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ORIGINAL PAPER

Assessing current and future risks of invasion by the "green cancer" *Miconia calvescens*

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Abstract *Miconia calvescens* D.C. appears in the list "100 of the world's worst invasive alien species", devised by the IUCN. It is considered the worst plant pest in Hawaii and French Polynesia. This species has also invaded the rain forest of Australia, New Caledonia and Sri Lanka, where it is extremely difficult to eradicate. To assess the susceptibility to invasion by *M. calvescens* in new areas, we investigated the current and future suitable areas for this aggressive invader worldwide. We also assessed the protected areas currently at risk of invasion by considering botanic gardens as a proxy for likelihood of introduction, since most successful invasions by *M. calvescens* originated from private or public garden escapees. Our results predict that about 7.2 % of total landmass is currently suitable for *M. calvescens*, with 54.8 % outside the native range including 44.5 % within tropical forests in the southern hemisphere. We identified 91 countries, 400 islands, and up to 364 protected areas with suitable environments outside of *M. calvescens* native range. By the 2080s, worldwide land suitable for *M. calvescens* is predicted to be reduced by up to half due to climate change. This decrease is mainly predicted to occur in *M. calvescens* native ranges as well as in countries where the presence of the species has not yet been reported. In contrast, the invaded range is predicted to slightly decrease, showing an interesting example of a double negative effect of climate change on the distribution of an invader. Our work provides information for land managers and stakeholders that can help to avert the introduction and spread of *M. calvescens* in their territories. We also emphasize the importance of risk assessments on the living collections of botanic gardens, as a common source of escapees of invasive plants.

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Introduction

Biological invasions are a major component of global change (Vitousek et al. 1996), representing an increasing concern for both scientists and managers, because of their ecological impact on ecosystems (Parker et al. 1999; Le Maitre et al. 2011). The process of invasion consists of a series of steps, ranging from the introduction of the species in a new area to the invasive state, in which the new species spreads and may dominate the landscape (Lockwood et al. 2007; Teoharides and Dukes 2007). In most cases, once the new species establishes and spreads, it is difficult and costly to eradicate (Rejmánek et al. 2005; Pimentel et al. 2005). Thus, prevention appears to be the most cost-effective management method (Genovesi 2005; Simberloff et al. 2013). In this context, identifying which areas provide the most suitable environmental conditions for any proven invasive species is an important tool to anticipate and prevent their success in new ranges, even before their introduction (Peterson and Vieglais 2001; Broennimann et al. 2007 but see Pheloung et al. 1999).

Miconia calvescens D.C. (Melastomataceae, hereafter *M. calvescens*) was designated by the IUCN Invasive Species Specialist Group as one of the "100 worlds worst invasive alien species" (Lowe et al. 2000). Known as the "green cancer", it is considered the worst plant pest in Hawaii and French Polynesia (Meyer 1996; Medeiros and Loope 1997). Currently, it has invaded most of the island of Tahiti (Meyer 1996) and threatens the rain forest of the Queensland region in Australia (Hardesty et al. 2011), Sri Lanka and New Caledonia (Meyer 2010). This species is native to the rain forest expanding from southern Mexico to southern Brazil and northern Argentina, where it occupies a wide altitudinal range from lowland to mountain tropical forests (up to 1,800 m). In its native range, *M. calvescens* does not form dense stands and is reportedly uncommon (Meyer 1996). In contrast, it forms monospecific, closed stands in the areas where it was introduced as a garden ornament (Meyer 1996).

The species has a dramatic impact on the native flora of invaded areas (Loope and Medeiros 1995; Meyer and Florence 1996), as its large, broad leaves decrease the amount of light reaching the soil, while its shallow root system contributes to soil erosion (Loope and Medeiros 1995). As a result of *M. calvescens* invasion, between 40 and 50 of the 107 endemic plant species of Tahiti are under high risk of extinction (Meyer and Florence 1996). Moreover, the fast decomposition of *M. calvescens* litter has been linked to rapid nutrient losses and to negative impacts on soil development in Hawaii (Allison and Vitousek 2004).

Control and eradication efforts of *M. calvescens* have required massive economic investments (Goarant and Meyer 2009; Hester et al. 2010; Meyer 2010). For example, the state of Hawaii spent approximately $1.7 million in an attempt to control the spread of *M. calvescens* in the year 2000 alone (Chan-Halbrendt et al. 2010). The negative impacts of *M. calvescens* on invaded territories, in addition to the huge costs and difficulties of its eradication, claim for the necessity of reliable information that can be used to prevent the introduction and spread of *M. calvescens* into new territories. Previous work aimed to describe the potential distribution of *M. calvescens*, though their primary focus was on local scales (see Florence 1993 in Tahiti; LaRosa et al. 2007 in Hawaii; Pouteau et al. 2011 in Moorea).

In this study, we identify areas across the globe that are suitable for invasion by *M. calvescens* based on climatic and altitudinal variables. We focus principally on evaluating the susceptibility of island invasion by *M. calvescens,* since: (1) most successful invasions by this species have occurred on island ecosystems (Meyer et al. 2011); and (2) islands have an extraordinary conservation value, harbouring more than 20 % of the world's biodiversity and showing a high rate of endemism (Kier et al. 2009).

We also assess the probability of invasion in the protected areas worldwide, by considering the proximity of botanic gardens to protected areas as a proxy for likelihood of introduction. This is based on: (1) botanic gardens have been implicated in the introduction of many of the world's worst invasive species into one or more global biodiversity hotspots (Hulme 2011); and (2) specifically, most invasions by *M. calvescens* originated from escapees from private and public gardens (Meyer et al. 2011). In addition, protected areas are an extremely relevant case study on the subject of biological invasions, due to the threat that invasive species may constitute for endagered natives (Beaumont et al. 2009a; Gallagher et al. 2010a; Foxcroft et al. 2013).

Finally, we also investigate how future climate change is predicted to alter the global distribution of *M. calvescens*. Throughout the 20th century, shifts in the latitudinal (see example in Parmesan and Yohe 2003) and altitudinal (Lenoir et al. 2008) ranges of different plant species have been observed and related to rising temperatures. Previous work suggests that the distribution of invasive species will likely increase due to climate and land-use changes (Pyšek et al. 2002; Kleinbauer et al. 2010; Vicente et al. 2010, 2011, 2013), but this is not always the case (Parker-Allie et al. 2009; Bertelsmeier et al. 2013; Gallagher et al. 2013). However, these results were associated with individual species and/or were locally dependent, and general conclusions are difficult to achieve (see Bellard et al. 2013). In this work, the potential distribution of *M. calvescens* is studied throughout the 21st century under the two most extreme representative concentration pathway emission scenarios and three global circulation models.

Materials and methods

Species distribution data

We used 379 occurrence data, collected from the Global Invasive Species Database (http://www.issg.org), published literature (Hardesty et al. 2011, 2012 for Australia; Meyer 1996, 1998, 2010) and invasive species databases (Hawaiian Ecosystems at Risk—www.hear.org, Invasive Species Compendium CAB International—www.cabi.org/isc/; Fig. 1a). These data comprise a representative worldwide occurrence of *M. calvescens* and include points from both the native and invaded distribution, as it has been previously shown that models calibrated on occurrences of exclusively the native range may misrepresent the potential invasive distribution (Beaumont et al. 2009b; Broennimann et al. 2007; Jiménez-Valverde et al. 2011).

Environmental predictors

Current climate and altitude range

Model predictors were selected among the 19 Worldclim database bioclimatic variables (http://www.worldclim.org/, Hijmans et al. 2005), at a 10 arcmin resolution (approximately 18.5 × 18.5 km pixel). These bioclimatic variables derive from monthly temperatures and rainfall data between the years 1950 and 2000 and represents annual, seasonal and extreme temperature and rainfall factors (Hijmans et al. 2005). Since both elevation and slope have proven important factors explaining *M. calvescens* distribution at local scales (Meyer 1994; Pouteau et al. 2011), we have additionally included the altitudinal range of each cell among our model predictors, as a proxy of spatial heterogeneity within each cell. We checked the correlation between variables at both worldwide scale and at the extent of the occurrence data (Pearson's $r < 0.70$; Braunisch et al. 2013). We analysed the contribution of each variable to the current distribution of the species by the randomisation procedure implemented in the Biomod v.2.0 platform, which uses Pearson correlations between the values fitted by the model and predictions in which each variable has been randomly permutated. A high value means that the variable permutated is highly important for the model (see Thuiller et al. 2009). Consequently, we selected the six following variables: annual mean temperature (bio1), temperature seasonality (standard deviation *100) (bio4), temperature annual range (bio7), precipitation of the driest month (bio14), precipitation of the wettest quarter (bio16) and altitudinal range. Among these, the temperature seasonality had the highest contribution to the final model, followed by the precipitation of the driest month (Table 1, Appendix S2). The lowest contributions were given by the altitudinal range and the precipitation of the wettest quarter (Table 1, Appendix S2).

Future climate

We used future climate data available from the Worldclim database. These data result from climate projections from global circulation models, downscaled and calibrated (bias corrected) using WorldClim 1.4 (Hijmans et al. 2005). We used data from three different global circulation models (GCM: IPSL-CM5A-LR, Institute Pierre Simon LaPlace, France; CCSM4, National Center for Atmospheric Research, USA and GISS-E2-R, NASA Goddard Institute for Space Studies, USA), two time horizons: 2050s (2041–2060) and 2080s (2061–2080) and two representative concentration pathway emission scenarios

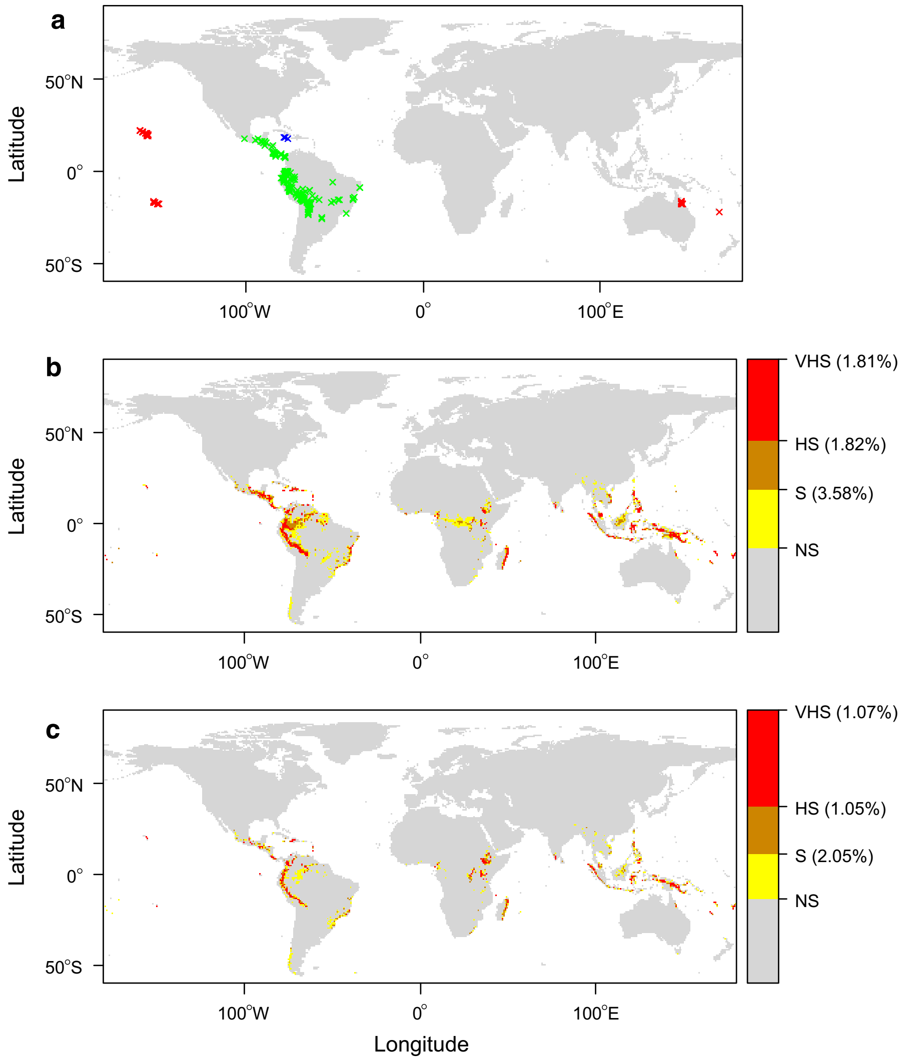

Fig. 1 a Occurrence data of *M. calvescens* in its native (green), invaded (red) and established (i.e., the species is naturalised, showing established populations) (blue) ranges [see Appendix S1 for details of the list of countries belonging to the native, cultivated, established, invasive and not reported ranges of *M. calvescens* (http://www.issg.org)]. b Map of potential distribution under current environmental conditions (five climatic variables and altitude range). c Consensus map for the representative concentration pathway RCP8.5 (IPCC 2013) and the time horizon 2080s (2061–2080). To obtain the consensus map, we averaged the projected maps of each global circulation model (IPSL-CM5A-LR, Institute Pierre Simon LaPlace; CCSM4, National Center for Atmospheric Research; GISS-E2-R, NASA). For b, c VHS very high suitability, HS high suitability, S suitable, NS not suitable. The percentage of worldwide surface of each category is indicated between brackets

Table 1 Variable importance in the ensemble model (according to the variable importance procedure implemented in Biomod v.2.0) and minimum, maximum, mean and median pixel value of each variable included in the whole worldwide suitable range for *M. calvescens*

	Alt_range	bio1	bio4	bio7	bio14	bio16
Importance	0.13	0.20	0.52	0.20	0.31	0.15
Min	0	1	126	6.2	0	53
Max	3041	28	5456	28.1	457	3280
Mean	268.31	23.11	980.61	13.33	81.70	839.77
Median	163	24.50	679	12.30	65	826

Alt_range (altitude range, m); bio1 (annual mean temperature, °C); bio4 [temperature seasonality (standard deviation *100, °C)]; bio7 (temperature annual range (bio5–bio6), °C); bio14 (precipitation of driest month, mm); bio16 (precipitation of wettest quarter, mm)

(RCPs; IPCC 2013). The emission scenarios are defined by their total radiative forcing (i.e., cumulative measure of green-house gases emitted by humans from all sources expressed in W/m^2) pathway and level by 2100. They assume a wide range of different technological, socioeconomic, and policy futures that could lead to a particular concentration pathway and climate outcomes (van Vuuren et al. 2011). Here, we used the two most extreme emission scenarios (low RCP2.6 and high RCP8.5). The RCP2.6 is characterized by a peak forcing level of 3 W/m^2 before 2100, followed by a decline, due to the use of bio-energy and carbon capture and storage, resulting in negative emissions (van Vuuren et al. 2006, 2007). In contrast, the RCP8.5 is characterized by increasing greenhouse gas emissions over time, as a result of high population growth and a lower rate of technological development (Riahi et al. 2007).

Species distribution modelling

Current environmental suitability

We used nine different niche-based modelling techniques, within the Biomod v.2.0 platform (Thuiller et al. 2009): Generalized Linear Models (GLM, McCullagh and Nelder 1989), Generalized Boosting Trees (GBT, Ridgeway 1999), Generalized Additive Model (GAM, Hastie and Tibshirani 1990), Multivariate Adaptive Regression Splines (MARS, Friedman et al. 2013), Random Forest (RF, Breiman 2001), Flexible Discriminant Analysis (FDA, Hastie et al. 1994), Classification Tree Analysis (CTA, Breiman et al. 1984), Artificial Neural Network (ANN, Ripley 1996; see Thuiller et al. 2009 for further details), and Maximum Entropy (MAXENT, see Elith et al. 2011 for more details). As the species distribution models required presence and absence data, we generated three sets of 3000 pseudo-absence data randomly selected following Barbet-Massin et al. (2012) recommendations. Pseudo-absences were selected from cells from which we did not have any record. Equal weight was given to occurrence points and pseudo-absences.

Models were calibrated with a randomly selected 70 % of the data and evaluated with the remaining 30 % (Guisan and Thuiller 2005). Three different statistical metrics were used for the model evaluation: the True Skills Statistics (TSS, Allouche et al. 2006), the Area Under the characteristic Curve (AUC, Fielding and Bell 1997) and the Coheńs Kappa (KAPPA, Fielding and Bell 1997). The TSS ranges from -1 to 1; the AUC from 0 to 1 and the KAPPA from -1 to 1. In general, TSS > 0.8, AUC > 0.8 and KAPPA > 0.4 are considered respectable (Fielding and Bell 1997). This process was repeated three times, in order to obtain an average value for model performances.

We applied an ensemble forecast approach to get the central tendency of the nine distribution models (Araújo and New 2007), keeping the projections for which the model evaluation estimated by the TSS was higher than 0.6 (Gallien et al. 2010). This ensemble forecast approach represents a significant improvement compared to the species distribution models that were calibrated with only one technique (Thuiller et al. 2009). The probability map obtained from the ensemble forecast was transformed into a suitability versus non-suitability map, using the probability threshold that maximizes the TSS (Allouche et al. 2006), to get the most accurate prediction in both sensitivity (probability of correctly predicting a presence point at a site) and specificity (probability of correctly predicting an absence point at a site; Liu et al. 2005, 2009).

Future environmental suitability projections

The final model obtained from the ensemble forecast approach was projected to obtain the suitability maps of *M. calvescens* for each global circulation model, representative concentration pathway scenario and time horizon (2050, 2080; 12 maps). We checked for differences between global circulation models, representative concentration pathway emission scenarios and periods in the global suitable surface for *M. calvescens* distribution using the Kruskal–Wallis test (p value <0.05).

The obtained maps of suitability at current and future conditions were divided into four categories, depending on the suitability cut-offs: very high suitability, high suitability, suitable and not suitable. Pixels were considered very highly suitable (VHS) if the suitability value was above the third quartile of the suitability values; highly suitable (HS) if the suitability value was between the third and the second quartile and suitable (S) if their suitability value was between the second quartile and the lowest value in which the calibrated model predicted presences (see Appendix S3 for the cut-off values).

Assessing the probability of invasion of worldwide protected areas

We collected the coordinates of all the botanic gardens known to exist in *M. calvescens* suitable distribution ranges (VHS, HS, and S) (BGCI, Botanic Gardens Conservation International, www.bgci.org/global/iabg/). The map of world protected areas was obtained from the UNEP World Conservation Monitoring Centre (UNEP-WCMC, http://protectedplanet.net/). For our analyses, we selected the botanic gardens that are located in the non-native range of *M. calvescens*. We are not aware if these botanic gardens already contained *M. calvescens* plants or seeds in their living collections. Overall, we determined the potential risk of introduction of *M. calvescens* in botanic gardens for analyses of probability of invasion and prevention purposes. We generated two "risk zones" around each botanic garden. The first risk zone (i.e., "optimistic zone") was calculated based on a conservative radius (radius = 899 m), estimated as the median of the radius of different cases of invasions based on reports in the literature and projected for a 30 year period (Murphy et al. 2008; Csurhes 1998; Meyer et al. 2011). The second risk zone (i.e., "pessimistic risk zone") was calculated based on a more extreme radius (radius = 10,160 m), estimated as the radius of the most aggressive case of invasion by *M. calvescens*, the case of the Islands of Tahiti, also projected for a 30 year period (Meyer et al. 2011).

For the case of marine protected areas, we only considered those that included mainland surface. We decided to keep marine protected areas in our assessment as *M. calvescens* can reach lowland surfaces close to coastal areas (Meyer 1996).

Results

Current potential distribution of *M. calvescens*

The TSS (0.82–0.92), AUC (0.95–0.99) and KAPPA (0.68–0.89) results indicated a good model performance (Appendix S4).

According to our models, *M. calvescens* current potential distribution was predicted to be related to low values of altitudinal range, warm and seasonal temperatures and wet conditions (Table 1, Appendix S5).

Our ensemble model predicted that 7.2 % of global landmass presents suitable climatic and altitude range conditions for *M. calvescens* presence (Fig. 1b). More specifically, around 1.8 % of worldwide surface is predicted to be very highly suitable, 1.8 % highly suitable and 3.6 % suitable for *M. calvescens* (Fig. 1b). Furthermore, within the 7.2 % of the predicted suitable area, 45.1 % corresponds to the native range, 1.3 % to the invaded, 13.5 % to the cultivated, 0.3 % to the established, and 39.7 % to areas where the presence of *M. calvescens* has not yet been reported (not reported range; ranges according to the Invasive Species Specialist Group, Fig. 1a, b, see Appendix S1 for details to each range).

Regarding *M. calvescens* non-native range, 44.5 % of its predicted environmentally suitable area (VHS, HS and S) is located in the tropical forests of the southern hemisphere (Fig. 1b). The land cover category that overlaps most prominently with *M. calvescens* suitable non-native range is "tree cover" (30.9 %), followed by "mosaic landscape" (6.7 %) and "human cultivated and managed areas" (3.9 %) (Global Land Cover 2000 database, see Bellard et al. (2013) for re-classification of land use categories). More specifically, our model identified suitable areas in 79 countries belonging to the non reported range of *M. calvescens* (see Appendix S1). Moreover, from the 421 islands located throughout the environmentally suitable range of *M. calvescens*, 167 are islands where its presence has not yet been reported (see Appendix S6 for a detailed list of the islands under risk of invasion).

Assessing the probability of invasion in protected areas worldwide

We found a total of 121 botanic gardens in the non-native but predicted suitable range of *M. calvescens*. In particular, 53, 24, and 44 botanic gardens are in the VHS, HS and S ranges, respectively (Fig. 2a, Appendix S7). According to our results, 46–364 protected areas of the world are predicted to be currently at risk of being invaded by this species (for the optimistic and pessimistic risk zones, respectively; Fig. 2b). More specifically, considering the pessimistic risk zone, up to 164 protected areas are located within VHS range of *M. calvescens* (including the mainland of 53 marine protected areas; Fig. 2b). The cumulated protected area under risk of invasion by *M. calvescens* ranges from 62,335 to 459,047 km^2

worldwide (Fig. 2b), depending on the risk zone considered. Moreover, if we only considered the "pessimistic risk zone", 9 (7 terrestrial and 2 marine) of the 364 protected areas currently under risk are Strict Nature Reserves (category Ia, IUCN; Fig. 2b).

Potential distribution of *M. calvescens* under climate change

There were differences in the worldwide potential distribution of *M. calvescens* projected by the two representative concentration pathway emission scenarios ($H_{1,12} = 7.410$, $p = 0.006$) but not among global circulation models ($H_{2,12} = 2.461$, $p = 0.292$) or time horizons (between 2050s and 2080s; $H_{1,12} = 0.924$, $p = 0.337$).

The global suitable surface for *M. calvescens* is predicted to decrease up to 3 % with respect to current conditions with in the most extreme scenario (RCP8.5, Fig. 1c and 3) and for the time horizon 2080s. The predicted decrease will mainly occur in the native and not reported ranges: 40.9 and 51.3 % reduction in these ranges respectively. In contrast, the decrease in the suitable area of the invaded range is predicted to be minor (14.6 % with respect to current conditions; Fig. 3). The predicted decrease in suitability will mainly occur in tropical biomes (Fig. 3), around a 30 % decrease by the 2080s. By the 2080s, the total number of islands predicted to be in the environmentally suitable range of *M. calvescens* will have reduced from 421 to 290 (RCP8.5).

Discussion

Susceptibility to invasion by *M. calvescens* at global scale

Our models predict that 7.2 % of global landmass presents suitable conditions for *M. calvescens* under current climatic conditions, from which about 45 % corresponds to its native range and nearly 40 % to areas in which the presence of the species has not yet been reported. Our results also show 79 countries and 167 islands with areas suitable for *M. calvescens* in the not reported range, and thus potentially exposed to invasion. These results should draw the attention of managers and stakeholders to these territories, both to avoid the introduction of this species and to search for evidence of *M. calvescens* presence, as prevention can preclude huge monetary costs (Pimentel et al. 2005; Genovesi 2005). For example, the total cost of eradication of *M. calvescens* in Hawaii was predicted to reach several billion dollars (Kaiser 2006).

With respect to habitat, 44.5 % of *M. calvescens* suitable non-native range is located in the tropical forests of the southern hemisphere, demonstrating a large overlap with the land use category "tree cover" and little with "human cultivated/managed areas". Tropical forests have an extraordinary conservational value, as they harbour 46 of the 51 botanically richest ecoregions of the world (Kier et al. 2009) and 18 of the 35 world's biodiversity hotspots (Williams et al. 2011). Until now, continental undisturbed tropical forests have been considered more resistant to the invasion of exotic plants (Corlett 2010), mostly due to their complex and diverse biota (Whitmore 1991). Our results predict that large continental tropical areas have environmentally suitable conditions for *M. calvescens*, calling for oriented efforts to avoid its introduction in these ecosystems.

We have assessed the probability of invasion by *M. calvescens* in protected areas worldwide, using neighbouring botanic gardens as a proxy for likelihood of introduction of the species in these areas. Botanic gardens play a key role in plant conservation (Marris 2006; Reichard and White 2001). However, they have also been implicated in the introduction of most of the invasive plants included in the list of "100 worlds´ worst invasive alien species" (Hulme 2011). In the specific case of *M. calvescens*, most invasions originated from escapees from private and public gardens (Meyer et al. 2011). For instance, the introduction of *M. calvescens* in Tahiti dates from 1937, from a private botanic garden (Papeari Botanical Garden), and from there it colonized most of the surface of the island (Meyer 1996). The same pattern has been reported for Australia, Hawaii, New Caledonia and Sri Lanka (Medeiros and Loope 1997; Csurhes 1998; Meyer 2010).

We found that up to 364 protected areas (459,047 km^2 of protected surface) are currently under risk of being invaded by this species. However, this value must be considered carefully. Indeed, the number of protected areas exposed can be even higher, as here we have considered risk zones surrounding identified botanic gardens, and *M. calvescens* can also escape from small, private gardens. Moreover, it can

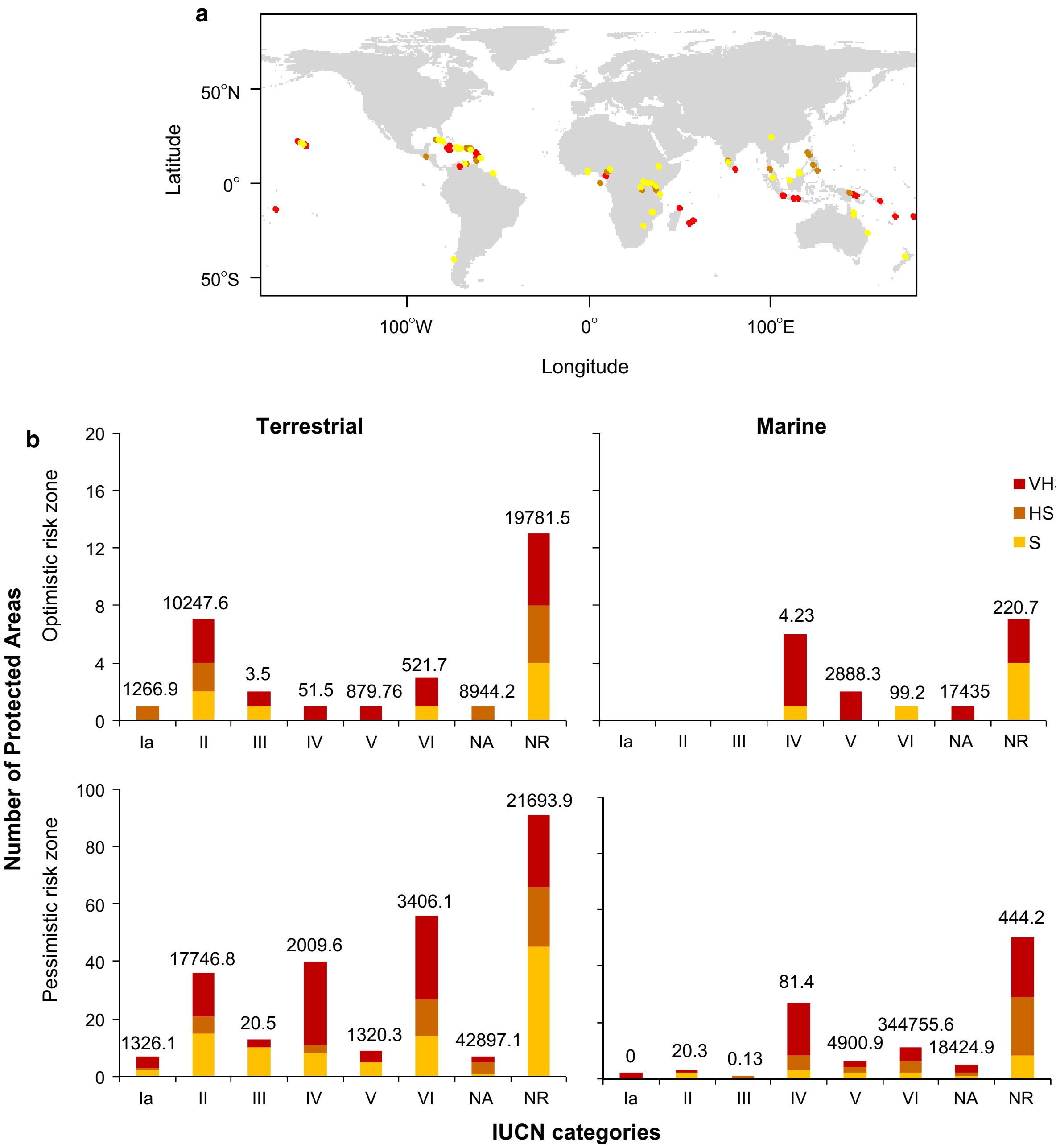

Fig. 2 a Botanic gardens existing in the non-native very highly suitable (*red*), highly suitable (*brown*) and suitable (*yellow*) areas for *M. calvescens*. b Number of terrestrial and marine protected areas per IUCN category overlapping with the "optimistic" and "pessimistic" risk zones (radius = 899 and 10,160 m, respectively) surrounding mentioned botanic gardens and according to the suitability of the area [very highly suitable (*red*), highly suitable (*brown*) and suitable (*yellow*). The total protected surface (km^2) under risk in each category is also indicated in the graphs. In the case of marine protected areas, the area indicated corresponds to the total surface of the landmass existing in the protected area. Categories of the IUCN: Ia, Strict Nature Reserve; Ib, Wilderness Area; II, National Park; III, Natural Monument or Feature; IV, Habitat/Species Management Area; V, Protected Landscape/Seascape; VI, protected area with sustainable use of natural resources; NA, not applicable; NR, not reported by the IUCN]

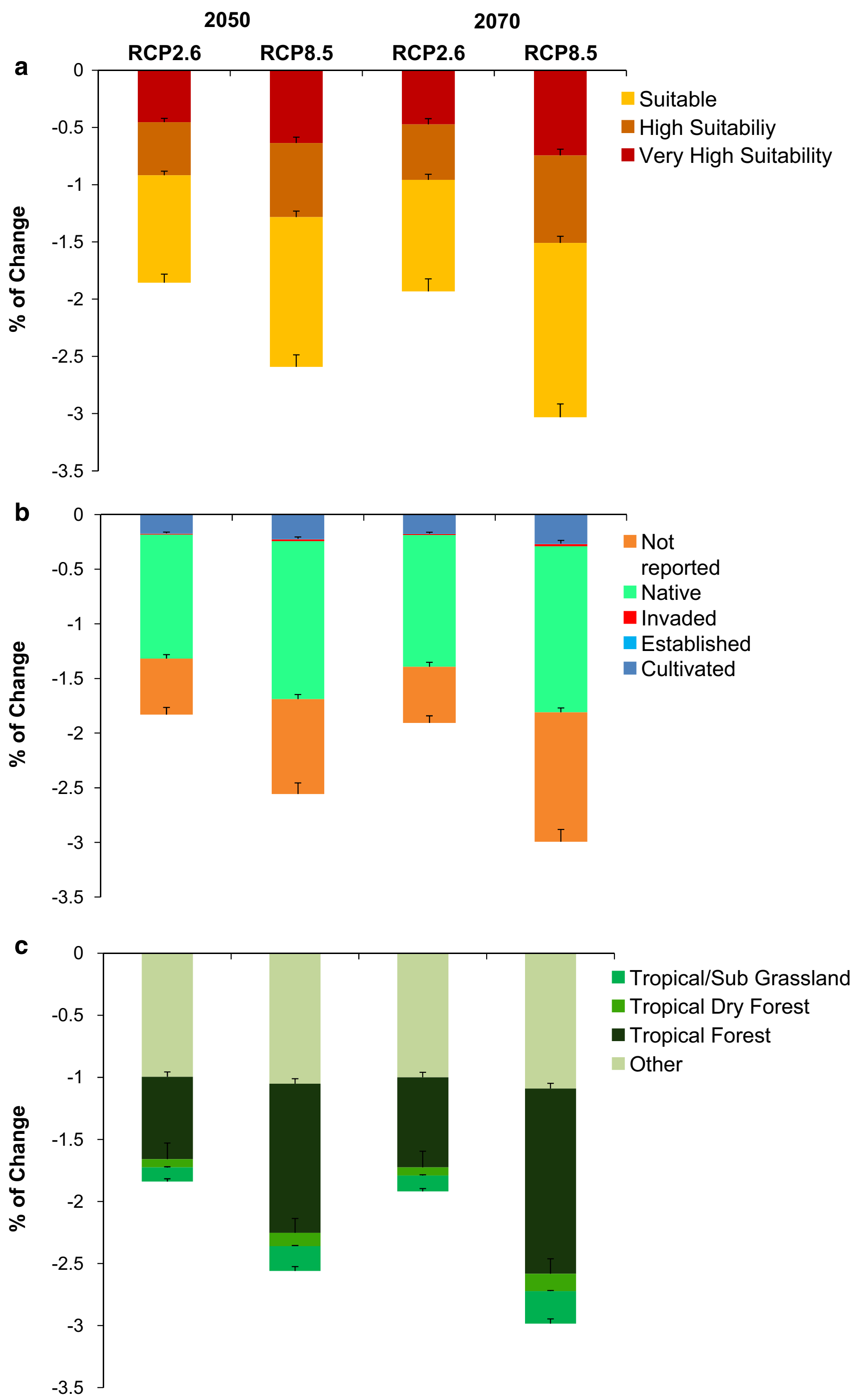

Fig. 3 Average percentage of change with respect to current conditions in each of the representative concentration pathways (RCP2.6/8.5) and for each time horizon (2050s and 2080s) ±SE, a per suitability range (suitable, highly suitable, very highly suitable); b per presence range (not reported, native, invaded, established, cultivated, according to the ISSG 2010); c per global terrestrial biome (the category other includes: Desert, Flooded Grasslands, Mangroves, Mediterranean Forests, Montana Grasslands, Taiga, Temperate Conifer Forests, Temperate Grassland, Temperate Mixed Forests, Tropical/Subtropical Conifer Forests, Tundra. Tropical/Sub grassland in the legend refers to Tropical and Subtropical grassland)

be voluntary or accidentally introduced in any protected area within its environmentally suitable range. Nevertheless, our results highlight some of the potential implications of inappropriate biosecurity measures in botanic gardens. Through the awareness of this potential responsibility, various precautions are being carried out in different botanic gardens to prevent and/or control plant invasions from their collections [see for instance Havens (2006) or Heywood and Sharrock (2013)].

Miconia calvescens precautionary actions have already been implemented across Australia. In June 2013, *M. calvescens* was detected in a public garden of Melbourne and promptly removed, and the presence of the species was tracked down in all major botanic and city public gardens of Australia (Mick Jeffery pers. communication). Following these examples, we recommend avoiding the inclusion of *M. calvescens* in the living collections of the botanic gardens found in its environmentally suitable range, unless the strictest biosecurity measures are followed to prevent escapees (Appendix S7). Monitoring the presence of *M. calvescens* in areas surrounding botanic gardens within our predicted range of suitability is also recommended if this species is in their collection. This precaution will help to rapidly detect possible escapees.

Impacts of climate change on *M. calvescens* potential distribution

Understanding the interactions between climate change and invasive species is key to making educated decisions for native biodiversity conservation in the coming years. Initially, ecologists hypothesized that climate change would increase the impacts and extent of plant invasions (Walther et al. 2002). Recent publications that have used species distribution models regarding very different plant species support this hypothesis (see Pyšek et al. 2002; Kleinbauer et al. 2010; Vicente et al. 2013, among others). In contrast, our results predict that the future suitable area for *M. calvescens* will be strongly reduced with respect to its current potential distribution. This is not an isolated example, and a negative impact of climate change in the suitable distribution area of several invasive species has been previously reported (see for instance: Bradley et al. 2009; Beaumont et al. 2009a; Gallagher et al. 2013; Bellard et al. 2013). These contrasting examples highlight the species specific character of predictions about invasive species distribution under climate change, as well as the difficulties of making generalizations.

In the specific case of *M. calvescens*, we found two striking results: most of the decrease in its suitable area will occur in *M. calvescens* native and not reported ranges whereas little decrease is predicted for the invasive range. These results point at three different management actions regarding *M. calvescens*. First, in its native range, efforts should be focused on the conservation of this species. Second, control, eradication and also prevention efforts should not be reduced in those areas where *M. calvescens* is currently invading. Finally, for those countries located in areas in which the presence of the species has not yet been reported, we recommend avoiding its introduction, as well as monitoring the plant presence, especially in areas surrounding botanic gardens, in order to minimize the establishment of new populations.

Modelling approach limitations

Species distribution models have been successfully employed to assess the susceptibility to invasion under current and future conditions. However, they possess inherent limitations, which in this study we have tried to prevent (Buisson et al. 2010, Jiménez-Valverde et al. 2011). Firstly, we used ocurrence data of a wide area of the known distribution of *M. calvescens*. We included data from both the native and invaded ranges, as the niche of some invasive species have reportedly shifted in invaded ranges (see Pearman et al. 2008; Gallagher et al. 2010a, b; Petitpierre et al. 2012). Secondly, our models performed effectively (see Appendix S4) and we used an ensemble forecast approach, which takes into account uncertainty (Araújo and New 2007; Thuiller et al. 2009). Finally, we did not find differences in the predictions among the different global circulation models we used, which also reduces the uncertainty in our predictions for the future (Buisson et al. 2010).

Even though our results give robust and useful information on a global scale for both current and future climates, species distribution model predictions must be interpreted with caution. For our models, only climatic variables and altitudinal ranges were considered. Species traits (i.e., dispersion ability, propagule pressure, reproductive success), species interactions or local environmental characteristics (such as slope or soil, type) can be important factors explaining *M.*

calvescens distribution and were not included in our models (Meyer 1996; Meyer and Lavergne 2001; Murphy et al. 2008; Hardesty et al. 2011; Pouteau et al. 2011).

Conclusions

Our results can be used by managers and stakeholders to prevent the current and future risk of invasion by *M. calvescens* in their regions. The results illustrate the relevance of conducting risk assessments on the living collections of botanic gardens, which are a common source of escapees of invasive species. They also present an interesting example of a double negative effect of climate change: climate change is predicted to have a minimal effect on the worryingly large invaded range of one of the worst invasive plants worldwide, whereas the suitable surface in its native range is predicted to decrease. Consequently, long-term management plans are recommended, in particular for those regions suitable for *M. calvescens* with a conservation interest (islands and protected areas), wherein introductions are likely to occur.

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