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## Irrigation as an important factor in species distribution models

Roy Federman\*, Yohay Carmel, Rafi Kent

Faculty of Civil and Environmental Engineering, The Technion – Israel Institute of Technology, Haifa 32000, Israel

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### Abstract

Species distribution models (SDMs) that employ climatic variables are widely used to predict potential distribution of invasive species. However, climatic variables derived from climate datasets do not account for anthropogenic influences on microclimate. Irrigation is a major anthropogenic activity that influences microclimate conditions and alters the distribution of species in anthropogenic landuses. SDM-based studies appear to ignore the effects of irrigation on microclimatic conditions. This study incorporated irrigation as a correction to precipitation data, to improve the predictive capacity of SDM. As a case study, we examined a SDM of *Wasmannia auropunctata*, an invasive species that originates in South and Central America, which has invaded tropical and subtropical regions around the world. The potential distribution of *W. auropunctata* was predicted using Maxent. The model was built based on climatic variables and species records from non-irrigated sites in the native range and then projected on a global scale. Invasive species records were used to evaluate the performance of the model. Precipitation-related variables were modified to approximate actual water input in irrigated areas. Precipitation correction relied on an estimate of irrigation inputs. The model with irrigation correction performed better than the corresponding model without correction, on a global scale and when it was examined in five different geographical regions of the model. These results demonstrate the importance of irrigation correction for assessing the distribution of *W. auropunctata* in various geographical regions. Accounting for irrigation is expected to improve SDMs for a variety of species.

### Zusammenfassung

Artenverteilungsmodelle (SDM), die auf Klimavariablen basieren, werden weithin verwendet, um die potentielle Verbreitung von invasiven Arten vorherzusagen. Indessen berücksichtigen Klimavariablen, die Klimadatensätzen entnommen wurden, menschliche Einflüsse auf das Mikroklima nicht. Bewässerung ist eine wichtige menschliche Aktivität, die die mikroklimatischen Bedingungen beeinflusst und die Verteilung von Arten mit der Landnutzung variiert lässt. SDM-basierte Studien haben offenbar den Einfluss der Bewässerung vernachlässigt. Die vorliegende Untersuchung schloss Bewässerung als Korrekturfaktor zu Niederschlagsdaten ein, um die Vorhersagefähigkeit der SDM zu verbessern. Als eine Fallstudie nutzten wir ein SDM von *Wasmannia auropunctata*, einer invasiven Ameisenart, die aus Süd- und Mittelamerika stammt und weltweit tropische und subtropische Regionen besiedelt hat. Die potentielle Verbreitung von *W. auropunctata* wurde mit Hilfe des Maxent-Programms vorhergesagt. Das Modell basiert auf Klimavariablen und Verbreitungsdaten aus nicht bewässerten Regionen im Herkunftsgebiet und wurde dann auf den globalen Maßstab projiziert. Invasionsdaten der Art wurden benutzt, um die Leistungsfähigkeit des Modells zu prüfen. Die Niederschlagsdaten wurden modifiziert, so dass sie dem tatsächlichen Wasserinput in bewässerten Gebieten annähernd entsprachen. Das Modell mit Bewässerungskorrektur lieferte bessere Ergebnisse als das Modell ohne Korrektur, sowohl für das globale Verbreitungsgebiet als auch für fünf kleinere geographische Regionen. Diese Ergebnisse

\*Corresponding author. Tel.: +972 50 6662292; fax: +972 4 6629280.

E-mail address: [royfederman@gmail.com](mailto:royfederman@gmail.com) (R. Federman).

zeigen, wie wichtig es ist, eine Korrektur für die Bewässerung einzuführen, um die Verbreitung von *W. auropunctata* zu beschreiben. Generell erwarten wir, dass die Bewässerung zu berücksichtigen, die SDM von vielen Arten verbessern wird.  
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**Keywords:** Climate databases; Invasive species; Maxent; Precipitation; SDM; The little fire ant; *Wasmannia auropunctata*

## Introduction

Invasive species affect agriculture, forestry, fisheries, human health and natural ecosystems (Sandlund, Schei, & Viken, 1999; Baskin 2002), and threat global biodiversity (Simberloff, 2004). Species distribution models (SDMs) are indispensable tools for early detection, control, and eradication of invasive species (Peterson, 2003; Vaclavik & Meentemeyer, 2009; Jones, Acker, & Halpern, 2010). SDMs analyze statistical relations between species occurrence data and a set of environmental variables, using a computer algorithm (Guisan & Zimmermann, 2000). Climatic variables are frequently used in SDM studies (e.g. Elith et al., 2006; Ward, 2007; Jones et al., 2010). Other variables, related to topography, soil and land cover, may also be used (e.g. Roura-Pascual et al., 2004; Elith et al., 2006; Saatchi, Buermann, TerSteege, Mori, & Smith, 2008).

Fewer studies have included anthropogenic variables in SDMs (Austin, Thomas, Houston, & Thompson, 1996; Suàrez-Seoane, Osborne, & Alonso, 2002; Ficetola, Thuiller, & Miaud, 2007; Lippitt et al., 2008). Anthropogenic influences on climatic variables have not yet been considered in SDM studies. A prominent and ubiquitous example that demonstrates the impact of anthropogenic factors is the effect of agricultural and urban irrigation on local microclimate conditions. Irrigation has the potential to alter environmental conditions and facilitate colonization by invasive species in populated areas (Brotóns, Mañosa, & Estrada, 2004; Wetterer 2005; Federman & Werner, 2007). To date, no SDM-based study has considered irrigation as an explanatory factor (but see Brotóns et al., 2004). This may have led to a significant bias in the prediction of species distribution. In particular, locations which might appear too dry for certain species could in fact be sufficiently humid to sustain these species, due to the water added through irrigation during the dry periods. In the case of invasive species, such bias may hamper species distribution prevention and mitigation efforts.

The little fire ant, *Wasmannia auropunctata*, is a damaging invasive species, due to its impact on native biological diversity and human activities at introduced locations (Wetterer & Porter, 2003). The negative impact of *W. auropunctata* on local ant species diversity following invasion was documented in some of the locations where it was introduced: in Gabon (Walker, 2006), New Caledonia (Le Breton, Chazeau, & Jourdan, 2003), and Israel (Vonshak, Dayan, Ionescu-Hirsh, Freidberg, & Hefetz, 2010). *W. auropunctata* was shown to have a negative impact on other invertebrates, such as arachnids and insects on the Galápagos Islands (Lubin,

1984) and in Israel (Vonshak et al., 2010). Its negative impact on reptiles in New Caledonia (Jourdan, Sadlier, & Bauer, 2001) and on the Galápagos Islands was also reported (<http://www.issg.org/database>).

The new invasion of *W. auropunctata* into areas within the dry Mediterranean climate raised the hypothesis that water availability is a key to the species' spread in this region (Vonshak et al., 2010). Water availability in natural habitats is mainly influenced by precipitation. In contrast, within anthropogenic habitats, water availability may also be determined by anthropogenic factors such as irrigation or altered water run-off. We hypothesized that modifying precipitation variables to express actual water input would improve the prediction of *W. auropunctata* distribution in irrigated areas. Here we introduce and evaluate a method for correcting climatic variables in order to incorporate the effects of irrigation intensity on the potential distribution of *W. auropunctata*.

## Methods

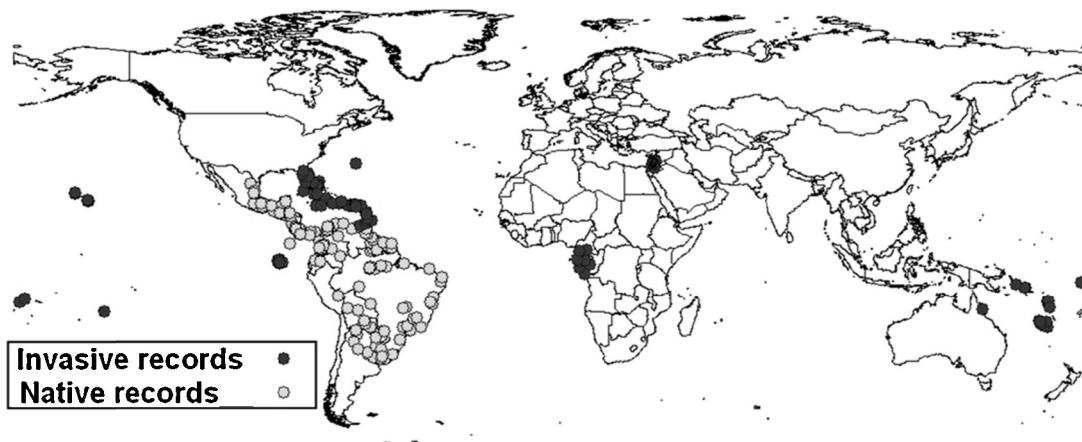
### Model species

*W. auropunctata* is native to Central and South America (Wetterer & Porter 2003). During the past century, exotic populations of this species invaded other tropical and subtropical areas around the world. Fig. 1 shows the worldwide outdoor occurrence records to date.

### Modeling procedure

We used the Maxent model to predict potential invasion and establishment of the little fire ant, *W. auropunctata* (Maxent Version 3.3.1) (Phillips, Anderson, & Schapire, 2006; Phillips & Dudík, 2008). Maxent is a machine learning method that estimates the distribution of a species by finding the probability distribution of maximum entropy subject to constraints derived from environmental layers (Phillips et al., 2006). We chose Maxent since model comparison studies ranked it among the most effective methods for species distribution modeling from presence-only data (Elith et al., 2006; Phillips et al., 2006; Jeschke & Strayer, 2008).

The model was constructed based on the relationships between records from non-irrigated sites in the species' native range (training records) and environmental layers of that range. The model was first applied over the native range and then projected on a global scale, to evaluate the environmental suitability of each grid cell. The model was not extrapolated



**Fig. 1.** Global map with native and invasive *W. auropunctata* occurrence records.

to regions where variable ranges exceeded the native variable range.

## Species data

Occurrence records of *W. auropunctata* were obtained from two online databases: Landcare Research (Harris & Rees, 2004 and updates) and Global Biodiversity Information Facility (GBIF). The final dataset consisted of 183 records from the native range and 135 global invasive range records (Fig. 1).

## Environmental variables

Bioclimatic variables were obtained from the WorldClim dataset (Hijmans et al., 2005). These variables were derived from the monthly temperature and rainfall values, in order to generate biologically meaningful variables. The bioclimatic variables represent annual trends, seasonality, and extreme or limiting environmental factors. Yearly reference evapotranspiration was obtained from the database of the Food and Agriculture Organization of the United Nations (FAO) (Hoogeveen, 2004). We selected nine climatic variables that we assumed would affect the distribution of *W. auropunctata*: maximum temperature of the warmest month, minimum temperature of the coldest month, annual mean temperature, annual temperature range, precipitation of the driest month, precipitation of the wettest month, mean annual precipitation, and precipitation coefficient of variation (CV). Yearly reference evapotranspiration and mean annual precipitation were used to calculate precipitation minus evaporation. Precipitation minus evaporation has been used in water balance models (Seager et al., 2007) to represent soil moisture (Dirmeyer, Schlosser, & Brubaker, 2009). The spatial resolution of the variables was 10" (18.6 km × 18.6 km at the equator).

In order to avoid a redundant set of inter-correlated variables in the model, we calculated Pearson correlation coefficients between all pairs of variables, and in cases of

high correlation coefficients ( $r > 0.8$ ), we omitted one of the variables from further analyses. Correlation coefficients were calculated for records from the species' native range only, which were used to construct the models. We found four pairs with  $r > 0.8$ . Annual precipitation was highly correlated with the precipitation of the wettest and the driest months (0.906 and 0.821, respectively), and was thus omitted. Minimum temperature of the coldest month was highly correlated with mean annual temperature and annual temperature range (0.808 and -0.837, respectively). We omitted the two latter variables.

## Correcting for irrigated habitats

Precipitation data typically differ greatly from actual water input in irrigated areas. Here, we modified precipitation data in irrigated areas in order to approximate actual water input. Irrigated areas included irrigated agricultural as well as urban areas (which may include irrigated urban gardens). We used a land cover layer (Velthuizen et al., 2007) to construct a global map of irrigated areas. This layer is a global raster at a resolution of 5". Each pixel is classified as urban, irrigated, closed forest, or available for rainfed agriculture.

Irrigation correction was based on the notion that irrigation compensates for water loss through evapotranspiration (Brouwer & Heibloem, 1986). Based on this general principle, we quantified irrigation as the difference between evapotranspiration and precipitation. In order to represent actual water input in irrigated areas, three precipitation data layers were corrected. (1) Precipitation minus evaporation: the difference between annual evapotranspiration and annual precipitation was added to the annual precipitation and yielded the corrected annual precipitation. Subtracting evapotranspiration from the resulting corrected annual precipitation yielded the corrected "precipitation minus evaporation". This calculation yielded zero values in irrigated areas where reference evapotranspiration values were higher than annual precipitation. (2) Precipitation of the driest

month: subtracting the natural precipitation values of the driest month from the monthly average of corrected annual precipitation yielded an approximation of the water input in the driest month in irrigated areas. (3) Precipitation coefficient of variation (CV): We assumed that water input due to irrigation in the dry months is similar to water input due to precipitation in the wet months, thus the CV value of water input in irrigated areas was set to zero.

## Model validation

Model performance was evaluated using the Area Under the Curve (AUC) of the Receiver Operating Characteristic (ROC) (Elith et al., 2006; Hernandez, Graham, Master, & Albert, 2006; Marmion, Parviainen, Luoto, Heikkinen, & Thuiller, 2009). Following Phillips et al. (2006), we used a pseudo-absence approach to create ROC curves which distinguished presence from random, rather than presence from absence. This test was applied to randomly selected “pseudo-absence” records instead of to observed absences. “Pseudo-absence” records are locations selected uniformly at random from the study area. Following Phillips and Dudík (2008), we used 10,000 “pseudo-absence” locations.

Initial model validation was executed based on the native occurrence records within non-irrigated areas. These records were randomly split into 70% calibration and 30% test datasets (Huberty, 1994). ROC curves and AUC values were calculated with and without irrigation correction for both calibration and test datasets. Additional evaluation of the native range model was based on species records in irrigated areas within the native range.

A set of global records of invasive records was used to evaluate the model. In addition, the invasive records were divided into five geographical regions and model performance was examined for each group of records. These geographical regions were: Israel (40 records), Oceania and pacific islands (33 records), Florida (30 records), Caribbean (25 records) and West Africa (7 records). AUC values were calculated for models without irrigation correction as well as for those with irrigation correction. ROC and AUC calculations were produced in “ROC\_AUC” program (Schroder, 2004).

There is an ongoing debate regarding the efficiency of AUC as an evaluator of Maxent performance (e.g. Lobo, Jiménez-Valverde, & Real, 2008); however, it is still considered the standard method for assessing prediction accuracy, as it is easily interpretable and thresholds are independent (Bar Massada, Syphard, Stewart, & Radeloff, 2012). We therefore used an additional performance index, an adjusted version of the Boyce metric for evaluating SDMs based on occurrence records (Boyce, Varinier, Nielsen, & Schmiegelow, 2002). This measure is based on the weighted area of the predicted probability values produced by the Maxent model. When dividing the output map into equal interval bins of probabilities, it is expected that the proportion of cells occupied by the modeled species in each probability bin will be highly

correlated to the weighted area of that bin. High correlation values between the number of occurrences in the probability bins and the bins’ weighted area indicate high model performance. Boyce et al. (2002) suggested an iterative jackknifing approach, using different subsets of the data as test data to calculate weighted correlations. Here we used the results of the model to calculate the weighted areas of 10 probability bins of the global model and correlated them with the set of test occurrences used in the same model ( $n = 135$  records), using the Spearman correlation method. We repeated the same procedure using the irrigation corrected and non-corrected global model, and compared the Spearman correlation coefficients, to evaluate the change in model performance.

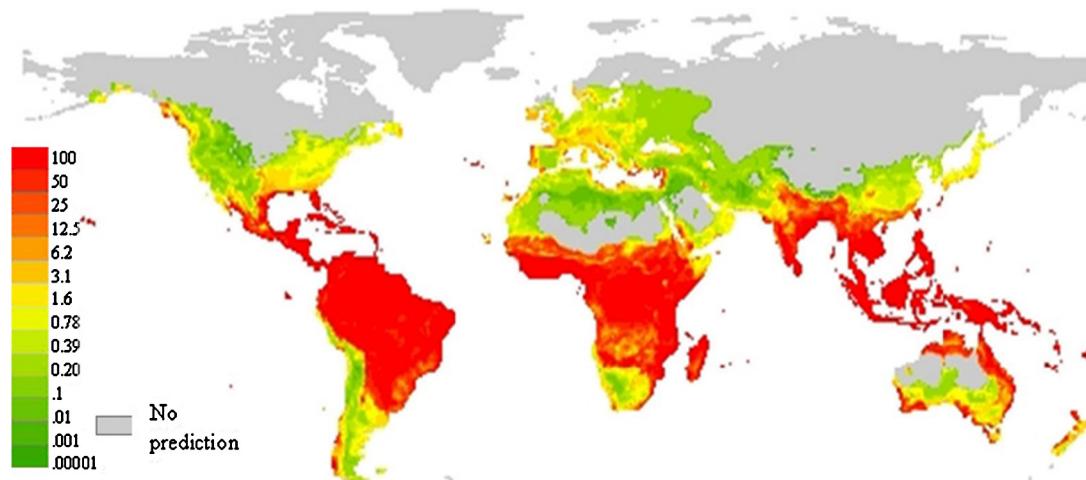
## Results

The global model of the potential distribution of *W. auropunctata* with irrigation correction predicted high establishment potential in the tropic and sub-tropic regions of America, Africa and Asia (Fig. 2). Low establishment potential was predicted in the arid and temperate climate zones of the globe. Regions with no prediction (with climatic conditions outside the range of the training data) were located in the northern regions of the north hemisphere, Sahara Desert, Arabian Desert and desert regions in Australia (Fig. 2). The model with irrigation correction performed better than the model without irrigation correction in predicting both the global set of invasive species records as well as the five separate sets of invasive species records from different regions (Table 1). Fig. 3 presents a noteworthy example for the discrepancy between the regional map of Israel taken from the global model without irrigation correction and the same map taken from the global model with irrigation correction. In addition, the corrected model better predicted species records from irrigated sites in the native range (not used for model building) and a set of records from non-irrigated sites (calibration data). A set of test data from the native range showed the same prediction value for the corrected and non-corrected models (Table 1). In north India, the model with irrigation correction predicted higher establishment potential for *W. auropunctata* than the model without irrigation correction. This region has no documented records of *W. auropunctata* to date.

The adjusted Boyce metric for evaluating model performance showed increased Spearman correlation between the predicted weighted areas in 0.1 probability bins of the global models when applying the irrigation correction. The non-corrected model had a Spearman correlation coefficient of  $r = 0.79$  ( $p\text{-value} = 0.01$ ) and the irrigation-corrected model had a Spearman  $r = 0.9$  ( $p\text{-value} = 0.002$ ).

## Discussion

Species distribution models can facilitate crucial actions such as monitoring for early detection, direct



**Fig. 2.** Global model map with irrigation correction. Warm colors indicate high establishment suitability values, cold colors indicate low suitability values. Gray indicates areas with no prediction (variables are out of the training range). Color scale is logarithmic.

intervention for containment, and possible extirpation of invasive species. However, action effectiveness is directly related to model accuracy, which in turn is dependent on the coherent and accurate representation of the environmental parameters. We identified a major source of inaccuracy stemming from a group of environmental variables frequently used in SDMs, namely, evapotranspiration and precipitation. Although excellent predictors of soil moisture in most land uses, these variables become misleading in urban and irrigated agricultural areas. As these land uses are ubiquitous in some regions, this bias may lead to under-prediction of tropical invasive species in non-tropical regions.

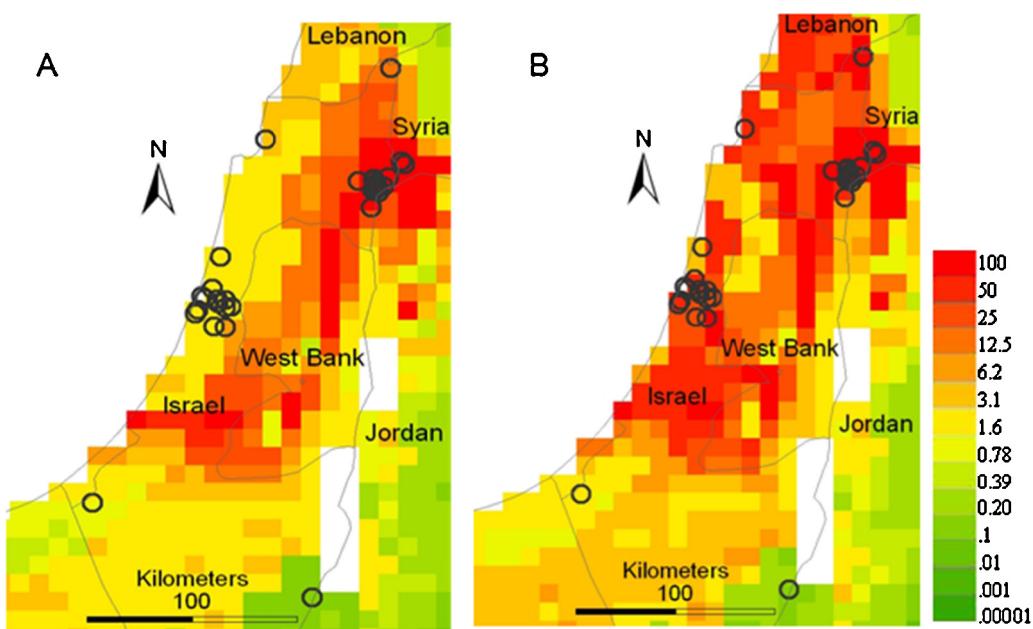
Here, we used irrigation estimated data to correct precipitation data, and found a subsequent improvement in the predictive capacity of the models. Performance of the model with irrigation corrections was better than that of the corresponding model without correction for eight out of nine test data sets. The only exception was in the case of the test data set within the native range, which did not show any

change in prediction capacity following irrigation correction (Table 1). Improvement in model prediction due to irrigation correction occurred in all five independent sets of records from different geographical regions. In two cases (Florida and Israel) the improvement was substantial. These results indicate the importance of irrigation correction in species distribution models constructed for *W. auropunctata* in particular, as well as for numerous other species that are limited by soil moisture.

Irrigation correction was based on the principle that the purpose of irrigation, and thus its intensity, is to compensate for natural evapotranspiration. This may explain the fact that improvement in model performance following the irrigation correction was higher in non-equatorial regions (Israel and Florida) than for equatorial regions (Oceania and Pacific, West Africa and Caribbean; Table 1). In some cases irrigation do not precisely compensate water loss and in order to further improve the predictive capacity, region-specific irrigation characteristics should be included in the irrigation correction.

**Table 1.** AUC values derived from the ROC analysis of native and global models without irrigation correction and with irrigation correction.

	AUC values		Differences	N
	Without correction	With correction		
<b>Native</b>				
Irrigated	0.674	0.730	+0.056	49
Calibration data	0.871	0.883	+0.012	94
Test data	0.801	0.801	0	40
<b>Global</b>				
Oceania and pacific	0.542	0.556	+0.014	33
West Africa	0.639	0.690	+0.051	7
Caribbean	0.748	0.810	+0.062	25
Florida	0.717	0.852	+0.135	30
Israel	0.628	0.83	+0.202	40
All	0.875	0.899	+0.024	135



**Fig. 3.** Map of Israel region taken from the global model without irrigation correction (A) and with irrigation correction (B). Circles indicate locations with *W. auropunctata* records.

Interestingly, the irrigation correction was effective despite its reliance on rough estimates of irrigation inputs. Volumetric irrigation data are difficult to obtain in a spatial format, specifically at large scales, since irrigation intensity varies over time and over various crops and land uses (Wisser et al., 2008).

The use of native records located in irrigated areas for model construction could bias model results due to inaccurate representation of microclimate conditions. Despite this potential bias, we are not aware of any studies in which species records pertaining to irrigated agricultural and urban land-uses were omitted. Harris, Abbott, and Lester (2005), in their attempt to predict the invasion potential of *W. auropunctata* into New Zealand, partly accounted for this limitation by omitting *W. auropunctata* records from greenhouses and heated buildings in the invaded range, but they kept records from irrigated areas in the analysis. An important aspect of the present study is that the models are based on records only from non-irrigated areas. Habitat characterization was conducted using species data sets, land use layers, and visual examination of satellite images, in order to determine the irrigation status in species occurrence locations. These methods are simple to use and are recommended for future SDM studies.

Our approach stipulates that native occurrence records pertaining to irrigated lands should be omitted from SDMs. An alternative to the omission of native records is to build the model using precipitation-corrected versions of these records. This approach is likely to provide a better prediction of species distribution, assuming that accurate irrigation intensity data are available. However, if accurate irrigation data are not available in the native range, the use of

inaccurate records in the model could drastically bias model results.

Accounting for irrigation inputs is expected to improve SDMs for a variety of species that inhabit areas of anthropogenic land use. These species include invertebrates, reptiles, amphibians, birds, small mammals and plants. Correction of climatic and other variables in SDMs is not limited to irrigation and its effect on the invasive potential of tropical species into non-tropical regions. On the contrary, corrections can be applied to any variable affected by anthropogenic disturbances. Corrections should be applied according to the focal species, the conditions in its native range, and the conditions in potential areas of occupancy.

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