Austral Ecology A Journal of ecology in the Southern Hemisphere

Austral Ecology (2019) **44**, 28–35

Predicting invasion risk of 16 species of eucalypts using a risk assessment protocol developed for Brazil

SÍLVIA R. ZILLER,[1] MICHELE DE SÁ DECHOUM[1,2]* AND RAFAEL DUDEQUE ZENNI[3]
[1]*Instituto Hórus de Desenvolvimento e Conservação Ambiental, Florianópolis, SC, Brazil (Email: mdechoum@gmail.com),* [2]*Programa de Pós Graduação em Biologia de Fungos, Algas e Plantas, Universidade Federal de Santa Catarina, Caixa Postal 476, Campus Universitário Trindade, Florianópolis, SC 88040-900, Brazil; and* [3]*Setor de Ecologia, Departamento de Biologia, Universidade Federal de Lavras, Lavras, MG, Brazil*

Abstract Risk analyses are predictive systems designed to detect the risk of invasion by non-native species. Although eucalypts are often considered moderately invasive given the extent of cultivation on a global scale, some species are widely recognized as invasive for transforming and impacting natural areas in several countries. These problems may be due to propagule pressure derived from human interest in forest production and aesthetic values. Risk analyses were carried out for 16 eucalypt species cultivated in Brazil using a protocol adapted from an Australian model to Brazilian conditions. The species were: *Corymbia citriodora*, *Corymbia maculata*, *Corymbia torelliana*, *Eucalyptus benthamii*, *Eucalyptus brassiana*, *Eucalyptus camaldulensis*, *Eucalyptus cloeziana*, *Eucalyptus dunnii*, *Eucalyptus globulus*, *Eucalyptus grandis*, *Eucalyptus pellita*, *Eucalyptus robusta*, *Eucalyptus saligna*, *Eucalyptus tereticornis*, *Eucalyptus urophylla* and *Eucalyptus viminalis*. Results indicate high risk for seven species, moderate risk for eight species and low risk for one species. The only low risk species is *E. dunnii*, while the highest risk scores refer to *C. torelliana*, *E. tereticornis* and *E. grandis*. These results are consistent with the history of invasion of the species around the world and should be considered for plantations especially when investment capacity to prevent and permanently control spread is low or not associated with forest certification standards. Risk analysis is a valid tool for discriminating between species and making decisions on species to be introduced or cultivated. The results of this study show that there are many species that can be cultivated without incurring biological invasions.

Key words: forestry, invasive non-native species, management, prevention, tree invasion.

INTRODUCTION

Risk analyses are predictive systems that can provide valuable information on the likelihood of biological invasions and their consequences. Risk analysis results have been used as a basis for decision-making, management and public policies for invasive non-native species (National Research Council 2002). The most important factors influencing the establishment potential of species introduced to new habitats often are propagule pressure, climatic similarity and history of invasion elsewhere (National Research Council 2002; Hayes & Barry 2008; Richardson & Pyšek 2012). Propagule pressure is a combined measure of the number of individuals released in an area where they are not indigenous, considering the number of propagules per introduction effort, and the number of introduction efforts. It also considers the number of source populations, as the higher the genetic diversity between populations, the higher the chance of establishment (Lockwood *et al.* 2005; Crawford & Whitney 2010; Zenni & Simberloff 2013). The results of risk analyses provide a base for science-based decision-making in the selection of species to be introduced and used for different purposes while considering requirements of environmental conservation and sustainability. They also indicate the need for management of non-native species which are likely to invade, providing opportunities to prevent biological invasions and their impacts on native species, habitats and ecosystem services (Rejmánek 2001; Stohlgren & Jarnevich 2010; Lonsdale 2011).

Risk analyses also consider species traits, such as persistence, reproduction and dispersal, as well as climatic and environmental characteristics (Daehler *et al.* 2004), impacts on the environment, to people, the economy and health, and the feasibility of control and eradication. History of invasion elsewhere is one of the most consistent predictive factors of potential invasiveness (National Research Council 2002; Dawson *et al.* 2008). For instance, among 155 tropical and subtropical forage grasses established in Australia, 98.7% are registered as invasive in other

*Corresponding author.
Accepted for publication June 2018.

doi:10.1111/aec.12649

countries and 93.5% are invasive in Australia (Van Klinken *et al.* 2013).

While risk is the product of the likelihood of an event or process and its consequences (National Research Council 2002), the consequences of impacts by invasive non-native species are more difficult to predict (Williamson 2001; Kumschick *et al.* 2014). Therefore, a preventative approach may consider blocking all species introductions or eradicating all non-native species from legally protected areas (Rejmánek 2001). Rather than adopting radical measures without clear decision-making criteria, it is best to try to filter those species whose introduction should be avoided, decide which new species should be sought for use and which non-native species already present are a priority for control or eradication (Rejmánek 2001), as well as identifying which economically relevant species require continuous management to prevent and control biological invasions.

The majority of terrestrial plants currently acknowledged as invasive in Brazil was introduced intentionally for ornamental and economic use (Zenni 2013). Although ornamental plants represent most of these species, trees used in forestry, agroforestry and related uses such as shade, wind-breaks, poles, firewood, charcoal production, erosion control and, more recently, carbon sequestration (Richardson 2011a; Dickie *et al.* 2014), and energy production based on biomass (Gordon *et al.* 2012) are disproportionally invasive all over the world (more than 70 species), probably due to the extent and ample distribution of plantations and provenance trials (Richardson 2011b; Gordon *et al.* 2012). Furthermore, many of the characteristics of species useful for biomass production overlap those associated with invasiveness (Barney & DiTomaso 2008; Quinn *et al.* 2014). In Australia, 24% of the species introduced for forestry are naturalized and 17% are aggressive invaders. In North America, 13% of all invasive plants are forestry species, and in Europe, the proportion is 24% (Gordon *et al.* 2012). The great bulk of forest production worldwide relies on pine, eucalypt and acacia species, as well as a number of other legumes (Richardson 2011a).

Around one hundred of all introduced plants in Brazil are eucalypts, with about 30 species and hybrids having commercial value (Flores *et al.* 2016). The most widely planted species are currently *Eucalyptus grandis* and *Eucalyptus urophylla* (Silva *et al.* 2011). There are records of about 98 species of eucalypts introduced by 1984 (Tomazello Filho 1987). The Edmundo Navarro de Andrade State Forest, also known as 'Horto Florestal Rio Claro', was created in 1909 as an experimental forestry station for trials with eucalypts, but more than 50 species in the genus had already been introduced in Brazil in the 19th Century (Castellano *et al.* 2013).

There are more than 800 species of eucalypts (currently in the genera *Angophora*, *Corymbia* and *Eucalyptus*) native to Australia and a few islands in the Pacific Ocean (Rejmánek & Richardson 2011). Only occasional invasion processes are observed from eucalypt plantations in Brazil (Miolaro *et al.* 2017). They are most often not very aggressive, with a few exceptions in open ecosystems, especially grasslands and savannas as well as in deforested areas (Instituto Hórus de Desenvolvimento e Conservação Ambiental 2017; Miolaro *et al.* 2017).

Because more than 70 species of eucalypts are established in different countries outside their native ranges, considering the global extension of more than 20 million hectares in tropical, subtropical and temperate regions, they seem to be less aggressive invaders than other genera of cultivated trees (Rejmánek & Richardson 2011; Booth 2014). The total area of eucalyptus plantations in Brazil is 4.87 mha (Valduga *et al.* 2016). Even where invasion does occur, there are few cases of long-distance dispersal and regeneration is often occasional. There are apparently three main reasons to explain the limited invasion capacity of eucalypts: (i) seed dispersal is relatively limited, as the seeds lack morphological adaptations for long-distance dispersal; (ii) high seedling mortality, as the endosperm is practically non-existent, therefore requiring quick rooting and damp, litter-free soil for the seeds to land on; and (iii) the absence of compatible ectomycorrhizal fungi (Rejmánek & Richardson 2011). These reasons may explain the only occasional eucalypt invasions in Brazil. Bare soils are not common in natural ecosystems (Silva *et al.* 2016), especially in humid climates. Still, some eucalypt species have a history of invasion in other countries and therefore require careful management and constant monitoring. Proactive management measures to reduce the opportunities for biological invasion and eradicate plants in early stages of invasion must be incorporated in silvicultural practices for all forestry species (Richardson 2011a).

Assuming that it is feasible to discern invasion potential between species (Copp *et al.* 2009), risk analyses were conducted for 16 eucalypt species cultivated in Brazil (genera *Eucalyptus* and *Corymbia*). The objective of this study was to identify distinct levels of risk as an asset for practical management so that species of low risk are given preference for use, while the management of species of high risk already in use should incorporate prevention and control practices to avoid biological invasions and derived impacts.

METHODS

The protocol used for the risk analyses was adapted from the Australian system (Pheloung *et al.* 1999; Pheloung 2001) and its adaptation to the Galapagos Islands (Rogg

 doi:10.1111/aec.12649

et al. 2005) in a joint effort of the private company Proflor and the NGOs Horus Institute for Environmental Conservation and Development and The Nature Conservancy of Brazil. The protocol was developed and adjusted between 2007 and 2009. The main modifications were made on climatic matching questions and to reduce the focus on oceanic islands included in the Galapagos protocol (Appendix S1). Climate types were listed in the Brazilian protocol based on the Köppen–Geiger classification. Climate matching was based on the native range of the species as well as on other areas where it has been introduced and is established or invasive in comparison with the climatic types in Brazil.

Some questions were not replicated to the Brazilian protocol because they were too specific to either Australia (areas with extended dry periods) or the Galapagos (volcanic islands, national parks). The question on fire hazard in the Australian protocol was expanded for the Galapagos and Brazil to include changes in more ecosystem processes such as soil erosion or hydrology. The weight given to trees as invasive species is higher in the Brazilian protocol (2 points) because a high proportion of the invasive alien species identified so far are trees (Zenni & Ziller 2011; Zenni 2015); all other life forms count 1 point. Bats were added to the question on dispersal by birds. The question on whether the non-native species benefits from scarification, fire or cultivation was eliminated for lack of evidence at the time and because fire is only part of two types of ecosystems in Brazil. Most of the questions in section 9 in the Galapagos protocol were not used because they are too specific to the islands or are covered in the protocol in slightly different ways.

Before the risk analysis protocol was considered ready for use, 51 plant species present in Brazil were tested, 26 of which were invasive in Brazil and 25 were not. Some species such as *Rhododendron* spp. and *Camelia sinensis* have been widely distributed in the world but there are no records of invasion for them, so the risk was expected to be low. Conversely, the risk for ruderal species such as *Bidens pilosa* was expected to be moderate, and the risk for species widely acknowledged to be invasive, such as those on the 100 of the worst invasive species list compiled by IUCN, was expected to be high. The average score for invasive species was 17.7, with a maximum value of 28, while the average for non-invasive species was 10.8, with a maximum value of 21 for a species that was inaccurately classified.

A level of accuracy of 90% in all results, from low to high risk, was calculated from the assessments carried out to adjust the model. Five species were not classified in the correct risk category for Brazil: three of them are considered invasive in only a few areas in the country for particular reasons (*Coffea arabica*, in abandoned cultivation areas; *Persea americana*, which is often planted in farms as a fruit tree and left behind upon land use changes such as conversion into protected areas, and *Sechium edule*, a climber that has been used to smother Atlantic forests in order to facilitate illegal forest suppression), and two species that are not invasive in Brazil were classified as low risk (*Plantago major* and *Rubus rosifolius*, both invasive elsewhere, but present in Brazil as ruderal species). Based on these results, risk thresholds were set to 8 points or less for low risk, 9–20 points moderate risk, requiring further analysis, and 21 points or more for high risk. Over 100 risk assessments were carried out afterwards, and are available at http://www.institutohorus.org.br/index.php?modulo=inf_analise_risco_plantas_horus.

The protocol consists of 45 questions organized into eight topics: cultivation, climate, records of occurrence and invasion, undesirable attributes, habit and competition potential, reproduction, dispersal mechanisms and attributes of persistence (see Appendices S1 and S2). As in the Australian (Pheloung *et al.* 1999) and Galapagos (Rogg *et al.* 2005) protocols, each answer corresponds to a specific score (Appendix S1). Some questions are more relevant than others, whereas others count negative points as they infer low invasion capacity. We established a standard of three references to validate each answer, which are registered in a parallel spreadsheet. References included scientific papers and technical reports, mainly found through searches on Google Scholar (see Appendix S3).

Scores vary from 0 to 49. Risk is low if the score is between 0 and 8 points, in which case the system recommends that the species be accepted for introduction; risk is moderate if the score is between 9 and 20 points, which means the species behaves as a ruderal and might become invasive or not, creating uncertainty; and risk is high if the score between 21 and 49 points, when the system recommends that the species be rejected. Moderate risk (9–20 points) indicates that species might not be very aggressive but their behaviour is less predictable, so further analyses are desirable. Species with moderate risk may be in the process of adapting to the new environment, often being established but not invading.

A minimum number of questions has to be answered in each section of the protocol in order to ensure that all groups of factors are considered: two in section A, six in section B and six in section C. If these conditions are not met, the system indicates that the analysis is not valid and complementary information is required. This was the case of the assessment of the hybrid *E. urophylla* × *E. grandis*. Not enough information was found to answer the questions, and the analysis was not completed.

This plant risk analysis protocol was used to conduct assessments of 16 eucalypt species, three in the genus *Corymbia* and 13 in the genus *Eucalyptus*. These are the eucalypts currently most commonly planted in Brazil (A. Higa, pers. comm., 2012). Each assessment demanded 6 h of work on average, varying with the amount of information available for each species.

RESULTS

Only one of the 16 species, *Eucalyptus dunnii*, was assessed as low risk. Eight species were assessed as moderate risk, and seven high risk (Table 1). Scores varied between five and 26. The highest scores were computed for *E. grandis* (26), *Corymbia torelliana* (24) *and Eucalyptus tereticornis* (24), while *E. dunnii* had the lowest score (5) (Table 1). Enough information was available to answer the minimum number of questions per section of the risk analysis. Between 35 and 41 questions were answered in each of the assessments.

doi:10.1111/aec.12649

Table 1. Results of risk assessment for 16 species of *Eucalyptus* and *Corymbia* introduced to Brazil

Latin name	Questions answered	Level of risk	Score
Eucalyptus dunnii	41	Low	5
Eucalyptus cloeziana	35	Moderate	9
Eucalyptus benthamii	37	Moderate	11
Eucalyptus viminalis	39	Moderate	11
Eucalyptus pellita	37	Moderate	13
Corymbia maculata	41	Moderate	14
Eucalyptus globulus	38	Moderate	18
Eucalyptus urophylla	38	Moderate	18
Corymbia citriodora	38	Moderate	20
Eucalyptus brassiana	42	High	21
Eucalyptus camaldulensis	35	High	22
Eucalyptus robusta	37	High	22
Eucalyptus saligna	36	High	22
Corymbia torelliana	40	High	24
Eucalyptus tereticornis	38	High	24
Eucalyptus grandis	39	High	26

The species are in order of increasing risk. The level of risk is divided into three categories: low (values less than 8 points), moderate (values between 8 and 20 points) and high (values above 20 points).

For 13 species (81%), the section related to biogeographical history contributed to more than 50% of the final score, especially those questions regarding records of occurrence/repeated introductions and invasion (Table 2). The exception was *Eucalyptus benthamii*, for which most of the scores were attributed to undesirable traits and potential competition for resources (Table 2). The questions on dispersal mechanisms lowered the risk of 11 species and were neutral for another three species (Table 2). The complete assessments and references are available in Appendices S2 and S3 respectively.

Climatic similarity was positive for all eucalypts assessed for at least one Köppen–Geiger climate type of groups A or C existent in Brazil, with more matches for group C, the predominant climate type in the species native ranges. These results were expected because most introductions were made after 1970, when climate matching studies had already been conducted (Golfari & Pinheiro Neto 1970; Golfari *et al.* 1978).

The question on repeated introductions outside the native range (a partial expression of propagule pressure) was answered positively for all species, as they have been used in forestry trials in several countries and has commercial value. No records of establishment or invasion were found for *E. benthamii*, *Eucalyptus cloeziana*, *E. dunnii*, *Eucalyptus pellita*, *E. urophylla* or *Eucalyptus viminalis*. Therefore, negative scores for this question reduced the overall risk of invasion for these species.

Records of impacts on ecological processes, especially due to high water consumption, and tolerance to low fertility, sandy soils were found for 13 species. The section on undesirable attributes, which includes structures that hinder management (thorns, climbing

Table 2. Final scores per section (A, B and C) and subsections (A1–A3, B1–B2 and C1–C3) of the risk assessment protocol used to assess the risk of biological invasion of each of the 16 species of *Eucalyptus* and *Corymbia* introduced to Brazil

	Species ID															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
A – Biogeographical history																
A1 – Cultivation/Domestication	−1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A2 – Climate	4	2	2	2	4	4	4	2	6	4	6	6	6	6	6	6
A3 – Records of occurrence and invasion	9	9	11	1	9	9	1	1	6	9	1	9	9	9	5	5
Total section A	12	11	13	3	13	13	5	3	12	13	7	15	15	15	11	11
B – Undesirable traits																
B1 – Undesirable traits	2	0	0	0	1	2	1	0	1	2	0	0	1	0	0	0
B2 – Habit and potential competition for resources in natural areas	4	6	6	6	5	6	4	3	2	5	6	5	4	3	0	0
Total section B	6	6	6	6	6	8	5	3	3	7	6	5	5	3	0	0
C – Biological and ecological traits																
C1 – Reproductive mechanisms	3	−1	2	2	1	2	1	2	0	5	1	2	2	1	0	0
C2 – Dispersal mechanisms	−4	−3	2	−2	−2	−2	−2	−2	0	−4	−2	−3	−3	1	0	0
C3 – Persistence attributes	3	1	1	2	3	1	0	−1	0	3	1	2	2	1	0	0
Total section C	2	−3	5	2	2	1	−1	−1	0	4	0	1	1	3	0	0

Species ID: (1) *Corymbia citriodora*, (2) *Corymbia maculata*, (3) *Corymbia torelliana*, (4) *Eucalyptus benthamii*, (5) *Eucalyptus brassiana*, (6) *Eucalyptus camaldulensis*, (7) *Eucalyptus cloeziana*, (8) *Eucalyptus dunnii*, (9) *Eucalyptus globulus*, (10) *Eucalyptus grandis*, (11) *Eucalyptus pellita*, (12) *Eucalyptus robusta*, (13) *Eucalyptus saligna*, (14) *Eucalyptus tereticornis*, (15) *Eucalyptus urophylla*, (16) *Eucalyptus viminalis*.

 doi:10.1111/aec.12649

habit), chemical changes in the soil, allelopathy, parasitism, toxicity or allergenic potential, nearly always had negative answers except for references on allelopathy for *Corymbia citriodora*, *Eucalyptus brassiana*, *Eucalyptus camaldulensis*, *Eucalyptus globulus*, *Eucalyptus grandis*, *Eucalyptus saligna*, *E. tereticornis* and *E. urophylla* (Ferreira *et al.* 2007; Zhang *et al.* 2010).

Auto-pollination was documented for nine of the 16 species assessed, whereas all species benefit from non-specialist pollinators (Silva *et al.* 2015), a factor which increases the level of risk. The section on dispersal mechanisms lowered the risk because all species reproduce by seed and dispersal occurs by wind or gravity, not involving animals, involuntary transport or vegetative fragments. The level of human interest in eucalypts, on the other hand, again increases the level of risk, as it is an important component of propagule pressure and the most relevant factor in the global distribution of eucalypt species (Lockwood *et al.* 2005; Rejmánek *et al.* 2005; Bomford 2008).

Plants with juvenile period shorter than 1 year receive the highest score on this question. None of the eucalypts was found to mature in less than 1 year, while references were found for maturity below 4 years of age for *C. citriodora*, *E. globulus*, *E. grandis*, *E. tereticornis* and *E. urophylla*. Species that reach maturity over 4 years of age score 0. Seed viability in the soil is a relevant factor to increase risk, but information is scarce for most species, especially in natural conditions. When viability is lower than 1 year, the score is negative as the risk is reduced. This was the case of *E. camaldulensis*, *E. cloeziana* and *E. dunnii*. If no data were available the score was null and does not interfere with the overall risk level. The question on the feasibility of management with reasonable costs was left blank for all species.

References on the absence of natural predators in Brazil that could function as classical biological control was found for nine of the species assessed. No information was found for *Corymbia maculata*, *C. torelliana*, *E. pellita*, *Eucalyptus robusta*, *E. tereticornis* and *E. urophylla*. Although some data are available on cutting ants of considerable impact to eucalypt plantations (Silva *et al.* 2011), they are not sufficient for generalization and it cannot be taken for granted that the same impact would apply to invaded areas where non-native eucalypts are mixed with native species.

DISCUSSION

The present study showed that 15 out of the 16 of the currently most commonly planted eucalypts in Brazil have some risk of becoming invasive somewhere in the country. Only one of the tested eucalypt species had low risk. Previous research had shown that the same traits that make some tree species adequate for forestry also make them more likely to invade (Essl *et al.* 2010; Pyšek *et al.* 2011; Zenni *et al.* 2017). Thus, our study provides further support to the notion that risk assessment can be an important tool to help screen species for their risk of becoming invasive. To improve the chances of preventing invasions, risk assessments may be performed before a species is introduced, promoted or widely used without specific regulations. Had risk analysis always been in use, only 10% of the current 194 invasive plant species would have been introduced in Brazil (Instituto Hórus de Desenvolvimento e Conservação Ambiental 2017). These results are corroborated by risk analyses carried out in other countries for many of the same species (Keller *et al.* 2006; Gordon *et al.* 2011, 2012; Pacific Island Ecosystems at Risk 2011; University of Florida – IFAS 2015).

The use of risk assessment to filter invasive species is a scientific alternative that respects environmental and economic sustainability. The adoption of risk assessment is planned in the Brazil National Strategy for Invasive Alien Species and meets the expectations and requirements of the Convention on Biological Diversity. It can also provide reliable data to country governments for impartial decision-making regarding species introductions and regulations for the use of non-native species. Article 8 h of the Convention requests signatory countries to prevent, eradicate or control species that threaten ecosystems, habitats or species.

Most invasive plants worldwide were introduced intentionally for ornamental use, cultivation, forestry and other human interests (Culley *et al.* 2011; Zenni 2013; Dickie *et al.* 2014; Hulme *et al.* 2017). Although no predictive system is 100% accurate, the accuracy of risk analysis has been verified in scientific studies to lie between 80 and 95% (Daehler *et al.* 2004; Keller *et al.* 2006). Risk assessments can therefore reduce the introduction of harmful species with an acceptable margin of uncertainty, as well as help identify species of low risk which do not impair production costs and do not incur management costs for the conservation of biodiversity, most often borne by tax payers.

In South Africa, *E. camaldulensis*, *Eucalyptus conferruminata*, *Eucalyptus cladocalyx*, *Eucalyptus diversicolor*, *E. grandis* and *E. tereticornis* are aggressive species listed in national legislation as non-native invasive species (South African Biodiversity Act 2004; Aliens and Invasive Species Regulations 2014). These species are the object of eradication efforts by the *Working for Water* Programme coordinated by the Ministry of Environmental Affairs, and subject to compulsory control in certain regions. Their use is permitted as

doi:10.1111/aec.12649

long as plantations are demarcated and control of outlier seedlings and trees is continuous (South African National Biodiversity Institute 2014).

In Hawaii (USA), *Eucalyptus amygdalina*, *E. globulus* and *E. robusta* are invasive in the Haleakala National Park (US National Park Service 2015). Risk assessment of species of interest for energy production conducted in Florida (USA) rejected *E. camaldulensis* and *E. grandis*, but accepted *Eucalyptus amplifolia* (Gordon *et al.* 2011) because the risk of invasion is low. Other risk analyses conducted for 38 eucalypts in the United States indicate high invasion risk, in increasing order, for *Eucalyptus paniculata*, *Eucalyptus sideroxylon*, *E. urophylla*, *Eucalyptus deglupta*, *E. saligna*, *E. grandis*, *E. tereticornis*, *E. viminalis*, *E. robusta*, *C. citriodora*, *C. torelliana*, *E. camaldulensis* and *E. globulus* (Gordon *et al.* 2012). Some of the species assessed in the present study resulted in high risk in the Pacific Islands (*E. globulus* and *E. grandis*), whereas *E. cloeziana*, *E. dunnii*, *E. pellita*, *E. robusta* and *E. tereticornis* resulted in low risk (Pacific Island Ecosystems at Risk 2011). The relatively small proportion of introduced eucalypts that have become invasive (~5%) may reflect the frequency and extent of plantations, number of propagules released or geographic range (propagule pressure) more than an increase in the risk of invasion (Gordon *et al.* 2012). The absence of specific ectomycorrhiza may also help explain the lack of biologic invasions by eucalypts in Brazil (Rejmánek & Richardson 2011).

The results obtained here indicate that the one eucalypt classified as low risk and the ones with lower moderate risk scores can be used in production with relative safety, not requiring the adoption of preventative and control measures. However, in the current scenario of increasing habitat loss and climate change, such species may more easily establish and trigger invasion processes (National Center for Environmental Assessment 2008; Liu *et al.* 2017). These species must therefore not be neglected, and should be monitored carefully for signs of dispersal and invasion.

Although the larger forest companies would be able to incorporate prevention and management practices into forest management, there are no specific legal regulations in Brazil to enforce these measures, there are many invaded areas where trees have been planted in the past that require clearing, and governance for biological invasions is still frail. Forest certification has a role in ensuring that biological invasions are dealt with (Richardson 2011a), but not all companies are certified, and certifiers often overlook this issue. Plantations in small properties, even when fostered by larger forest companies, are most often subject to less careful management, as they are not usually certified, owners are not aware of the problem, and tend to focus on profit only. Additionally, isolated trees such as those planted along roadsides and in small stands hold the greatest potential for spread (Moody & Mack 1988) and are not part of forest certification programmes. In the absence of specific legal regulations, environmental requirements for prevention and control of spread from plantations need to be defined on a case by case basis, which creates confusion, is not practical and not functional. Therefore, although management is not technically difficult, it becomes difficult in the lack of legal regulations and responsibilities (Richardson 2011a).

Despite the fact that more than 70 species reproduce and sustain populations outside their native ranges, the richness of eucalypt species and the extent of plantations on the global level tend to imply that eucalypts are not aggressively invasive (Rejmánek & Richardson 2011). Considering the potential of impacts on water consumption and the chances of seedling development on bare, degraded soils, eucalypts must never be planted close to water sources and small streams because they are high water consumers, as well as to avoid seed dispersal downstream (Rejmánek & Richardson 2011). Some eucalypts inhibit germination of native species through allelopathy, which can generate erosion for lack of soil cover, increase the risk of fire, and develop woodlots of low value for native animals (Rejmánek & Richardson 2011).

Considering that environmental degradation, climate change and the culture of growing non-native plants facilitate establishment and invasion by non-native species (Mooney & Hobbs 2000), the less high-risk trees that are planted, the better the chances that the use of eucalypts in Brazil respects criteria of sustainability, generating economic and social benefits without harming the environment and ecosystem functions. The species of highest risk identified through risk assessment are also acknowledged as invasive in other countries, especially *E. camaldulensis*, *E. robusta*, *E. saligna*, *C. torelliana*, *E. tereticornis* and *E. grandis*. These results indicate the need for careful management of already established plantations of these species, including routine prevention and control practices to avoid spread and invasion beyond plantations. They also provide reference for safer species that can be planted by those concerned with environmental conservation and ecosystem services, coherent with criteria of sustainability and the fate of future generations.

ACKNOWLEDGEMENTS

The authors thank the associate editor and the three referees who made constructive suggestions and helped improve the quality of the manuscript. The authors thank the Institute of Forest Research and

Studies (Instituto de Pesquisas e Estudos Florestais – IPEF) for funding the 16 risk assessments. The authors thank Maria José de Brito Zakia for her interest in the application of risk assessment in Brazil and her support on the development of these studies and also to Paulo Henrique Müller da Silva and Marcel Rejmánek for reviewing and making suggestions for the improvement of preliminary versions of the manuscript.

REFERENCES

Aliens and Invasive Species Regulations (2014) [Cited 2 October 2015.] Available from URL: https://www.environment.gov.za/sites/default/files/legislations/nemba10of2004_alienandinvasive_speciesregulations.pdf

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

Bomford M. (2008) *Risk Assessment Models for Establishment of Exotic Vertebrates in Australia and New Zealand*. Invasive Animals Cooperative Research Centre, Canberra.

Booth T. H. (2014) Modern tree colonisers from Australia into the rest of the world. In: *Invasion Biology and Ecological Theory – Insights From a Continent in Transformation* (eds H. H. T. Prins & I. J. Gordon) pp. 304–23. Cambridge University Press, Cambridge.

Castellano G. R., Camarinho R. J., Arthur Junior J. C., Sixel R. M. M. & Silva P. H. M. (2013) Crescimento de eucaliptos quase centenários no Horto de Rio Claro. *Circular Técnica do Instituto de Pesquisas e Estudos Florestais 205*. IPEF, Piracicaba.

Copp G. H., Vilizzi L., Mumford J., Fenwick G. V., Godard M. J. & Gozlan R. E. (2009) Calibration of FISK, an invasiveness screening tool for nonnative freshwater fishes. *Risk Anal.* **29,** 457–67.

Crawford K. M. & Whitney K. D. (2010) Population genetic diversity influences colonization success. *Mol. Ecol.* **19,** 1253–63.

Culley T. M., Hardiman N. A. & Hawks J. (2011) The role of horticulture in plant invasions: how grafting in cultivars of Callery pear (*Pyrus calleryana*) can facilitate spread into natural areas. *Biol. Invasions* **13,** 739–46.

Daehler C. C., Denslow J. S., Ansari S. & Kuo H.-C. (2004) A risk assessment system for screening out invasive pest plants from Hawai'i and other Pacific Islands. *Conserv. Biol.* **18,** 360–8.

Dawson W., Mndolwa A. S., Burslem D. F. R. P. & Hulme P. E. (2008) Assessing the risks of plant invasions arising from collections in tropical botanical gardens. *Biodivers. Conserv.* **17,** 1979–95.

Dickie I. A., Bennett B. M., Burrows L. E. *et al.* (2014) Conflicting values: ecosystem services and invasive tree management. *Biol. Invasions* **14,** 705–19.

Essl F., Moser D., Dullinger S., Mang T. & Hulme P. E. (2010) Selection for commercial forestry determines global patterns of alien conifer invasions. *Divers. Distrib.* **16,** 911–21.

Ferreira M. C., Souza J. R. P. & Faria T. J. (2007) Produção alelopática de extratos vegetais na germinação e no crescimento inicial de picão-preto e alface. *Ciência Agrotécnica* **31,** 1054–60.

Flores T. B., Alvares C. A., Souza V. C. & Stape J. L. (2016) *Eucalyptus no Brasil – Zoneamento climático e guia para identificação*. IPEF, Piracicaba.

Golfari L. & Pinheiro Neto F. A. (1970) Escolha de espécies de eucalipto potencialmente aptas para diferentes regiões do Brasil. *Brasil Florestal* **1,** 17–38.

Golfari L., Caser R. L. & Moura V. P. G. (1978) Zoneamento ecológico esquemático para reflorestamento no Brasil: 2a. aproximação. *Série técnica PRODEPEF, Brasília* **11,** 1–66.

Gordon D. R., Tancig K. J., Onderdonk D. A. & 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 Bioenerg.* **35,** 74–9.

Gordon D. R., Flory S. L., Cooper A. L. & Morris S. K. (2012) Assessing the invasion risk of *Eucalyptus* in the United States using the Australian weed risk assessment. *Int. J. Forestry Res.* **2012,** Article ID 203768.

Hayes K. R. & Barry S. C. (2008) Are there any consistent predictors of invasion success? *Biol. Invasions* **10,** 483–506.

Hulme P. E., Brundu G., Carboni M. *et al.* (2017) Integrating invasive species policies across ornamental horticulture supply-chains to prevent plant invasions. *J. Appl. Ecol.* **55,** 92–8. https://doi.org/10.1111/1365-2664.12953

Instituto Hórus de Desenvolvimento e Conservação Ambiental (2017) *National Invasive Alien Species Database*. [Cited 20 June 2017.] Available from URL: http://i3n.institutohorus.org.br/www

Keller R. P., Lodge D. M. & Finnoff D. C. (2006) Risk assessment for invasive species produces net bioeconomic benefits. *Proc. Natl Acad. Sci. USA* **104,** 203–7.

Kumschick S., Gaertner M., Vilà M. *et al.* (2014) Ecological impacts of alien species: quantification, scope, caveats, and recommendations. *Bioscience* **65,** 55–63.

Liu Y., Oduor A. M. O., Zhang Z. *et al.* (2017) Do invasive alien plants benefit more from global environmental change than native plants? *Glob. Change Biol.* **23,** 3363–70.

Lockwood J. L., Cassey P. & Blackburn T. (2005) The role of propagule pressure in explaining species invasions. *Trends Ecol. Evol.* **20,** 223–8.

Lonsdale W. M. (2011) Risk assessment and prioritization. In: *Encyclopedia of Biological Invasions* (eds D. Simberloff & M. Rejmánek) pp. 604–9. University of California Press, Berkeley.

Miolaro L. G., Gonçalves A. N., Mendes J. C. T., Moreira R. M., Brune A. & Silva P. H. M. (2017) Spontaneous regeneration of eucalypts from seed production areas. *Biol. Invasions* **19,** 1733–7.

Moody M. E. & Mack R. (1988) Controlling the spread of plant invasions – the importance of nascent foci. *J. Appl. Ecol.* **25,** 1009–21.

Mooney H. A. & Hobbs R. J. (2000) *Invasive Species in a Changing World*. Island Press, Washington.

National Center for Environmental Assessment (2008) *Effects of Climate Change on Aquatic Invasive Species and Implications for Management and Research*. Environmental Protection Agency, Washington.

National Research Council (2002) *Predicting Invasions of Non-Indigenous Plants and Plant Pests*. National Academy Press, Washington.

Pacific Island Ecosystems at Risk (2011) *Weed Risk Assessment*. [Cited 24 September 2015.] Available from URL: http://www.hear.org/pier/wra.htm

Pheloung P. C. (2001) Weed risk assessments for plant introductions to Australia. In: *Weed Risk Assessment* (eds

P. H. Groves, F. D. Panetta & J. G. Virtue) pp. 83–92. CSIRO, Collingwood.
Pheloung P. C., Williams P. A. & Halloy S. R. (1999) A weed risk assessment model for use as a biosecurity tool evaluating plant introductions. *J. Environ. Manage.* **57,** 239–51.
Pyšek P., Jarošík V. & Pergl J. (2011) Alien plants introduced by different pathways differ in invasion success: unintentional introductions as a threat to natural areas. *PLoS ONE* **6,** e24890.
Quinn L. D., Gordon D. R., Glaser A., Lieurance D. & Flory S. L. (2014) Bioenergy feedstocks at low risk for invasion in the USA: a "white list" approach. *Bioenergy Res.* **8,** 471–81.
Rejmánek M. (2001) What tools do we have to detect invasive plant species? In: *Weed Risk Assessment* (eds P. H. Groves, F. D. Panetta & J. G. Virtue) pp. 3–9. CSIRO, Collingwood.
Rejmánek M. & Richardson D. M. (2011) Eucalypts. In: *Encyclopedia of Biological Invasions* (eds D. Simberloff & M. Rejmánek) pp. 203–9. University of California Press, Berkeley.
Rejmánek M., Richardson D. M. & Pysek P. (2005) Plant invasions and invasibility of plant communities. In: *Vegetation Ecology* (ed E. Van der Maarel) pp. 332–55. Blackwell, Oxford.
Richardson D. M. (2011a) Forestry and agroforestry. In: *Encyclopedia of Biological Invasions* (eds D. Simberloff & M. Rejmánek) pp. 241–8. University of California Press, Berkeley.
Richardson D. M. (2011b) Trees and shrubs. In: *Encyclopedia of Biological Invasions* (eds D. Simberloff & M. Rejmánek) pp. 670–7. University of California Press, Berkeley.
Richardson D. M. & Pyšek P. (2012) Naturalization of introduced plants: ecological drivers of biogeographical patterns. *New Phytol.* **196,** 383–96.
Rogg H. W., Buddenhagen C. & Causton C. (2005) Experiences and limitations with pest risk analysis in the Galapagos Islands. In: *Identification of Risks and Management of Invasive Alien Species Using the IPPC Framework. Proceedings of the Workshop on Invasive Alien Species and the International Plant Protection Convention*, pp. 798–807. International Plant Protection Convention Secretariat, Braunschweig, Germany.
Silva P. H. M., Poggiani F., Sebbenn A. M. & Mori E. S. (2011) Can *Eucalyptus* invade native forest fragments close to commercial stands? *For. Ecol. Manage.* **261,** 2075–80.
Silva P. H. M., Sebbenn A. M. & Grattapaglia D. (2015) Pollen-mediated gene flow across fragmented clonal stands of hybrid eucalypts in an exotic environment. *For. Ecol. Manage.* **356,** 293–8.
Silva P. H. M., Bouillet J.-P. & Paula R. C. (2016) Assessing the invasive potential of commercial *Eucalyptus* species in Brazil: germination and early establishment. *For. Ecol. Manage.* **374,** 129–35.
South African Biodiversity Act (2004) *National Environmental Management: Biodiversity Act*. [Cited 24 September 2015.] Available from URL: http://ship.mrc.ac.za/biodiversity.pdf
South African National Biodiversity Institute (2014) *Gums & Bees – A Roadmap for Landowners in South Africa*. Department of Environmental Affairs, Cape Town.
Stohlgren T. J. & Jarnevich C. S. (2010) Risk assessment of invasive species. In: *Invasive Species Management – A Handbook of Principles and Techniques* (eds M. N. Clout & P. A. Williams) pp. 19–35. Oxford University Press, Oxford.
Tomazello Filho M. (1987) Variação radial da densidade básica em estrutura anatômica da madeira do *Eucalyptus globulus*, *E. pellita* e *E. acmenioides*. *Revista do IPEF* **36,** 35–42.
University of Florida – IFAS (2015) *Assessment of non-native plants in Florida's natural areas*. [Cited 24 September 2015.] Available from URL: http://assessment.ifas.ufl.edu/
US National Park Service (2015) *Invasive plants of Haleakala National Park*. [Cited 24 September 2015.] Available from URL: https://www.nps.gov/hale/learn/nature/invasive-plants.htm
Valduga M. O., Zenni R. D. & Vitule J. R. S. (2016) Ecological studies reveal broad and heterogeneous impacts of exotic tree species plantations – examples from a megadiverse country. *An. Acad. Bras. Cienc.* **88,** 1675–88.
Van Klinken R. D., Panetta F. D. & Coutts S. R. (2013) Are high-impact species predictable? An analysis of naturalised grasses in northern Australia. *PLoS ONE* **8**(7), e68678.
Williamson M. (2001) Can the impacts of invasive species be predicted? In: *Weed Risk Assessment* (eds P. H. Groves, F. D. Panetta & J. G. Virtue) pp. 20–33. CSIRO, Collingwood.
Zenni R. D. (2013) Analysis of introduction history of invasive plants in Brazil reveals patterns of association between biogeographical origin and reason for introduction. *Austral Ecol.* **39,** 401–7.
Zenni R. D. (2015) The naturalized flora of Brazil: a step towards identifying future invasive non-native species. *Rodriguésia* **66,** 1137–44.
Zenni R. D. & Simberloff D. (2013) Number of source populations as a potential driver of pine invasions in Brazil. *Biol. Invasions* **15,** 1623–39.
Zenni R. D. & Ziller S. R. (2011) An overview of invasive plants in Brazil. *Braz. J. Bot.* **34,** 431–46.
Zenni R. D., Dickie I. A., Wingfield M. J. *et al.* (2017) Evolutionary dynamics of tree invasions: complementing the unified framework for biological invasions. *AoB Plants* **9,** plw085.
Zhang D., Zhang J., Yang W. & Yu F. (2010) Potential allelopathic effect of *Eucalyptus grandis* across a range of plantation ages. *Ecol. Res.* **25,** 13.

SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article at the publisher's web-site:

Appendix S1. Comparison between the Australian system, its adaptation to the Galapagos Islands and to Brazil.
Appendix S2. Risk assessment protocol with answers for each of the 16 species of *Eucalyptus* and *Corymbia* assessed in the manuscript.
Appendix S3. List of the sources of information used for each question of the risk assessment protocols.

 doi:10.1111/aec.12649