The potential global distribution of the invasive alien species Melinis minutiflora under current and future climates

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Abstract

The invasive exotic plant *Melinis minutiflora* P.Beauv. is a globally invasive species and impacts the economy, biodiversity, and human well-being. The challenges of biological invasion may be intensified by climate change. The increase in temperatures and concentrations of greenhouse gases may favor the introduction, establishment, and expansion potential of this species. Climate change may influence the effective management of invasive species. The objectives of this study were, for the first time, to use CLIMEX software to determine the distribution potential of *M. minutiflora* in the world under current climatic conditions and global climate change scenarios for the 2030, 2050, 2070 and 2100. Modeling with CLIMEX was used to research the impacts of climate change on the potential global distribution of *M. minutiflora*. The potential worldwide distribution of *M. minutiflora* under current climatic conditions is broad, with suitable climatic conditions expanding in tropical and subtropical regions. Future climate scenarios of 2030, 2050, 2070, and 2100 *M. minutiflora* will grow poleward and upward as the climate warms. Where climate change results in expanding the species global potential range, strategies must be analyzed so that strategic control plans for biological invasion are often considered. Understanding this threat can help formulate effective prevention, introduction, and response measures in regions deemed inadequate.

1. Introduction

Biological invasions, climate change, and habitat disturbances are three global environmental challenges facing the 21st century (USGCRP 2018; Beaury et al., 2020). The scenario of plant invasions in the world and its impacts on biodiversity continue to mobilize scientists in the proposition of threat prevention, early intervention, and control (Banerjee et al., 2021). One of the challenges researchers faces is to assume and estimate the impacts that each invasive alien species will have on biodiversity, on a global and local scale, in current and future climates (Vallejo-Marín et al., 2021). Understanding the ecology of the invasive alien species, its distribution, and the impact on the invaded ecosystem is crucial to predicting the risk of invasion and formulating effective strategies to prevent the introduction of alien species (Carboni et al., 2021; Coakley e Petti, 2021).

Several arguments can be suggested to explain, such as greater plasticity in its response to environmental changes and, therefore, greater ability to change its physiological optimum (Maron et al., 2007). Habitat disturbances and biological invasions are the main drivers of global change that threaten biodiversity (Sala et al., 2000). Many introduced invasive alien species benefit from habitat disturbances because they have higher seed production, high reproductive production, seed dispersal efficiency, and better competitors than most native species (Xavier e D'Antonio 2017). Expected climate changes may favor invasive species range, abundance, and establishment compared to native species (Bellard et al., 2013; Ncube et al., 2020) and will challenge the effective management of invasive species. For example, research linking climate change to the geographic distribution of some invasive species shows a tendency to shift poleward and upward in elevation as the climate warms (Kriticos et al., 2003; Bradley et al., 2010) for species in future scenarios. Grasses, especially C4 species, are a model group that is

expected to have considerable changes in distributions in response to climate change (Angelo e Daehler 2013; Fahey et al., 2018). Furthermore, the photosynthetic pathway of C4 plants makes them better adapted to heat stress and high temperatures than C3 plants, leading to a better adaptation to the hotter, drier conditions that occur in their newly introduced range (Chuine et al., 2012).

Melinis minutiflora P.Beauv., (molasses grass) is a C4 perennial grass native to Africa but currently distributed throughout the tropics (Baruch e Gomez, 1996; Hoffmann et al., 2004). It flowers at the beginning of the dry season, in mid-May (de Oliveira Xavier et al., 2019), producing large amounts of seeds, and its occurrence is more limited by low temperatures than by soil quality (Carmona and Martins 2010). This plant was probably introduced accidentally or for commercial purposes in Brazil in the 18th century and is currently reported as an invasive species, reducing native vegetation in conservation units (Ribeiro et al., 2017; Nogueira et al., 2019). The species reduces biodiversity when it invades different ecosystems, impacting native species.

Melinis minutiflora has a wide geographic distribution in tropical and subtropical regions (Zenni and Ziller 2011). It is widely distributed in Central America, South America, Asia, Australia, Hawaii, and Oceania (Hughe et al., 1991; Neves et al., 2021). In Brazil, it occurs mainly in the neotropical savanna (Cerrado), a biodiversity hotspot of global significance (Damasceno et al., 2018). By threatening the native biota, it alters the functioning of the ecosystem, causes several economic and social impacts, in addition to the natural heritage, for example, the agricultural system of Serra do Espinhaço, the first recognized Agricultural Heritage in Brazil and the fourth in Latin America (Castro- Díez et al., 2019).

Climate-based modeling tools can aid the early prediction of different potential future trajectories of biological invasions. Bioclimatic models are tools used to analyze the potential distribution of species in space and time based on their ecology and climate (Ncube et al., 2020). Scenario analysis also allows searching for extensive possible variations of a species likely to establish itself in the future (Roura-Pascual et al., 2021). Studies on global and local climate changes provide an ideal opportunity to test the hypothesis that climate is an important determinant of species distribution limits. Understanding the environmental factors that drive invasion success is important for predicting potential models and early detection, especially in the context of climate change.

The objectives of this study were: (i) to use CLIMEX software to develop climatic parameters that describe the response of *M. minutiflora* to climatic variables, based on its global distribution and; (ii) estimate the potential distribution of *M. minutiflora* under current climatic conditions and global climate change scenarios for the years 2030, 2050, 2070 and 2100.

2. Materials And Methods

2.1 Global distribution of Melinis minutiflora

The current global distribution of *M. minutiflora* was obtained from the Global Biodiversity Information Facility (GBIF) (GBIF 2021) and published literature (Hughes et al., 1991; Ribeiro et al., 2017; Nogueira et

al., 2019). Occurrence records were checked and those with incomplete or duplicate location information were omitted.

2.2 CLIMEX Model

CLIMEX modeling software is a dynamic model (Kriticos et al., 2015) and was used in this study to create a model of the potential distribution of *M. minutiflora* in different climatic conditions around the world. CLIMEX is based on an eco-physiological growth model and includes weekly population responses to a climate by calculating annual indices. Based on growth, this model can be maximized when seasons are right and minimized in unfavorable seasons (Fig. 1). Climex calculates an annual growth index (GI_A) to describe the potential growth of a population under favorable conditions of soil moisture and temperature (Kriticos et al., 2015). Stress indices (cold, hot, wet, and dry) and their combinations (cold-wet, cold-dry, hot-humid, and hot-dry) can be entered into the model to calculate the probability that the population will survive during unfavorable conditions (Kriticos et al., 2015). Growth and stress indices are calculated weekly and combined into an overall annual Ecoclimatic Index (EI) of climate suitability. The EI ranges on a scale of 0 to 100, with 0 referring to locations unsuitable for the species to persist and ≥ 30 to locations where the climate is suitable for the species throughout the year (Kriticos et al., 2015). Completed EI values can be presented in tables and maps. In this study, the EI values were grouped into three climate suitability classes for *M. minutiflora*: inadequate (EI = 0), adequate (0 < EI < 30) and highly adequate (EI ≥ 30).

2.3 Setting parameters in CLIMEX

The temperature and soil moisture indices used as parameters of the CLIMEX model for *M. minutiflora* were obtained from tests in greenhouses, growth chambers (phytotrons), and literature review. Occurrence points with geographic coordinates of invaded areas (Brazil) in protected areas were used to improve the climatic limits of the invasive alien species by adjusting the model. Native or introduced ranges can be included where possible when adjusting parameters for ecoclimatic models for invasive species.

2.3.1 Growth rates

The values of the low threshold temperature (DV0) and high threshold temperature (DV3) parameters for *M. minutiflora* were adjusted based on germination and growth experiments, in which the species was found in areas with an average temperature of the coldest month of 5°C and germination rate and better tolerance to post-fire conditions of 45°C (Cook et al., 2005; Musso et al., 2015). Thus, the low threshold temperature (DV0) and high threshold temperature (DV3) used were 5 and 45°C, respectively. The optimal minimum and maximum temperature limits for growth (DV1 and DV2) were set at 18 and 40°C, respectively, based on experiments that evaluated minimum [base] temperature and maximum [ceiling] temperature of *M. minutiflora* between 13 and 43°C, respectively (Durán Puga et al., 2011).

2.3.2 Moisture index

Melinis minutiflora is a C4 plant that has a global distribution in humid tropical and humid subtropical climates. According to its worldwide distribution and to allow the growth of the species, the lower limit of humidity (SM0) was adjusted to the respective value of 0.2. The limits of ideal soil moisture (SM1 and SM2) were adjusted to 0.7 and 1.5, respectively, to approximate adequate moisture conditions for optimal growth of the species. The upper limit of soil moisture (SM3) was set at 2.5 to allow *M. minutiflora* to grow in humid subtropical climates such as Miami (USA), Curitiba (Brazil), Longhua District (China) and Tygalgah (Australia) where rainfall exceeds 1500 mm year $^{-1}$.

2.3.3 Stress indices

The cold stress index (TTCS) was 5°C based on the lower growth limit of the species and the rate of accumulation (THCS) was – 0.001 week $^{-1}$ (Cook et al., 2005). The heat stress index (TTHS) used was 45°C, based on the species upper growth limit, and the rate of accumulation (THHS) was 0.0001 week $^{-1}$ (Musso et al., 2015). The dry stress limit (SMDS) was 0.2, based on the lower limit of soil moisture (SM0). The accumulation rate (HDS) was – 0.0005 week $^{-1}$, due to the distribution in a tropical savanna climate, without periods of flooding and with a short period of annual water deficit (Xavier et al., 2017; Leite et al., 2018). The wet stress threshold (SMWS) was set at 2.5. The accumulation rate (HWS) was set at 0.001 week $^{-1}$, allowing *M. minutiflora* to grow in areas with increased rainfall and explaining that the species is moderately resistant to periods of flooding (Xavier et al., 2017).

2.4 Model verification and validation

This step was subdivided and in the first part, the verification was based on the distribution of *M. minutiflora* in Brazil. In the second step, the model was validated by comparing the result with the known distribution of *M. minutiflora* in Australia. The model results were displayed on maps, showing the ecoclimatic suitability of different areas for the growth of *M. minutiflora*. The model verification and validation results confirm true estimates and reliability in the final model.

2.5 Climate change scenarios

Climatic data from CliMond 10' were used in the CLIMEX model (Kriticos et al., 2012). The climate change scenario was used as meteorological data for the validated CLIMEX model to project the potential future distribution of *M. minutiflora*. This scenario was developed from Global Climate Models (GCMs). GCMs with grid spacing and the necessary weather variables at an appropriate temporal resolution for CLIMEX were chosen: CSIRO Mark 3.0 (CSIRO, Australia). The global distribution of *M. minutiflora* for 2030, 2050, 2070, and 2100 was modeled under the A2 emissions scenario using GCM, CSIRO Mark 3.0 (Gordon et al., 2002). The climatic variables required by CLIMEX (monthly averages of daily minimum and maximum temperature, relative humidity at 09:00 h (RH 09:00) and 15:00 h (RH 15:00), and monthly total precipitation) were extracted or estimated from the GCM data using techniques described in Stephens et al. (2007). The selection of CSIRO is due to the predictions grouping a 2.11°C increase in temperature and a 14% decrease in precipitation by 2100 (Chiew et al., 2009). The choice of scenario A2 is related to the relatively moderate increase in global greenhouse gas (GHG) emissions (Bernstein et al., 2007).

3. Results

3.1 Current distribution of Melinis minutiflora

A total of 125 *M. minutiflora* occurrence points with geographic coordinates worldwide are shown in Fig. 2.

The adjusted parameter values for *M. minutiflora* are listed in Table 1.

Table 1
Values of the fitted parameters used to generate bioclimatic models of the distribution of *Melinis minutiflora* using CLIMEX

Index	Parameter	Values	References
Temperature	DV0 = lower threshold	5°C	Cook et al., 2005
	DV1 = lower optimum temperature	18°C	Durán Puga et al., 2011
	DV2 = upper optimum temperature	40°C	Durán Puga et al., 2011
	DV3 = upper threshold	45°C	Musso et al., 2015
Moisture	SM0 = lower soil moisture threshold	0.2	-
	SM1 = lower optimum soil moisture	0.7	-
	SM2 = upper optimum soil moisture	1.5	-
	SM3 = upper soil moisture threshold	2.5	-
Cold stress	TTCS = temperature threshold	5°C	Cook et al., 2005
	THCS = stress accumulation rate	-0.001/week^{-1}	-
Heat stress	TTHS = temperature threshold	45°C	Musso et al., 2015
	THHS = stress accumulation rate	0.0001/week^{-1}	-
Dry stress	SMDS = soil moisture threshold	0.2	Leite et al., 2018
	HDS = stress accumulation rate	-0.0005/week^{-1}	-
Wet Stress	SMWS = soil moisture threshold	2.5	Xavier et al., 2017
	HWS = stress accumulation rate	0.001/week^{-1}	-
Degree Days	PDD = degree days per generation	0	-

3.2 Potential distribution of Melinis minutiflora under current climate

The model for the current climate showed an excellent fit to the *M. minutiflora* occurrence data. The occurrence points are within the areas predicted by the model as suitable for the development of *M. minutiflora* (Fig. 3). Climatic conditions are suitable for *M. minutiflora* in tropical and subtropical regions, except for desert areas where dry stress and/or excessive heat affect its distribution. Climatic conditions are proposed to be highly suitable in some warm temperate regions, for example, northern New Zealand and southern Mediterranean Europe. Parts of South America, Central America, the southeastern US, sub-Saharan Africa, Madagascar, the Indian subcontinent, and Australia are climatically ideal.

3.3 Model validation

Model validation is shown in Fig. 4. Approximately 39.2% of the species occurrence points are in Australia. The actual distributions of *M. minutiflora* in Australia agreed with the CLIMEX results, as the species only occurred in areas that were estimated to be climatically adequate by the model, thus proving the model. *Melinis minutiflora* was found in some localities such as Northern Territory, New South Wales and Queensland.

3.4 Potential distribution of Melinis minutiflora in future climate scenarios

The impact of future climate on the potential distribution of *M. minutiflora* showed that its distribution will probably extend towards the poles and at an altitude proportional to the rise in temperature (Fig. 5). Under current climate conditions, the appropriate environment, for example, in the USA occurs in parts of the South, while in future climate change scenarios, the proper distribution increases across other areas of the USA. In some regions in northeastern Brazil, the warming projected in future climate scenarios may decrease the threat of *M. minutiflora* invasion by 2100. Some areas go from being highly suitable to suitable, such as southern India. The projection of ideal climates for *M. minutiflora* in Africa and Australia is reduced, as it predicts that the climate will become drier. Climate change scenarios show that South America is likely to become warmer and wetter (Stephens et al., 2007).

The potential range areas of *M. minutiflora* may increase by 2100 compared to the present time. This forecast indicates risks of invasion and establishment of *M. minutiflora* in new areas globally. In Europe, the potential range of *M. minutiflora* is projected to expand northward. In the evaluated future climate scenarios, the climate suitability of much of Europe, USA and Southeast Asia increases until 2100. If the encroachment occurs as expected in the model, it could lead to large losses and forest fires, particularly in Europe.

4. Discussion

Exotic grasses are considered one of the main invasive species specifically in protected areas (Nogueira et al., 2019), and, in Brazil, the most considerable invasions by *M. minutiflora* correspond to these areas (Ribeiro et al., 2017). This species has spread over large areas of natural and anthropic environments,

becoming extremely competitive with native flora, being responsible for the decline and loss of biodiversity (Pivello 2011). *Melinis minutiflora* has also been identified as a regional problem in the Midwest and Southeast of Brazil (Carmona and Martins 2009; Damasceno et al., 2018; Rocha et al., 2017). Due to the great invasiveness in open areas, it has become a severe problem in the Cerrado Biome, being common in several protected areas (Nogueira et al., 2019).

Invasive grasses have a wide global distribution, due to variable plant physiology, morphology and anatomy (Rossi et al., 2014). Invasive grass species such as the *Miscanthus* genus are distributed in humid subtropical and tropical savanna climates (Hager et al., 2014) and the *Hyparrhenia hirta* species, which occurs mainly in subtropical, warm temperate or Mediterranean climates (Chejara et al., 2010). Species of the genus *Melinis* are also distributed in several countries (GBIF 2021) in tropical and subtropical regions (Zenni and Ziller, 2011). This distribution is related to its C4 metabolism, as it depends on a higher amount of energy for its growth, with optimal temperatures above 18°C (Carmona and Martins 2010). Countries like Brazil, with a tropical climate, are suitable for the growth of the species due to the optimal temperatures for its development, in addition to the characteristics of the species that reproduces by seeds and vegetatively, has seed viability and grows vigorously in soils poor in nutrients, the which facilitates its dispersion.

CLIMEX is being used to model species distributions, with success in research (Dhileepan and Senaratne, 2009). In this study, this tool was helpful in the formulation of the research methodology by identifying areas in countries that were climatically more suitable to invasion by *M. minutiflora*. The model also highlights the potential for *M. minutiflora* to spread. The distribution records to date agree with the model results. The results found in this research include the finding that *M. minutiflora* is a worldwide problem, in agreement with reports of being a significant invasive species (Foxcroft et al. 2010).

Modeling in CLIMEX generates predictors to guide future perspectives. This modeling is used to identify habitats where a potentially invasive species can establish viable populations, that is, the potential distribution of the species in climate change scenarios (Jiménez-Valverde et al., 2011). Due to local rainfall and temperature changes, many plant species have already changed their distribution towards higher latitudes or elevations, with the temperature being one of the main drivers of distribution patterns (Araújo et al., 2005). Most studies that analyze responses to climate change have focused on the direct effects of environmental conditions, individual physiology, and population demographics (Keith et al., 2008).

This species must be monitored to avoid possible invasions and so that a quick response and management actions can be implemented after possible detection of the invasive species. Furthermore, research such as these and the maps produced contribute to the formulation of management strategies, such as developing a government strategic plan and management plans for protected areas, such as National and State Parks. The subsequent use of modeling programs using CLIMEX advances the results of these research.

Efforts will be made to raise public awareness about the biological invasion and reduce dispersion at entry points, identification, and appropriate control techniques. The results of this study are based on climate only and do not contain non-climatic factors. Furthermore, the results are also subject to the uncertainties surrounding the future of climate change.

5. Conclusion

Using the CLIMEX model, it was possible to conclude how changes in the invasive alien species *M. minutiflora* in areas can be expected as climate change occurs and how these changes vary between countries.

Where climate change results in expanding the species global potential range, particularly in Europe and the United States, strategies must be analyzed so that strategic control plans for biological invasion are often considered.

Declarations

Data availability

All data generated or analysed during this study are included in this published article [and its supplementary information files].

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Author statement

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Figures

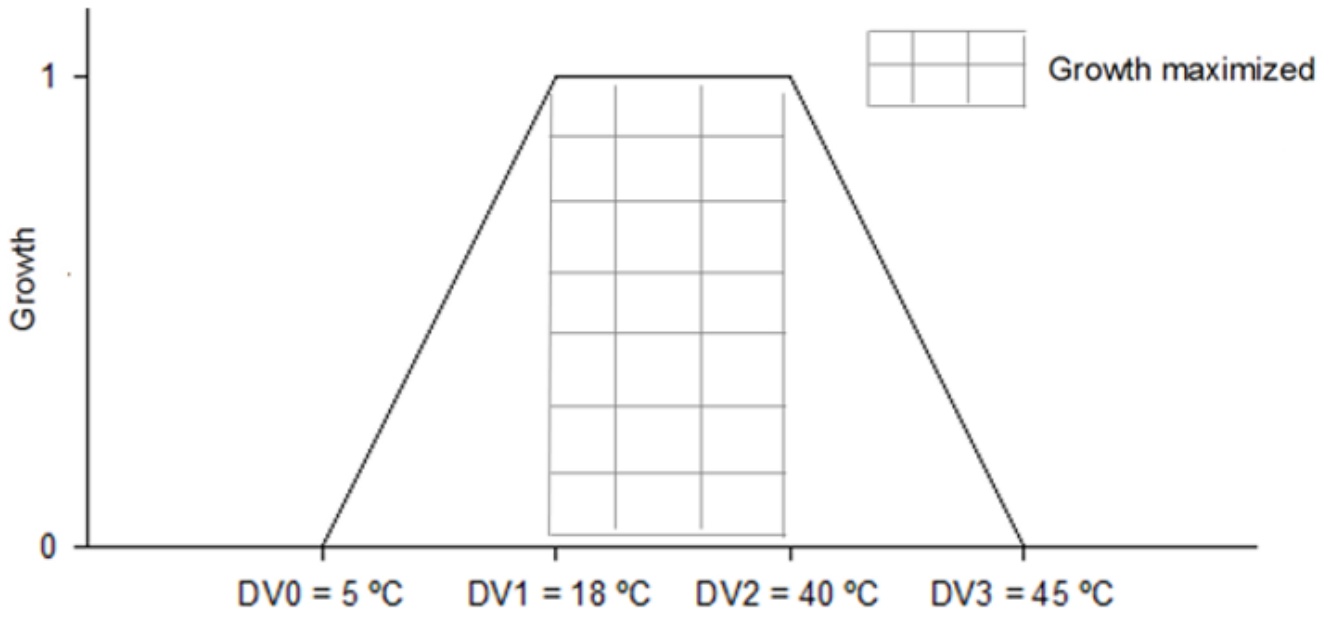

Figure 1

Temperature is a function of the population growth of the species under study. The parameters used to define the optimal temperature range for population growth are DV0, DV1, DV2, and DV3. DV0 is the lower temperature limit, DV1 is the lower optimum temperature, DV2 the upper optimum temperature, and DV3 the upper temperature limit.

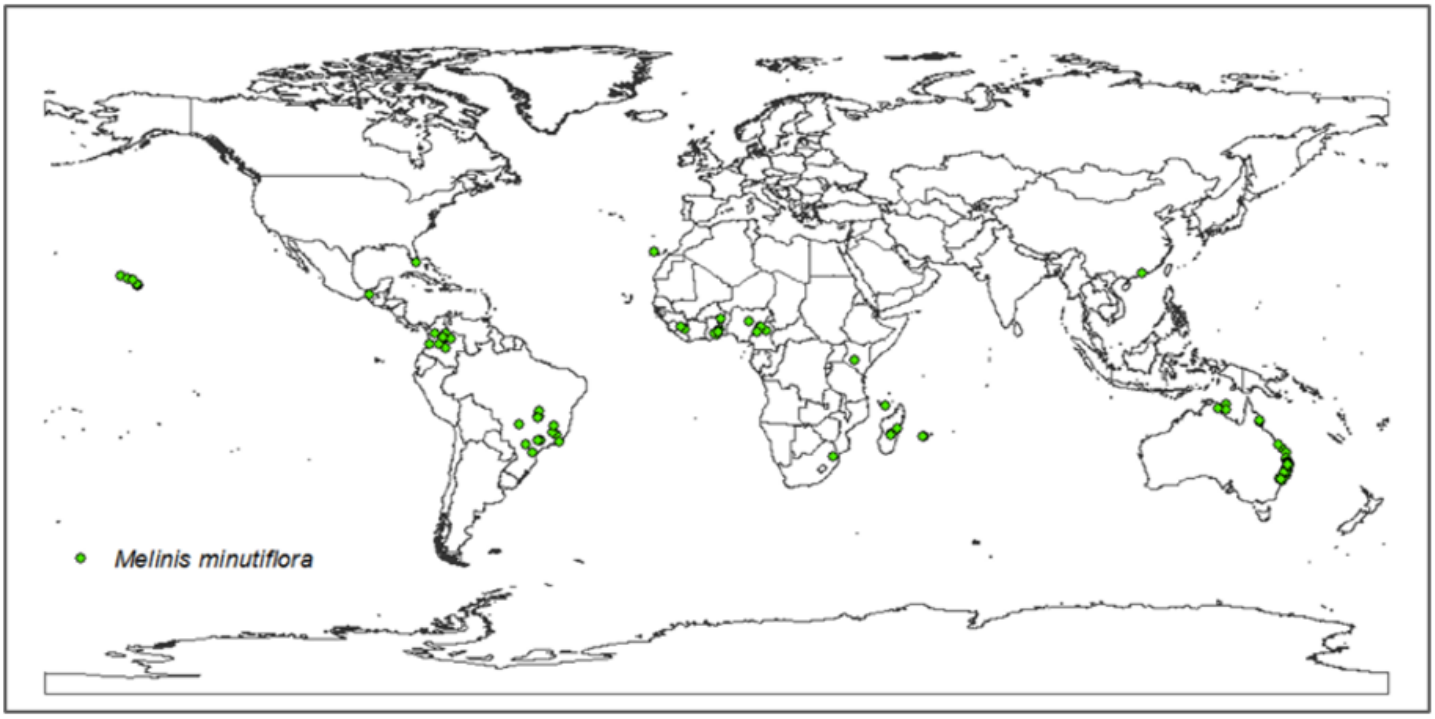

Figure 2

Map of the known global distribution of *Melinis minutiflora*.

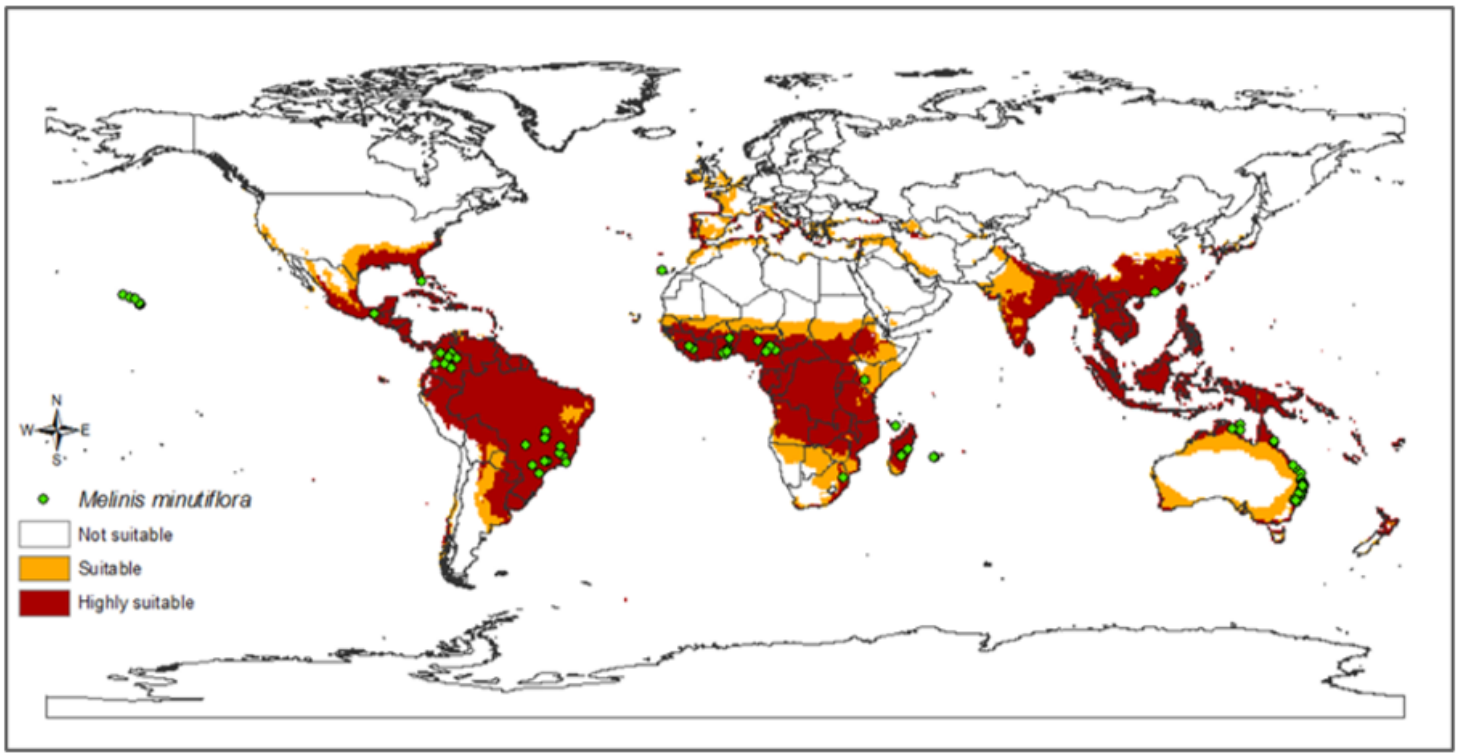

Figure 3

Ecoclimatic Index (EI) modeled for *Melinis minutiflora* using CLIMEX for current climate. The not suitable areas in white (EI = 0), suitable in yellow (0 <EI <30) and highly suitable in red (EI ≥ 30).

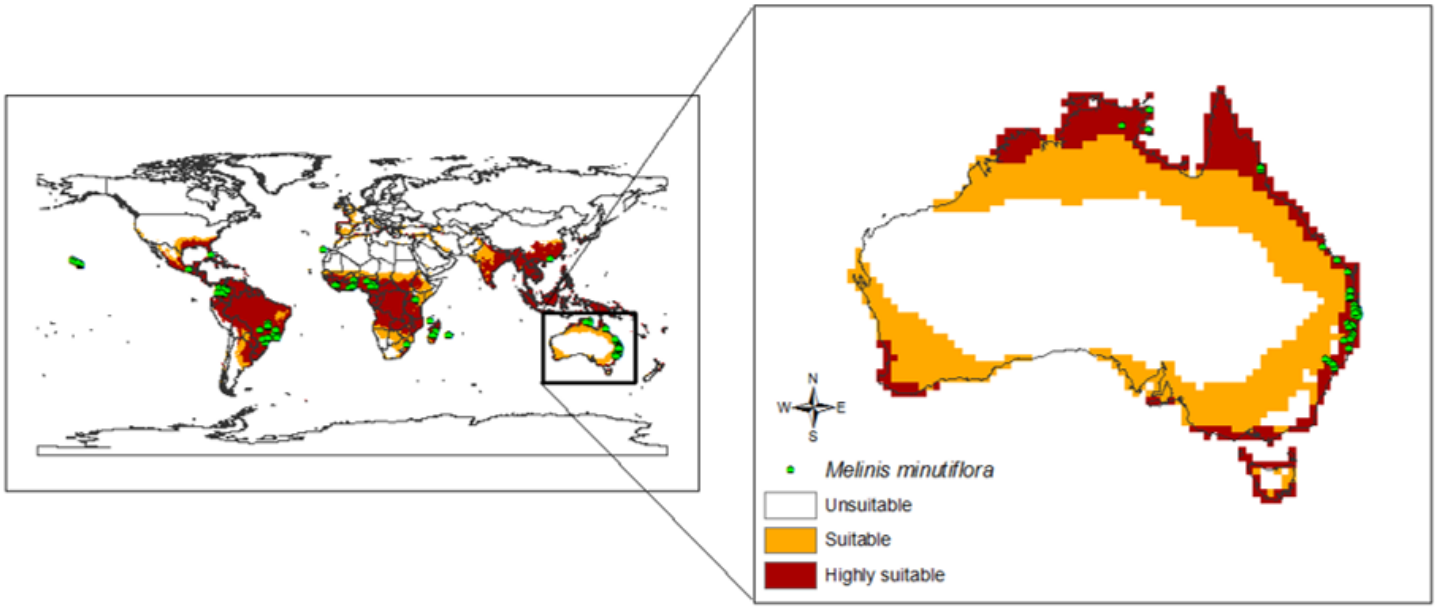

Figure 4

Current and potential distribution of *Melinis minutiflora* in the validation regions based on the Ecoclimatic Index (EI). The not suitable areas in white (EI = 0), suitable in yellow (0 <EI <30) and highly suitable in red (EI ≥ 30).

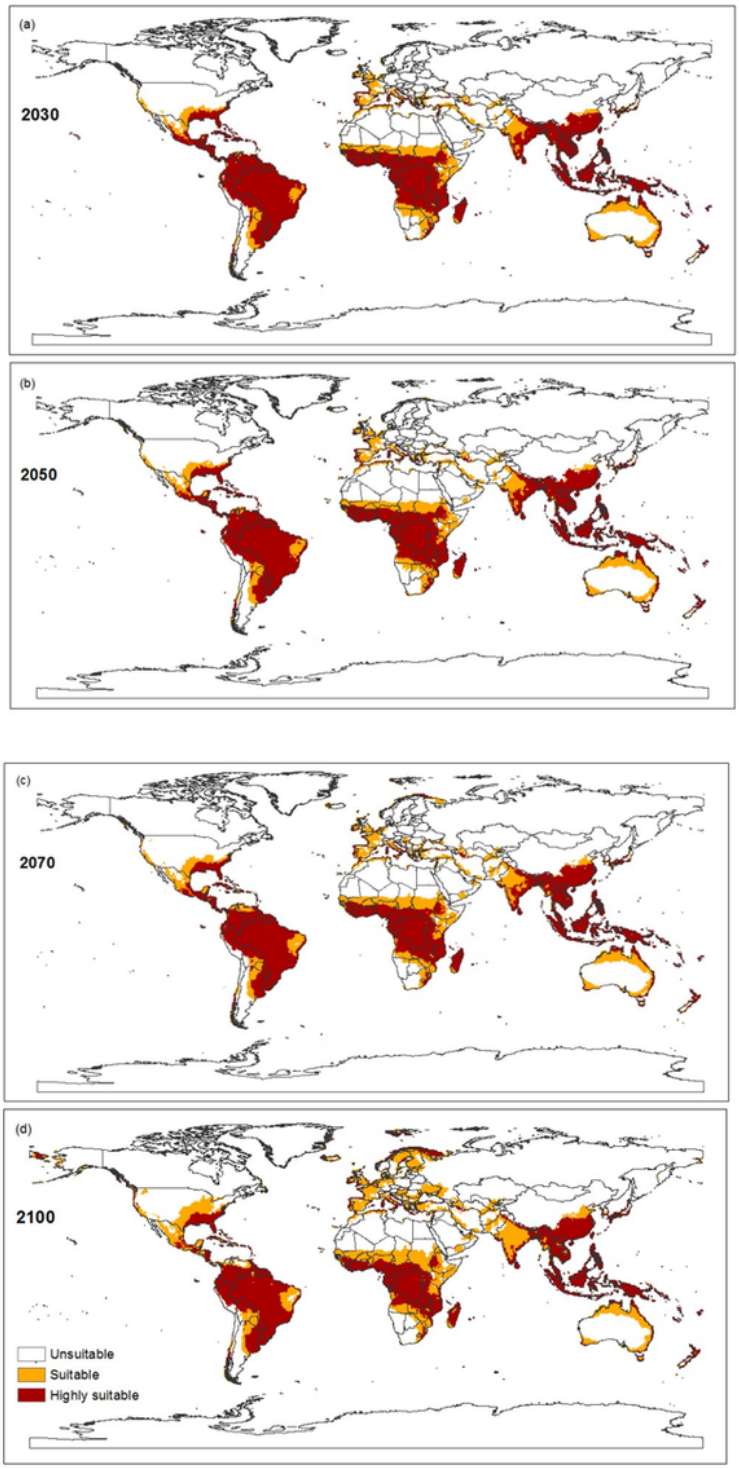

Figure 5

World map showing the change in climate suitability for *Melinis minutiflora*, under climate change scenarios for 2030 (a), 2050 (b), 2070 (c) and 2100 (d) derived from CSIRO Mark 3.0, run with the emission scenario A2. The not suitable areas in white (EI = 0), suitable in yellow (0 <EI <30) and highly suitable in red (EI ≥ 30).

Supplementary Files

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- AnnexI.docx