



The future of invasive African grasses in South America under climate change

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ABSTRACT

Climate change will promote substantial effects on the distribution of invasive species. Here, I used an ensemble of bioclimatic envelope models (Gower Distance, Chebyshev Distance, and Mahalanobis Distance) to forecast climatically suitable areas of South America for 13 invasive African grass species under future climate conditions (year 2050). Under current climatic conditions, the areas with the potential for the highest invasive species richness are located mostly in the tropical climates of South America, except for the Amazon region. In the year 2050, the overall pattern of invasive species richness will not change considerably, and increases in northeastern Amazon and portions of the temperate regions of South America are predicted.

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1. Introduction

Invasive species are one significant threat to natural ecosystems (Mack et al., 2000). On the global scale, invasive grass species are among the most successful invasive plants (Pysek, 1998) and can cause substantial changes in biodiversity and ecosystem function (D'Antonio and Vitousek, 1992; Williams and Baruch, 2000).

Climate change will promote substantial effects on key components of invasive plants (see Hellmann et al., 2008 for more details on consequences of climate change for invasive species). For instance, climate change may modify the impact of non-native invasive species on native species and ecosystems and facilitate the establishment and spread of new invasive species (Bradley et al., 2010a). Therefore, the identification of climatically suitable areas for invasive grasses under climate change will provide valuable information to prioritize in conservation and preventive strategies.

In recent years, bioclimatic envelope models (henceforth BEMs) have been used to forecast climatically suitable areas under climate change for individual invasive grass species (e.g., Bradley, 2009; Bradley et al., 2009; Bradley et al., 2010b; Curtis and Bradley, 2015) and multiple invasive grass species (e.g., Parker-Allie et al., 2009; Gallagher et al., 2013). Bioclimatic envelope models are built using modeling methods that establish correlations between the occurrence records of species and current climatic variables (Peterson et al., 2011). The model fit is then projected onto the entire study area in a future scenario of climate change, producing a map that shows climatically suitable areas for species (Peterson et al., 2011).

In South America, many African grasses were introduced intentionally forage or ornamental purposes and accidentally through contaminated crop seeds (Williams and Baruch, 2000). Some of these grasses escaped from cultivated areas and invaded natural ecosystems (Williams and Baruch, 2000), causing serious ecological damage. For instance, invasive grass species in natural environments of South America have reduced native diversity (e.g., Hoffmann and Haridasan, 2008; Almeida-Neto et al., 2010; Rossi et al., 2014) and modified species composition and ecosystem processes (e.g., disturbance regimes and biogeochemical cycling rates; D'Antonio and Vitousek, 1992; Williams and Baruch, 2000). Moreover, populations of invasive species are difficult to eradicate and/or control once established (Pimentel et al., 2001) and, according to Thalmann et al. (2015), BEMs are a useful and cost-effective tool for conservation planning and biodiversity management.

In this study, I built an ensemble of BEMs to forecast climatically suitable areas of South America for invasive African grass species under future climate conditions. I focus on 13 important invasive species (C4 species) in South America: *Andropogon gayanus* Kunth, *Brachiaria brizantha* Hochst (Ex A. Rich), *Brachiaria decumbens* Stapf., *Chloris gayana* Kunth, *Eragrostis curvula* (Nees) Schrad., *Eragrostis plana* Nees, *Hyparrhenia rufa* (Nees) Stapf., *Melinis minutiflora* Beauv., *Panicum coloratum* L., *Panicum clandestinum* L., *Panicum purpureum* Schum., *Rhynchelytrum repens* (Willd) C.E. Hubb and *Urochloa mutica* Forsk (Williams and Baruch, 2000). As the invasive species were mostly from tropical areas in Africa, my general expectation was an increase in the area occupied by species toward temperate regions of South America.

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2. Materials and methods

2.1. Species data

I compiled worldwide native and invasive presence records (latitude and longitude coordinates) for these 13 grasses from four online databases: (i) Global Biodiversity Information Facility (GBIF; <http://www.gbif.org>), (ii) Instituto Hórus (<http://www.institutohorus.org.br>), (iii) SpeciesLink (<http://splink.cria.org.br>) and (iv) Tropicos (<http://www.tropicos.org>). For *E. plana*, I also included presence records from Barbosa et al. (2013). I removed duplicate presence records using ENMTools version 1.3 software (Warren et al., 2010). My final datasets comprised 692 presence records for *A. gayanus*, 580 for *B. brizantha*, 210 for *B. decumbens*, 1699 for *C. gayana*, 2584 for *E. curvula*, 3216 for *E. plana*, 986 for *H. rufa*, 497 for *M. minutiflora*, 454 for *P. coloratum*, 1941 for *P. clandestinum*, 685 for *P. purpureum*, 749 for *R. repens* and 487 for *U. mutica*.

2.2. Bioclimatic variables

I characterized current climate conditions using 19 current bioclimatic variables obtained from the WorldClim database (Hijmans et al., 2005; <http://www.worldclim.org>) with a spatial resolution of 10 arcmin. I then selected six bioclimatic variables that were not collinear (pair-wise $r_{\text{Pearson}} < 0.75$): (i) mean temperature diurnal range (mean of the monthly difference between maximum and minimum temperatures), (ii) temperature seasonality, (iii) mean temperature of the wettest quarter, (iv) annual precipitation, (v) precipitation of the driest month, and (vi) precipitation seasonality. These bioclimatic variables were selected based on the basis of related studies (Parker-Allie et al., 2009; Bradley et al., 2010b; Gallagher et al., 2013; Curtis and Bradley, 2015), excluding highly correlated variables (pair-wise $r_{\text{Pearson}} < 0.75$; Braunisch et al., 2013) to reduce multicollinearity and subsequent model over-fitting (Jiménez-Valverde et al., 2011).

In order to characterize future climate conditions, I used the same six bioclimatic variables projected for the year 2050 from three Atmosphere-Ocean Circular Models (AOGCMs: CCSM4, GISS-E2-R and MIROC5) using the RCP45 carbon emission scenario. I used three AOGCMs to include variation and uncertainty between mathematical simulations (Diniz-Filho et al., 2009). I obtained future data for each AOGCM from the WorldClim database (Hijmans et al., 2005; <http://www.worldclim.org>) with a spatial resolution of 10 arc-minutes.

2.3. Bioclimatic envelope modeling and ensemble forecast

For each species, I built the BEMs using default options of three presence-only methods: Gower Distance (Carpenter et al., 1993), Chebyshev Distance (Carpenter et al., 1993), and Mahalanobis Distance (Farber and Kadmon, 2003). Presence-only methods were chosen because absence records do not always imply a lack of climatic suitability (see Bradley, 2009 for more details). I used worldwide distribution data (i.e., presence records from both the native and invaded range) for each species (Broennimann and Guisan, 2008). The current and future BEMs were fit on the global scale and then projected onto South America to forecast areas that would be climatically suitable for invasive grasses. The BEMs were built using openModeller version 1.1.0 software (Souza-Muñoz et al., 2011).

To assess the predictive power of the models, I used the area under the curve (AUC) derived from receiver operating characteristics ROC (Fielding and Bell, 1997). AUC values range from 0 to 1, and according to Swets (1988), an AUC above 0.8 is considered to have good discrimination abilities.

My modeling procedure yielded three maps of climatic suitability per species for current climatic conditions and nine (three modeling methods \times three AOGCMs) maps of climatic suitability per species for future climatic conditions. In order to produce robust forecasts and reduce the sources of uncertainty (i.e., differences between modeling methods and AOGCMs), I applied an ensemble forecast approach (Araújo and

New, 2007) to combine the maps of climatic suitability. The final current and future consensus map for each invasive grass was obtained by averaging values of each grid cell in a map (Marmion et al. 2009).

I transformed the final current and future consensus maps into binary suitable/non-suitable maps using the Reclassify tool in Spatial Analyst of ArcGIS 10 (ESRI, 2010) and a threshold of 0.5 (Bertelsmeier and Courchamp, 2014; Thalmann et al., 2015). I then built a current and future species richness map using a simple summation of each grid cell of the binary suitable/non-suitable maps of the invasive grass. This was performed using the raster calculator tool in the spatial analyst capability of ArcGIS 10 (ESRI, 2010).

2.4. Measuring sources of uncertainty

I followed the protocol proposed by Diniz-Filho et al. (2009) and used the total sum of squares (SS) from a two-way analysis of variance (ANOVA) without replication to quantify the relative importance of each of the sources of uncertainty studied here (i.e., modeling methods and AOGCMs). I carried out the ANOVA using invasive species richness as the response variable and modeling methods and AOGCMs as factors.

3. Results

For all species, AUC values were within the accepted range of high-performing models (mean AUC value 0.983 ± 0.01 ; see Appendix S1). All the invasive African grasses, except *H. rufa*, showed losses of climatically suitable areas in South America under climate scenarios (Table 1).

Under current climatic conditions, the areas with potentially highest invasive species richness are located mostly in the tropical climates of South America, except for the Amazon region (Fig. 1a). For the year 2050, the overall pattern of invasive species richness will not change considerably (Fig. 1b). Reductions in the number of invasive species are forecasted to affect northern and western portions of South America, while increases in species richness of invasive grasses are located in the north-eastern Amazon, southern Brazil and Uruguay and central portions of Argentina (Fig. 1c).

Modeling methods were the main source of uncertainty and accounted for 82% of the total sum of squares (SS). The interaction between AOGCMs and BEMs and the main effects of AOGCMs each accounted for 0.8% of SS.

4. Discussion

Studies have examined sources of uncertainty to forecast climatologically suitable areas under climate change. My uncertainty analysis indicated that the modeling method component is the most important source of uncertainty, as indicated in other studies (Diniz-Filho et al., 2009;

Table 1
Percentage of climatically suitable land area in South America for 13 invasive African grasses under current and future climate conditions.

Species name	% Climatically suitable area in South America		$\Delta\%$
	Today	Future	
<i>Andropogon gayanus</i>	76.07	72.86	−3.21
<i>Brachiaria brizantha</i>	83.36	81.74	−1.62
<i>Brachiaria decumbens</i>	77.54	71.50	−6.04
<i>Chloris gayana</i>	86.71	77.36	−9.34
<i>Eragrostis curvula</i>	70.58	60.45	−10.13
<i>Eragrostis plana</i>	60.01	50.84	−9.17
<i>Hyparrhenia rufa</i>	83.69	83.90	+0.21
<i>Melinis minutiflora</i>	81.21	78.94	−2.27
<i>Panicum coloratum</i>	59.80	54.58	−5.22
<i>Pennisetum clandestinum</i>	84.89	69.21	−15.68
<i>Pennisetum purpureum</i>	85.55	84.32	−1.22
<i>Rhynchelytrum repens</i>	84.94	84.03	−0.91
<i>Urochloa mutica</i>	82.28	79.74	−2.53

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