii, E. dunnii,* and *E. dorrigoensis*) are predicted to be low invasion risks, and two (*E. camaldulensis* and *E. viminalis*), high risks. The remaining two taxa likely to be cultivated (*E. macarthurii* and *E. urograndis*) need further evaluation. *Eucalyptus grandis, E. robusta,* and *E. saligna*, which have also received increasing attention

[14, 41], are all predicted to pose a high risk of invasion. We suggest a precautionary approach for using eucalypts in pulp, bioenergy, and other products by focusing on the taxa that have a low probability of becoming invasive [42] or by selection against traits likely to increase invasion risk (Figure 2).

Examination of the WRA results for high risk taxa may indicate specific traits that may be modified through plant breeding or genetic alteration that significantly reduce that risk [43, 44]. Selection, plant breeding, and genetic modifications have been used to reduce the probability of invasion in other taxa [3, 43, 44]. The biofuel grass hybrid *Miscanthus* × *giganteus* is sterile, unlike one of its highly invasive parents, *Miscanthus sinensis* [43]. Allelopathy, a trait that can support invasiveness, has been modified in species such as rice (*Oryza sativa*) [45]. Not surprisingly, our results suggest that reducing fecundity would reduce the probability that taxa will become harmful invaders. While reducing the time to maturity may negatively influence productivity, eliminating seed production appears feasible [46–48] and would effectively eliminate concerns about invasion.

If predicted high risk eucalypts are cultivated, those plantings should be treated as experimental testing of the predictions made by the WRA [49]. Maximizing the utility of that approach would require careful tracking of seedling establishment over multiple decades. These data are critical for evaluation of the actual invasiveness of taxa and refinement of weed risk assessment approaches.

5. Conclusions

Given the growing interest in identifying and cultivating bioenergy crop species, the WRA is increasingly being used to evaluate the invasion risk of those species (e.g., [24, 26, 42, 43]). An accompanying approach is to specify the best management practices that reduce invasion risk. These practices might span from taxon selection as described above, to cultivation and monitoring practices. Examples for eucalypts may be to avoid cultivation near waterways [15] and manage plantations to reduce seed production, including harvesting stems prior to seed maturation (see additional specific and limited uses for *E. grandis* cultivars identified by the University of Florida at http://plants.ifas.ufl.edu/assessment/conclusions.html). If the risk of invasion is outweighed by the likely benefits, creation of a fund designed to cover any necessary control costs for species with WRA scores > 6 would be advisable. If propagule pressure is the key to invasiveness in eucalypts [15, 38], one approach might be to restrict the extent of cultivation of any one taxon. However, the key to avoiding costly invasion impacts will likely be selection for sterility and vigilant control of even apparently slow spread from cultivation sites.

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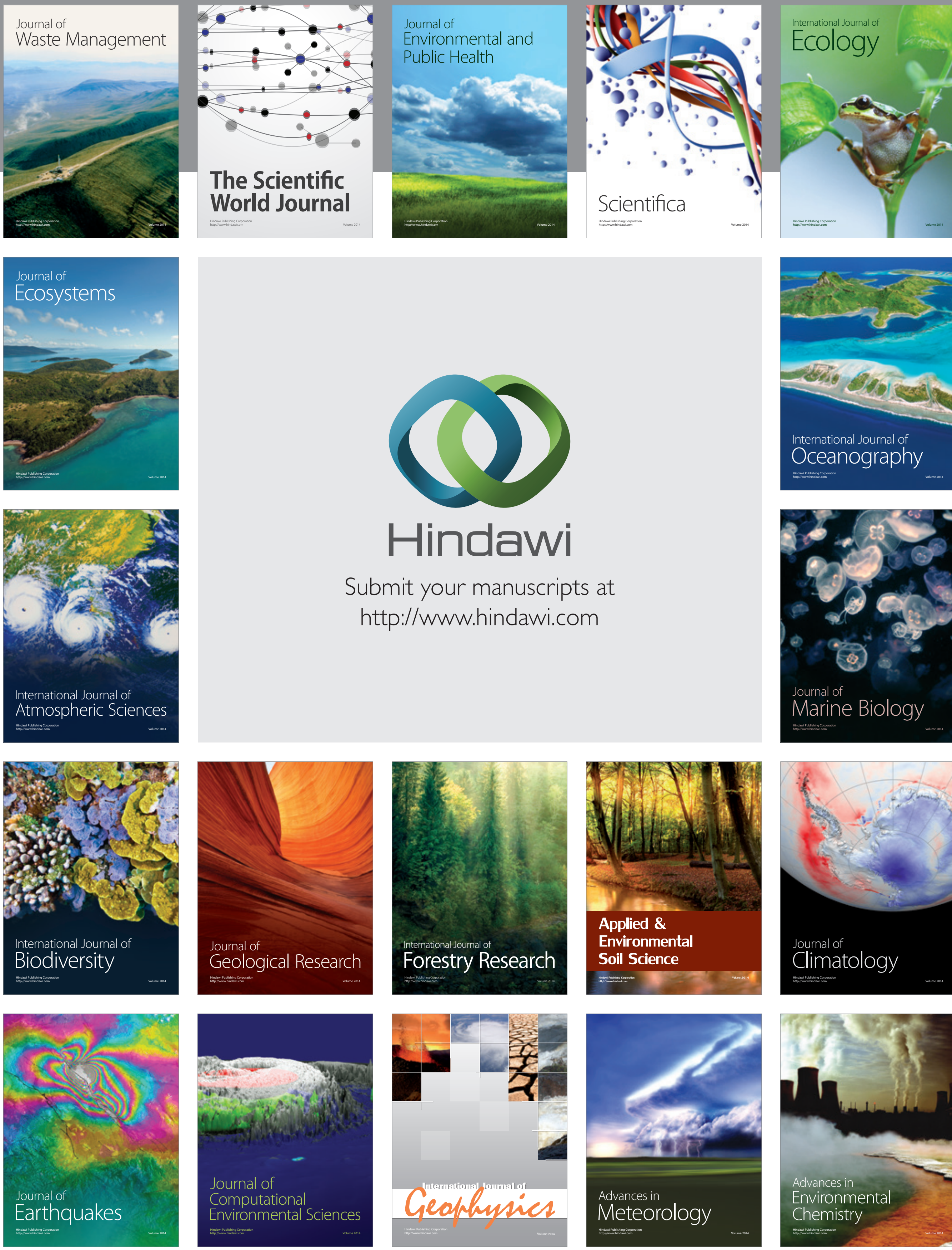
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