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ORIGINAL PAPER

Mapping the geographic distribution of *Aglaia bourdillonii* Gamble (Meliaceae), an endemic and threatened plant, using ecological niche modeling

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Abstract *Aglaia bourdillonii* is a plant narrowly endemic to the southern portion of the Western Ghats (WG), in peninsular India. To understand its ecological and geographic distribution, we used ecological niche modeling (ENM) based on detailed distributional information recently gathered, in relation to detailed climatic data sets. The ENMs successfully reconstructed key features of the species' geographic distribution, focusing almost entirely on the southern WG. Much of the species' distributional potential is already under protection, but our analysis allows identification of key zones for additional protection, all of which are adjacent to existing protected areas. ENM provides a useful tool for understanding the natural history of such rare and endangered species.

Keywords *Aglaia bourdillonii* · GARP · Niche modeling · Southern Western Ghats · Species distribution modeling

Introduction

Geographic distributions of species and their relation to environmental variables have been studied for centuries, and have long fascinated scientists and naturalists (Darwin 1859; Fisher 1958; Krishtalka and Humphrey 2000). Association of particular

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species with particular environmental conditions has long been documented (Colding and Folke 1997; Hubbell 2005), but quantitative analyses have been possible only recently (Cutler et al. 2002), with the advent of new tools, as well as broad availability of continuous spatial information about various environmental parameters (Kerr and Ostrovsky 2003).

Inferential procedures that provide robust and reliable predictions of species' geographic and ecological distributions are thus critical to biodiversity analyses. This approach has recently been explored under the rubric of "ecological niche modeling" (ENM; (Soberón and Peterson 2005), and refers to reconstruction of ecological requirements of species that are analogous to the Grinnellian ecological niche (Grinnell 1917). ENM can provide diverse insights into the ecological and geographic extents of species' distributions (Soberón and Peterson 2004).

In this study, we develop a fine-scale distributional understanding of a threatened plant species (*Aglaia bourdillonii*) endemic to the Western Ghats (hereafter "WG") using ecological niche modeling, and explore areas of highest conservation concern, given the current management scenario. Since ENM focuses on the ecological dimensions that are distributed across geographic landscapes, we also explore the range of environmental conditions prevailing within the larger landscape of Southern Western Ghats. The WG forms a homogenous biome running along a 1600 km escarpment parallel to the southwestern coast of the Indian Peninsula, recognized as a global biodiversity hotspot (Myers et al. 2000). WG biodiversity is influenced by gradients in rainfall (east to west and north to south), length of dry season (south to north), temperature (south to north), and topography. WG is home to a wide range of endemic tree species, including wet evergreen, dry deciduous, and scrub forest types. Within evergreen forests, ~63% of tree species are endemic to the region (Ramesh et al. 1991). The Agastyamalai Hills, near the southern end of the region, are known for particularly high species diversity and endemicity, harboring ~2,000 flowering plant species, with 7.5% endemism (Henry et al. 1984).

Aglaia bourdillonii is a microendemic species apparently confined to the Agastyamalai Hills region. IUCN places this species under its "VU B1+2c" category (extent of occurrence $< 20{,}000\ \text{km}^2$ or distributional area $<2{,}000\ \text{km}^2$, with estimates indicating that habitat is severely fragmented or known to exist at ≤ 10 locations and populations continuing to decline). In this particular case, large areas of the species' distribution have been exposed to fire, grazing, establishment of commercial plantations and cutting for fuelwood. About 1,000 km^2 of forest in the region are protected within sanctuaries (Pannell 1998).

This species, however, apparently requires both specialized habitat conditions and specific plant associations to survive and maintain populations (Pascal 1988). Being an understory species, it requires protection from emergent species (e.g., *Cullenia exarillata* and *Palaquium ellipticum)* for survival (Ganesh et al. 1996; Pascal 1988). *Aglaia bourdillonii* is also sensitive to anthropogenic disturbance (e.g., logging), and is reduced in numbers where selective logging of *Palaquium ellipticum* and *Gluta travancorica* has occurred (Giriraj 2005; Pascal 1988); it is restricted to flatter topographies, seldom occurring in deep valleys (Giriraj 2005). Such restricted-range plants are often the most vulnerable, as they have narrow ecological tolerances.

Accurate distributional information thus becomes crucial for management and conservation efforts. Most often, management decisions for conservation are based on known occurrence sites—sites associated with field observations or specimens in museums and herbaria. Such records are generally used in constructing crude range maps: vaguely extrapolated polygons that enclose known occurrences, based on subjective interpolations. These maps are often highly biased towards accessible or well sampled areas, and rarely can be extended to remote and poorly known locations. Detailed, finescale, validated maps, however, can be developed based on known occurrences and are essential in designing conservation strategies; moreover, specific requirements of species regarding favorable environmental conditions can educate these decisions enormously.

Methods

Input data

We collected, in all, 53 spatially unique point locations for *Aglaia bourdillonii's* current distribution from various primary and secondary sources. Records of the species' current distribution were derived from on-ground surveys using GPS during the regional biodiversity inventory of WG (Roy 2002). To include historical occurrences, herbarium specimen data were gathered from the French Institute of Pondicherry (Ramesh et al. 1997; Ramesh and Pascal 1997), and Botanical Survey of India (BSI; Ahmedullah and Nayar 1987). All records were geocoded via reference to large scale (1:50,000 scale) topographic maps.

We used 19 "bioclimatic" variables derived from globally interpolated datasets of monthly temperature and precipitation available from (Hijmans et al. 2004), including annual and seasonal aspects of temperature and precipitation that are presumed to be maximally relevant to plant survival and reproduction (Hutchinson et al. 2000). We also included elevation, slope, aspect, and compound topographic index from the USGS Hydro-1K dataset (USGS 2001). All analyses were conducted at the native 30″ (~ 1 × 1 km pixels) spatial resolution of the environmental data sets.

Ecological niche modeling

ENM has been used in numerous applications and subjected to various tests, based on diverse analytical approaches (Csuti 1996; Gottfried et al. 1999; Manel et al. 1999a, b; Miller 1994; Tucker et al. 1997). The particular approach to modeling species' ecological niches and predicting geographic distributions used herein (summarized below) is described in detail elsewhere (Peterson et al. 2002a; Stockwell and Peters 1999; Stockwell and Noble 1992). Previous tests of the predictive power of this modeling technique for diverse phenomena in various regions have been published elsewhere (Anderson et al. 2002, 2003; Peterson 2001; Peterson et al. 1999, 2002a, b; Peterson and Vieglais 2001; Stockwell and Peterson 2002a, b).

The ecological niche of a species can be defined as the set of ecological conditions within which it is able to maintain populations without immigration (Grinnell 1917; Holt and Gaines 1992). Several approaches have been used to approximate species' ecological niches (Austin et al. 1990; Nix 1986; Scott et al. 1993, 1996, 2002; Walker and Cocks 1991), of these, one that has seen considerable testing is the Genetic Algorithm for Rule-set Prediction (GARP), which includes several inferential approaches in an iterative, evolutionary computing environment (Stockwell and

Peters 1999). All modeling in this study was carried out on a desktop implementation of GARP now available publicly for download.[1]

For GARP analyses, we initially divided (randomly) available occurrence points as follows: (1) 8 training data points (for rule generation), (2) 8 intrinsic testing data points (for model optimization and refinement), (3) 17 extrinsic testing data points (for choosing best subsets models), and (4) 20 independent validation data points (for final model validation); this procedure was repeated four times, based on different random subsets of available data. After validation trials were completed, to maximize occurrence data available to the algorithm, we eliminated the validation step, and thus provided 13 training points, 13 intrinsic testing points, and 27 extrinsic testing points to the algorithm.

GARP is designed to work based on presence-only data; absence information is included in the modeling via sampling of pseudo-absence points from the set of pixels where the species has not been detected (Stockwell and Peters 1999). GARP works in an iterative process of rule selection, evaluation, testing, and incorporation or rejection: first, a method is chosen from a set of possibilities (e.g., logistic regression, bioclimatic rules), and then is applied to the training data and a rule developed; rules may evolve by a number of means (e.g., truncation, point changes, crossing-over among rules) to maximize predictivity. Predictive accuracy is then evaluated based on 1,250 points resampled with replacement from the intrinsic testing data and 1,250 points sampled randomly from the study region as a whole to represent pseudoabsences. The change in predictive accuracy from one iteration to the next is used to evaluate whether a particular rule should be incorporated into the model, and the algorithm runs either 1,000 iterations or until convergence.

We developed 100 replicate model runs for *Aglaia*, and filtered out suboptimal models based on characteristics in terms of omission (leaving areas of known presence out of predictions) and commission (including areas not actually inhabited) error statistics. Following recent recommendations (Anderson et al. 2003) and also to represent a balance between optimizing model selection and practicalities of computing time required for the analysis, we selected best models in DesktopGARP using a 0% extrinsic hard omission threshold and 50% commission threshold. Experiments with different thresholds indicate that results are quite robust to minor variation in thresholds chosen. Throughout our analysis, we masked analyses to include only the southern WG region.

To permit visualization of patterns of *Aglaia* ecological niche variation, we combined the input environmental grids with the final ENM to create a new grid with a distinct value for each unique combination of environments; we exported the attributes table associated with this grid in ASCII format for exploration in a graphic program.

The initial validation step was repeated four times, in each of which 20 randomly selected points were set aside for testing. The coincidence between the independent points and model prediction was used as a measure of model predictive ability. Binomial tests (based on the proportional area predicted present and the number of independent test points successfully predicted) were used to compare observed predictive success with that expected under random (null) models of no association between predictions and test points. As model results are in the form of a 'ramp' of model agreement from 0 to 10, we repeated binomial tests across all thresholds of model agreement (prediction levels 1 to 10).

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[1] http://www.lifemapper.org/desktopgarp/.

Results and discussion

Predictions of the distribution of *Aglaia bourdillonii* were good, given current knowledge of the species. To date, this species has been reported only from middle-elevation evergreen pockets of the southern WG, particularly in the Agastyamalai Hills region adjoining the Kalakkad Mundathurai Tiger Reserve (KMTR). The species has never been documented from other sectors of the WG.

In each of four replicate validations of *Aglaia* model predictions, 20 points were available to test predictions. For each replicate, we calculated binomial probabilities for each of the 10 predictive levels, eliminating the need to choose a single threshold for prediction of presence/absence. In all cases (four replicate tests, 10 predictive levels each), agreement between test occurrence points and model predictions was statistically significantly better than random (binomial tests, all $P \ll 0.05$).

Given our successful model validation, we used all data to produce a final model. The distribution of *Aglaia bourdillonii*, as predicted by all 10 best-subsets models in this analysis (Fig. 1) occupies 947 km^2 out of the 20,750 km^2 that constitute the southern WG, or ~5% of the total. Correspondence between known occurrences and the predictions of this final model is very close. The species occupies small areas in four districts, two in each of Tamil Nadu and Kerala states: ~71% (670 km^2) of the species' distribution is predicted in Tamil Nadu State, while the remaining ~29% (277 km^2) falls in Kerala State.

Much of the Agasthyamalai Hills region is included in four protected areas: Neyyar, Peppara, and Shendurni Wildlife Sanctuaries (WLS) and the Kalakkad

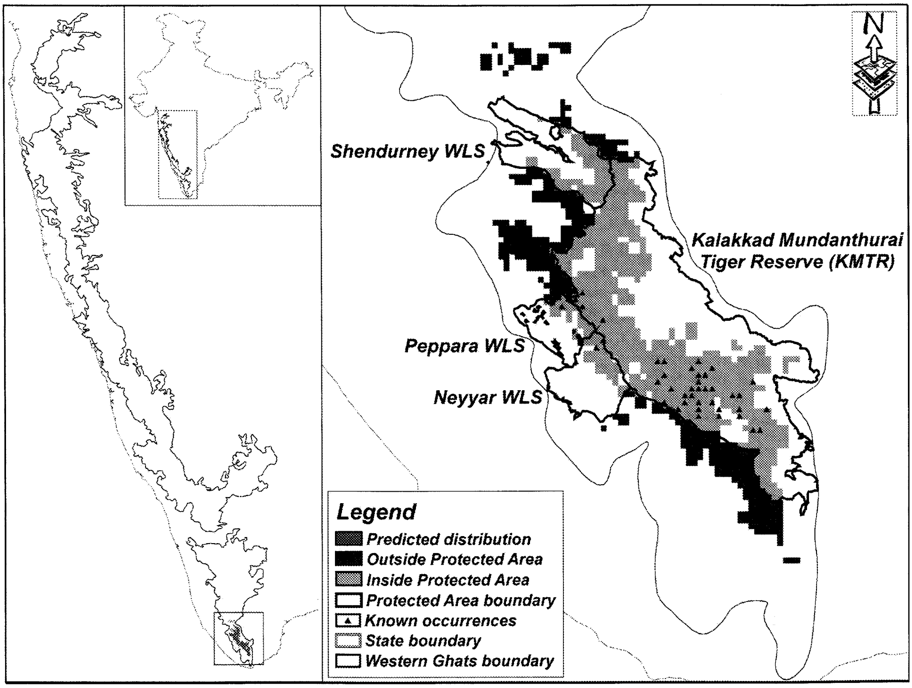

Fig. 1 Map showing known and predicted distribution of *Aglaia bourdillonii*, within Western Ghats

Mundanthurai Tiger Reserve (KMTR); as such, almost 66% (624 km^2) of the species' distribution is already under protection. KMTR alone covers >54% (516 km^2) of the species' total predicted distribution, and the remaining 3 WLSs cover 11% (108 km^2); the remaining 34% (323 km^2) that is unprotected is nonetheless close to protected areas. An augmentation of 5 km along the western boundary of the protected areas (Fig. 2) would cover an additional 27% (259 km^2) of the species' distribution, bringing the total to 97% (883 km^2) of its total distribution.

Further explorations of the implications of our models explored the species' distribution in ecological dimensions. As such, we compared ecological characteristics of areas predicted present for the species with the complete environmental range in the southern WG. For the 19 bioclimatic and physiographic variables, we removed eight highly correlated, redundant variables, and then developed bivariate plots to summarize the species' distribution (Fig. 2). These explorations reveal a very narrow niche (even against the already specialized conditions of the southern

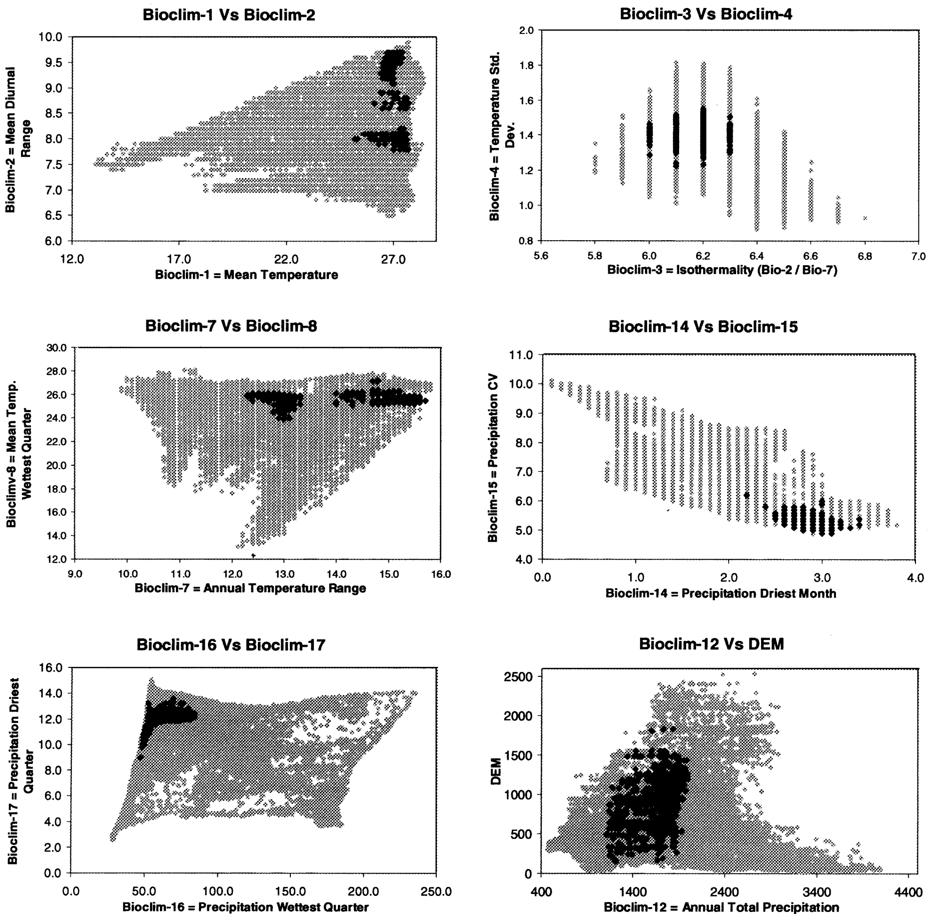

Fig. 2 Exploratory visualization of *Aglaia bourdillonii* niche in environmental space. Gray = Conditions available in the Southern Western Ghats, and Black = modeled potential distribution of species

WG) for the species—restricted to areas preserving narrow ranges of annual mean temperatures (25–28°C) in three distinct zones of diurnal temperature variability, and high precipitation (1100–2000 mm).

These results are crucial in addressing conservation issues related to a species that is so narrowly restricted, occurring only in the Agasthyamalai Hills region of the southern WG. Protected area boundaries have rarely been defined in light of real data on biodiversity, more frequently following existing administrative limits and land tenures. In the Agasthyamalai Hills region, protected area boundaries simply follow state boundaries. The results developed here—combined with results of similar ongoing studies that address other restricted range species—suggest clear ways to modify boundaries to include ecologically significant areas based on scientific evidence. This is even crucial to bring about protection from widespread logging of the species and its associates as mentioned in the IUCN Red List of Threatened Species (Pannell 1998).

Conclusions

Aglaia bourdillonii is a low-to-middle elevation evergreen species narrowly endemic to the southern WG. As such, its conservation will depend critically on a few well-placed protected areas. Indeed, much of its small distributional area is already under protection, although this protection could be improved considerably with a quite-small addition to those existing protected areas. ENM is a useful tool in outlining and understanding the distributions—in geographic and ecological spaces—of such species, and may prove useful in a variety of applications to biodiversity conservation, bioprospecting, and any application that requires detailed information about species' geographic distributions.

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