The genus *Acacia* (Fabaceae) in East Africa: distribution, diversity and the protected area network

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Background and aims – Plants are often overlooked in conservation planning, yet they are the foundation of all terrestrial ecosystems. The East Africa region is used to investigate the effectiveness of protected areas for conserving plants. With a wide range of ecosystems and 771 protected areas covering nearly one quarter of the land area, East Africa is an ideal location to assess the effectiveness of protected areas through distribution modelling of the genus *Acacia*.

Methods – Herbarium specimen data (2,047 records) were collated from East Africa for 65 taxa (species, subspecies, varieties) from the genus *Acacia*. Generalised Additive Models were used to determine climatic drivers, and thence to extrapolate climatic suitability across the region. For two *Acacia* taxa, we investigated the potential for climate-induced range-shifts using a downscaled regional climate model under two IPCC scenarios.

Key results – Approximately two thirds of *Acacia* diversity hotspots had < 10% coverage by protected areas. Furthermore, the protected area network covered less of the predicted ranges of the *Acacia* taxa and contained fewer taxa per unit area than would be expected under randomised placement. Areas with suitable climate for high-elevation, moisture-dependent taxa such as *A. abyssinica* subsp. *calophylla* are predicted to contract their potential range by up to 80% towards mountain peaks, where protected areas are dominated by low-level protection forest reserves. Conversely, the area of suitable environment for a xerophytic low-elevation species (*A. turnbulliana*) is predicted to increase by up to 77%.

Conclusions – East Africa's national parks may not be preserving an important component of ecosystem diversity, a situation exacerbated by climate change. Even within the genus *Acacia*, different species are predicted to respond differently to climate change. Priority areas for research and conservation are identified based on overlap between predicted high *Acacia* diversity and gaps in the collection record, with northern and eastern Kenya highlighted as particularly important. High elevation protected areas are also predicted to become increasingly important as climatic refugia in a warmer future.

Key words – gap analysis, climate change, nature reserve, *Senegalia*, species distribution model, *Vachellia*.

INTRODUCTION

The majority of Africa's protected areas were established in response to declining large animal numbers since the early 20th century (Balmford et al. 1992). Only recently have more broadly defined biodiversity metrics been used to establish areas for the protection of nature or natural resources (Lockwood et al. 2006, Marshall et al. 2007). Plants have long been overlooked in the design of protected area systems (Jaffré et al. 1998, Vargas et al. 2004, Burgess et al. 2005), despite their role as the foundation of all terrestrial ecosystems, harnessing the sun's energy and thus providing nutrition for

the entire food chain. Plants are the structural component of habitats, providing shelter and nesting sites for animals, as well as contributing to climate-change mitigation through carbon sequestration and moderation of nutrient and hydrological flows. As conservation continues to develop a 'biodiversity for livelihoods' mandate, information on plant distributions and the ways in which ecosystems will respond to future climatic and economic developments is crucial.

Distribution modelling is one of a range of tools used to predict suitable environmental conditions for a taxon (hereafter used to mean a species, subspecies, or variety) across a landscape based on limited information (fig. 1). Environmental conditions at locations of known taxon occurrence are used to parameterise a niche or multidimensional envelope that can be used to infer the suitability of other geographic locations across a broader region. The application of Distribution Models (hereafter, DMs) is increasingly far-reaching, and includes use for managing resources, predicting the spread of invasive species/pathogens, predicting the impacts of climate change, and planning the design of protected area networks (Franklin 2010). DMs are particularly useful where logistical difficulties such as poor infrastructure or large geographic scale preclude full inventories. DMs also allow for the exploration of 'what if' scenarios, in the present case exploring the impact of climate change on current species distribution.

A major aim in designing a reserve network is to conserve the maximum level of biodiversity based on available resources. However, reserve design cannot consider every species in an ecosystem, particularly in the tropics, where the numbers of species involved are extremely high. There are, for example, approximately 12,500 plant species in the area covered by the *Flora of Tropical East Africa* (Kenya, Tanza-

nia, and Uganda) alone (Beentje & Smith 2001, H. Beentje, Royal Botanic Gardens, Kew, UK, pers. comm.). An alternative to measuring absolute biodiversity is to determine a set of indicator taxa whose presence signals high overall biodiversity in an area. An ideal indicator taxon should: be easily recognisable and easy to locate, be found in reasonable densities, not be highly mobile, have a high degree of specialisation, and be representative of a fully functional ecosystem (Caro & O'Doherty 1999, Hilty & Merenlender 2000). Many species of plants fulfil these criteria but have traditionally been less often used than faunal indicators.

The genus name *Acacia* Mill. is here applied broadly, including the segregate genera *Senegalia* Raf. and *Vachellia* Wight & Arn., but excluding *Faidherbia* A.Chev. Under this circumscription, *Acacia* includes a number of species that dominate the structure and floristic composition of extensive areas of East African woodland, wooded grassland and bushland (Pratt & Gwynne 1977, Coe & Beentje 1991). The genus occurs across a wide range of ecosystems, from arid deserts to montane forests, with growth forms that include small shrubs, lianas and large trees (New 1984). There are 64 species of *Acacia* known from the five eastern African countries of Burundi, Kenya, Rwanda, Tanzania and Uganda (Dharani 2006). None of these species have been assessed as globally threatened (IUCN 2011); however very few of them have been evaluated by the IUCN Red List process and many occur in woodland habitats that are threatened by anthropogenic influence, particularly charcoal production, burning, livestock damage and agricultural encroachment (New 1984, Sinclair et al. 2008). These habitats are mostly unprotected by legislation and have therefore received little attention in previous regional biodiversity assessments. As one of the better studied plant genera in Africa, *Acacia* also
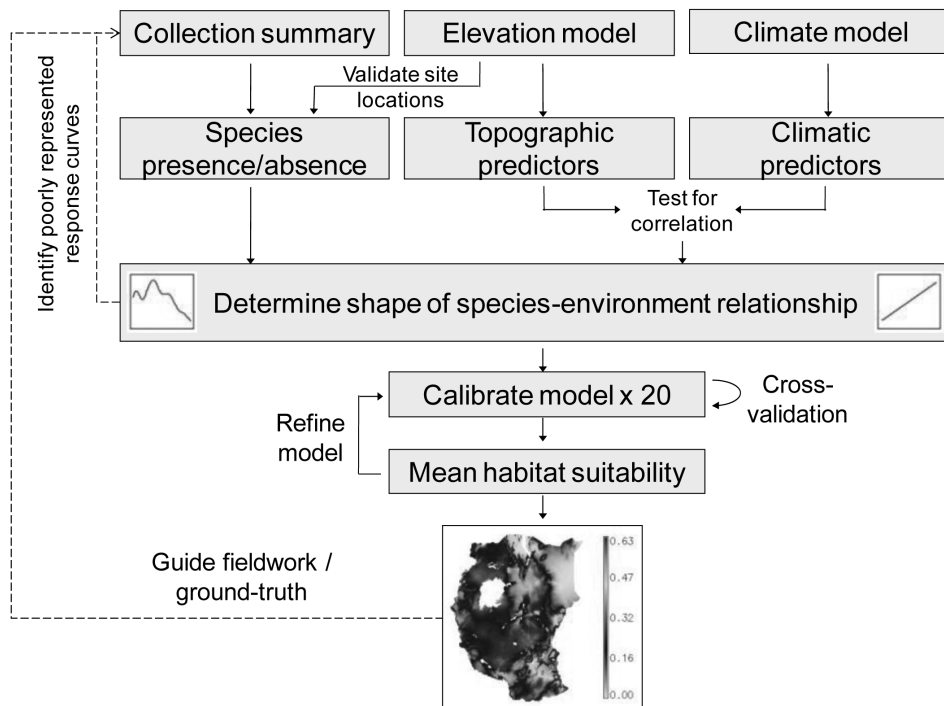

Figure 1 – The process of distribution modelling (adapted from Platts et al. 2008).

has an advantage for data acquisition in that it has been well curated in a number of major herbaria (in particular, the East African Herbarium, the Royal Botanic Gardens, Kew, and the Missouri Botanical Garden), with reliable identification and associated meta-data.

The aim of this paper is to predict the present day distribution of *Acacia* in East Africa and to establish how well members of the genus are conserved under the current protected area network. The various taxa are modelled against climatic and topographic variables and their spatial distributions extrapolated to the broader landscape. A composite of the most successfully modelled taxa is then used to estimate the geographic distribution of *Acacia* diversity in relation to protected areas. Regional climate forecasts are used to estimate the potential impact of climate change on future *Acacia* distribution and how this changed distribution will interact with protection areas. Finally, we make suggestions for geographical priorities for management and taxonomic research.

MATERIAL AND METHODS

Study area

The region used for modelling included the five eastern East African countries of Burundi, Kenya, Rwanda, Tanzania and Uganda (defined here as 'East Africa'). East Africa was selected for its wide range of ecosystems, extensive areas of unsurveyed or logistically difficult landscape, and also for its globally recognised importance for wildlife tourism. The area contains 771 protected areas, covering 23.3% of the total land area, including 65 world-renowned national parks and game reserves (UNEP-WCMC 2009), which attract approximately 3.5 million tourists annually (http://www.statistics.eac.int). Despite the outstanding importance of biodiversity, tourism and cultural resources in the East African region, biological data that are essential for setting conservation priorities are not currently available in a format that managers can use, being spatially incomplete and deposited in widely scattered museum collections. Rapidly growing human populations and increasing land fragmentation have restricted wildlife and pastoral movements across much of East Africa, causing range loss and aggravating effects of periodic drought (Western & Manzolillo Nightingale 2004). Compounding these human impacts, the extent and speed of climate change in the area pose a serious threat to the natural capital that is vital to individual livelihoods and national economies.

Data collation and refinement

A total of 2,047 *Acacia* herbarium records were collated from 65 taxa and 46 species (59 taxa excluding species also represented at infraspecific level; table 1). Our data include 71.9% of the 64 *Acacia* species known from the region (Dharani 2006). Collection data were collated from five herbaria: East African Herbarium, National Museums of Kenya (Nairobi); Royal Botanic Gardens, Kew (UK); Missouri Botanical Garden (USA); National Herbarium of Tanzania (Arusha); University of Dar es Salaam (Tanzania). We collated environmental data for the region at a spatial resolution of 1 arc-minute. Environmental variables included mean and range in annual temperature, mean annual rainfall, potential evapotranspiration (PET), maximum water deficit, slope, and aspect. Details are given as supplementary material (electronic appendix 1).

Model calibration and performance

Distribution data consisted only of presence records for each taxon. We also generated pseudo-absence data to constrain the models (Phillips et al. 2009; electronic appendix 1). The probability of occurrence of each taxon in 1 arc-minute grid cells was determined based on Generalised Linear or Additive Models (GLM/GAM) of taxon presence versus environmental conditions. Since collection data were too sparse to partition into independent sets for training and testing, we used cross-validation to assess generality. We also assess envelope uncertainty as the proportional difference between extreme values of each climate variable and the known range at collection localities (Envelope Distance Maps, EDMs). See the supplementary material for full explanation of model calibration and performance (electronic appendix 1).

Biodiversity and protection

Estimates of *Acacia* taxon richness (hereafter termed '*Acacia* diversity') were based on the spatial predictions of all robust models (n=45). Predictions were considered robust if and only if (1) both sensitivity and AUC_{cv} exceeded 0.7, (2) the modelled response shapes were biologically plausible (i.e. with no more than one point of inflection), and (3) the spatial predictions were in agreement with known distributions according to collection locations and the most recent *Acacia* field guide (Dharani 2006).

Presence-absence maps were derived from the probability surfaces by maximising the sum of sensitivity and specificity (Liu et al. 2005). These binary predictions were then summed across taxa and averaged across the ten model runs to give an estimate of *Acacia* diversity. We focussed on two subsets of taxa with robust predictions: (1) those with excellent agreement between collection locations and predicted climate suitability, and (2) these same 'excellent' taxa plus those with range extensions compared with collection records and/or the most recent field guide (Dharani 2006), which we define as 'good'. Probability surfaces were considered 'poor' where collection records were lacking from the most extensive geographic locations of predicted climate suitability. Models defined as poor were not used in biodiversity estimates. Geographic locations corresponding to the upper quartiles of richness estimates were used to indicate hotspots of *Acacia* diversity.

Acacia diversity predictions were compared to the spatial distribution of three levels of protected area. In decreasing order of strength, the protected area levels assessed were (1) IUCN protected area management category I-IV (excluding forest reserves, which are not typically guarded by patrols and in many instances have high levels of habitat degradation due to illegal activity; e.g. Ahrends et al. 2010), (2) IUCN category V-VI (including forest reserves I-IV), and (3) protected areas not internationally recognised (UNEP-WCMC 2009). To determine a quantitative estimate of the

Table 1 – Distribution modelling summary for 65 *Acacia* taxa.
Columns show the number of 1 min grid cells in which a taxon was recorded (n), cross-validated AUC score (AUC$_{cv}$), percentage deviance explained (%D), proportion of presences (sens) and pseudo-absences (spec) predicted correctly by the models, and the level of constraint to areas of known distribution according to collection locations (conf1) and the most recent field guide (conf2; Dharani 2006).
*Eighteen taxa with excellent fit to collections. † 24 taxa with good fit to collections plus minor range extensions (parentheses indicate taxa removed from biodiversity calculation due to species/infraspecies overlap either within () or between [] the good and excellent model subsets).

Indicator taxon	n	AUC$_{cv}$	%D	sens	spec	conf1	conf2
Acacia abyssinica subsp. *calophylla* *	26	0.94	0.61	0.97	0.86	Excellent	Good
Acacia adenocalyx †	32	0.92	0.66	0.95	0.90	Good	Good
Acacia amythethophylla	29	0.71	0.26	0.63	0.76	NA	NA
Acacia ancistroclada †	12	0.91	0.79	0.99	0.94	Good	Good
Acacia ataxacantha †	17	0.83	0.55	0.88	0.87	Good	Good
Acacia brevispica subsp. *brevispica*	83	0.65	0.35	0.74	0.58	NA	NA
Acacia burttii †	11	0.91	0.78	0.99	0.94	Good	Good
Acacia bussei †	36	0.85	0.59	0.93	0.82	Good	Excellent
Acacia dolichocephala	8	NA	NA	NA	NA	NA	NA
Acacia drepanolobium †	60	0.74	0.34	0.73	0.74	Good	Poor
Acacia elatior †	26	0.88	0.62	0.90	0.84	Good	Good
Acacia elatior subsp. *elatior*	7	NA	NA	NA	NA	NA	NA
Acacia elatior subsp. *turkanae*	19	0.89	0.61	0.94	0.87	Poor	No data
Acacia etbaica subsp. *platycarpa*	21	0.67	0.49	0.77	0.78	NA	NA
Acacia fischeri †	11	0.87	0.66	0.97	0.89	Good	Good
Acacia gerrardii *	139	0.76	0.41	0.81	0.67	Excellent	Good
Acacia gerrardii var. *calvescens*	16	0.74	0.45	0.91	0.73	Poor	NA
Acacia gerrardii var. *gerrardii* (*)	86	0.74	0.29	0.70	0.78	Excellent	NA
Acacia gerrardii var. *latisiliqua* [†]	26	0.93	0.74	0.98	0.90	Good	NA
Acacia goetzei (†)	48	0.79	0.47	0.84	0.72	Good	Poor
Acacia goetzei subsp. *goetzei* †	30	0.75	0.48	0.83	0.73	Good	NA
Acacia goetzei subsp. *microphylla* †	24	0.85	0.59	0.91	0.86	Good	NA
Acacia hamulosa	6	NA	NA	NA	NA	NA	NA
Acacia hockii	136	0.67	0.43	0.79	0.56	NA	NA
Acacia horrida subsp. *benadirensis* *	25	0.91	0.70	0.97	0.90	Excellent	Good
Acacia kirkii subsp. *kirkii* *	31	0.81	0.41	0.88	0.76	Excellent	Good
Acacia laeta *	19	0.79	0.44	0.78	0.87	Excellent	Good
Acacia lahai †	28	0.96	0.72	0.98	0.90	Good	Good
Acacia mbuluensis	4	NA	NA	NA	NA	NA	NA
Acacia mellifera (*)	155	0.71	0.19	0.77	0.62	Excellent	Good
Acacia mellifera subsp. *detinens*	11	0.81	0.61	0.86	0.90	Poor	Poor
Acacia mellifera subsp. *mellifera* *	140	0.73	0.30	0.73	0.69	Excellent	Good
Acacia montigena *	25	0.91	0.55	0.94	0.87	Excellent	Good
Acacia nigrescens	15	0.81	0.45	0.85	0.78	Poor	Poor
Acacia nilotica subsp. *leiocarpa* *	17	0.89	0.67	0.97	0.93	Excellent	NA
Acacia nilotica subsp. *subalata*	178	0.62	0.35	0.66	0.61	NA	NA
Acacia oerfota †	24	0.72	0.44	0.80	0.81	Good	Good
Acacia paolii *	41	0.88	0.65	0.88	0.86	Excellent	Excellent
Acacia paolii subsp. *paolii*	5	NA	NA	NA	NA	NA	NA
Acacia paolii subsp. *paucijuga*	4	NA	NA	NA	NA	NA	NA
Acacia persiciflora *	30	0.94	0.72	0.98	0.90	Excellent	Excellent
Acacia pilispina	8	NA	NA	NA	NA	NA	NA
Acacia polyacantha subsp. *campylacantha*	114	0.69	0.33	0.68	0.65	NA	NA
Acacia pseudofistula *	29	0.88	0.68	0.99	0.89	Excellent	Good
Acacia reficiens subsp. *misera* *	10	0.89	0.69	0.95	0.92	Excellent	Excellent
Acacia robusta subsp. *usambarensis* †	46	0.75	0.27	0.78	0.75	Good	Poor
Acacia rovumae	13	0.89	0.71	0.98	0.90	Excellent	Good

Table 1 (continued) – Distribution modelling summary for 65 *Acacia* taxa.

Indicator taxon	n	AUC$_{cv}$	%D	sens	spec	conf1	conf2
Acacia schweinfurthii var. *schweinfurthii* [†]	13	0.78	0.63	0.88	0.92	Good	Poor
Acacia senegal var. *leiorhachis* [†]	11	0.75	0.60	0.96	0.83	Good	NA
Acacia senegal var. *senegal*	88	0.66	0.36	0.70	0.64	NA	NA
Acacia seyal	51	0.60	0.36	0.67	0.64	NA	NA
Acacia seyal var. *fistula*	21	0.63	0.44	0.70	0.77	NA	NA
Acacia seyal var. *seyal*	24	0.62	0.41	0.65	0.72	NA	NA
Acacia sieberiana var. *sieberiana* [†]	20	0.80	0.59	0.90	0.87	Good	NA
Acacia sieberiana var. *woodii* *	46	0.80	0.51	0.78	0.82	Excellent	NA
Acacia stuhlmannii	33	0.68	0.50	0.79	0.70	NA	NA
Acacia tanganyikensis [†]	16	0.90	0.63	0.99	0.88	Good	Good
Acacia thomasii [†]	24	0.82	0.54	0.96	0.75	Good	Good
Acacia tortilis subsp. *raddiana*	4	NA	NA	NA	NA	NA	NA
Acacia tortilis subsp. *spirocarpa*	56	0.68	0.41	0.82	0.59	NA	NA
Acacia turnbulliana *	10	0.99	0.92	1.00	0.99	Excellent	Excellent
Acacia xanthophloea *	17	0.80	0.55	0.88	0.85	Good	Good
Acacia zanzibarica [(†)]	49	0.85	0.54	0.81	0.86	Good	Good
Acacia zanzibarica var. *microphylla* [†]	15	0.93	0.77	0.98	0.96	Good	NA
Acacia zanzibarica var. *zanzibarica* [†]	29	0.84	0.58	0.86	0.85	Good	NA

protected area coverage in *Acacia* diversity hotspots, we calculated the degree of overlap (area and proportion) between the 36 predicted ranges and the protected area network. *Acacia* taxa were deemed likely to be present in an area if presence was predicted in five or more model runs. The areas and proportions were averaged over all taxa and 95% confidence limits calculated (999 bootstraps). We then used a binomial test (Crawley 2005) to determine whether the mean proportion of *Acacia* taxon range protected was significantly different to the proportion of the region covered by protected areas (23.3%, UNEP-WCMC 2009). This binomial test allowed us to estimate whether the protection of *Acacia* taxa range was significantly different to a randomised placement of protected areas.

Climate change

Model predictions were extrapolated into the future for the montane tree *Acacia abyssinica* Hochst. ex Benth. subsp. *calophylla* Brenan and for the xerophytic lowland tree *A. turnbulliana* Brenan. These two taxa were chosen for their contrasting ecology and their reliable prediction compared with known distributions.

Climate scenarios for 2020, 2055 and 2090 were derived from the Global Circulation Model ECHAM5, and were subsequently downscaled via the Regional Climate Model REMO (Potsdam Institute for Climate Impacts Research, Germany). We used two scenarios from the Fourth Assessment Report of the International Panel for Climate Change (IPCC-AR4, IPCC 2007). The first of these (scenario A1B) represents an increase in global temperature, peaking mid-century, following a minor reduction in greenhouse gas emissions. The second (scenario B1) is a less pessimistic scenario with global population equivalent to scenario A1B, but with more rapid improvement in public services and economic structures. Under scenario A1B, the East African regional

temperature is predicted to increase by mean 3.8 ± 0.2 s.d. °C (min 3.0, max 5.0) by 2090, and under scenario B1, by mean 2.6 ± 0.1 s.d. °C (min 1.8, max 3.9). These represent the two most divergent scenarios up to 2060 in terms of temperature and atmospheric CO_2 (IPCC 2007) and hence provide upper and lower estimates of predicted climate change.

Future climate data were downscaled from 0.5 to 0.0167 decimal degrees (30 arc-minutes to 1 arc-minute; 1.85 km) by imposing the forecast change-factors (REMO anomalies) upon the baseline temperature and rainfall grids (WorldClim and TRMM, respectively) used to model present-day distributions (Platts 2012).

Nomencalture of the *Acacia* taxa

The circumscription and nomenclature of the *Acacia* taxa (species, subspecies, varieties) in this paper (see table 1) follows that of Brenan (1959), revised in accordance with the following treatments:

Brenan (1970): *A. brevispica* Harms subsp. *brevispica*, *A. montigena* Brenan & Exell, *A. robusta* Burch. subsp. *usambarensis* (Taub.) Brenan, *A. senegal* (L.) Willd. var. *leiorhachis* Brenan.

Asfaw & Thulin (1989): *A. amythethophylla* Steud. ex A. Rich., *A. hamulosa* Benth., *A. oerfota* (Forssk.) Schweinf., *A. paolii* Chiov. subsp. *paolii*, *A. paolii* Chiov. subsp. *paucijuga* Brenan, *A. sieberiana* DC. var. *woodii* (Burtt Davy) Keay & Brenan.

RESULTS

Acacia distribution: (a) taxa

Models of predicted current distribution were produced for 58 *Acacia* taxa (51 excluding species/infraspecies overlap; table 1, electronic appendix 2), each with records of occur-

rence spanning ten or more unique grid cells in the East African region. Of these, 45 taxa (40 excluding overlap) were robust according to validation statistics (AUC$_{cv}$ 0.70-0.99; sensitivity 0.70-0.99). The predictive success of these models is further supported by expert knowledge on the distribution of *Acacia*: 18 taxa (16 excluding overlap) produced models very similar to known distributions, and a further 23 (21 excluding overlap) produced models largely in agreement with known distributions but with some range extension (table 1, fig. 2, electronic appendix 2). Four taxa showed poor comparison to known distributions and were dropped from further analyses [*Acacia elatior* Brenan subsp. *turkanae* Brenan, *A. gerrardii* Benth. var. *calvescens* Brenan, *A. mellifera* (Vahl) Benth subsp. *detinens* (Burch.) Brenan and *A. nigrescens* Oliv.].

Envelope distance was found to be high only at the summits of Mt. Kilimanjaro and Mt. Kenya, where models were forced to extrapolate down to 52.3% below the parameter range of the training data (electronic appendix 3). Maximum water deficit and annual precipitation also showed uncertainty up to 65.0% above the parameter range in the hottest and driest parts of northeast Kenya (electronic appendix 3). These knowledge gaps highlight both environmental and spatial bias in the herbarium record (fig. 3A, table 2). In particular, northern and eastern Kenya, southern and west-central Tanzania and western Uganda have the fewest *Acacia* records.

Acacia distribution: (b) biodiversity and protection

Acacia diversity estimates are presented for the 16 taxa that showed excellent fit to known distributions, and then combined with 20 of the taxa that showed minor range extension to known distributions (table 1, fig. 3; the 20 taxa reduced from 21 to account for species/infraspecies overlap with the first 16 taxa).

Among the herbarium records, 40 of the 51 *Acacia* taxa (78.4%) have been recorded from protected areas in IUCN categories I-IV, excluding forest reserves (46 in IUCN I-VI; 48 in all protected areas). However, of considerable management importance is that many of the predicted *Acacia*-rich areas (fig. 3C & D) were outside of the current protected area network (fig. 3B). Of the 17 potential hotspots identified for the genus (fig. 3C & D, table 2), 11 (64.7%) have low coverage by protected areas (0–10% geographic area) and seven (41.1%) have no overlap with IUCN category I-VI protected areas. Per unit area, the number of taxa predicted to occur in protected areas (IUCN I-VI: 3.96 ± 0.01; non-IUCN protected areas: 4.03 ± 0.01 km^{-2}; all protected areas: 3.99 ± 0.01 km^{-2}) is less than for East Africa as a whole (4.05 ± 0.002 km^{-2}).

The predicted ranges of the 36 *Acacia* taxa used in biodiversity mapping lay predominantly outside the protected area network (21.6%; table 3, electronic appendix 4), leaving an average of 78.4% (237.0 km^2) of ranges unprotected. Comparing this proportion of protection to the protected area coverage of the East Africa region (23.3%) reveals that the
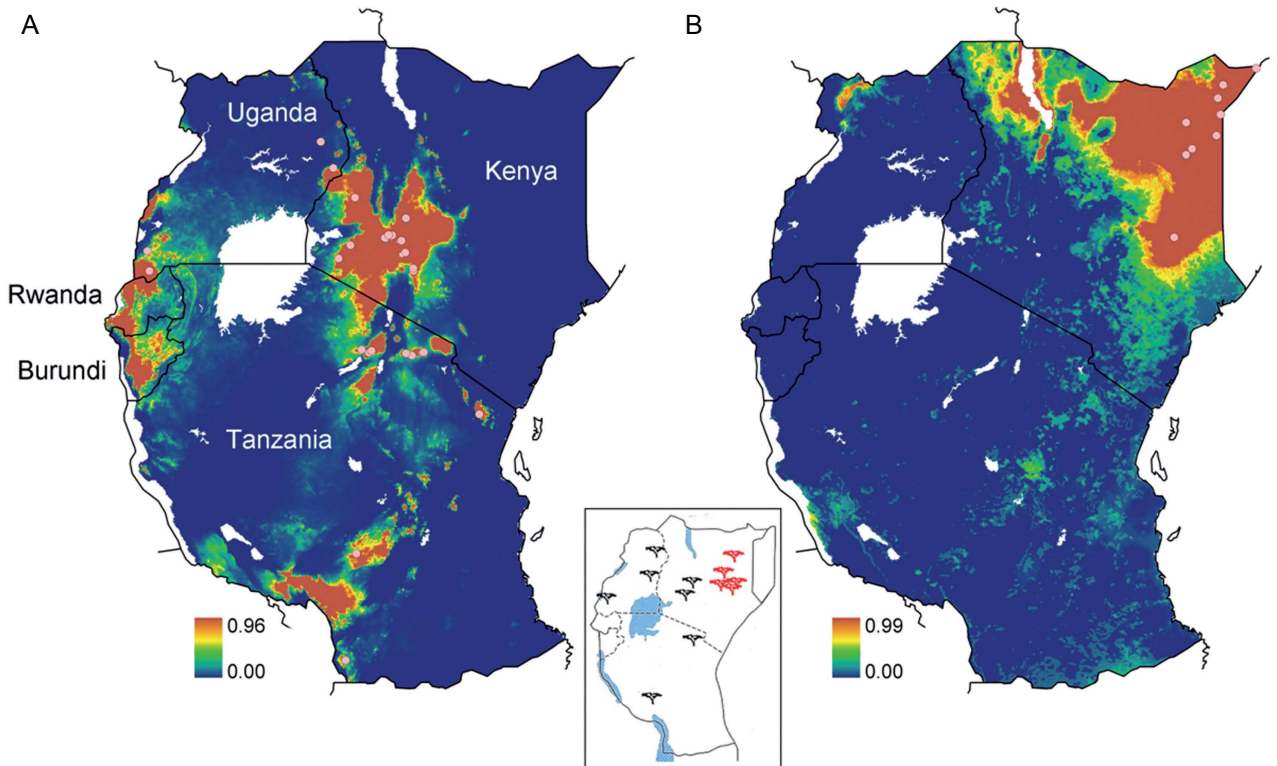

Figure 2 – Predicted habitat suitability for: A, *Acacia abyssinica* subsp. *calophylla* and B, *Acacia turnbulliana*. Scale bars indicate mean suitability from ten repeated model runs. Pink dots indicate presence localities used to develop the models. Inset shows known distribution of *A. abyssinica* subsp. *calophylla* (black tree icons) and *A. turnbulliana* (red), adapted with permission from Dharani (2006).
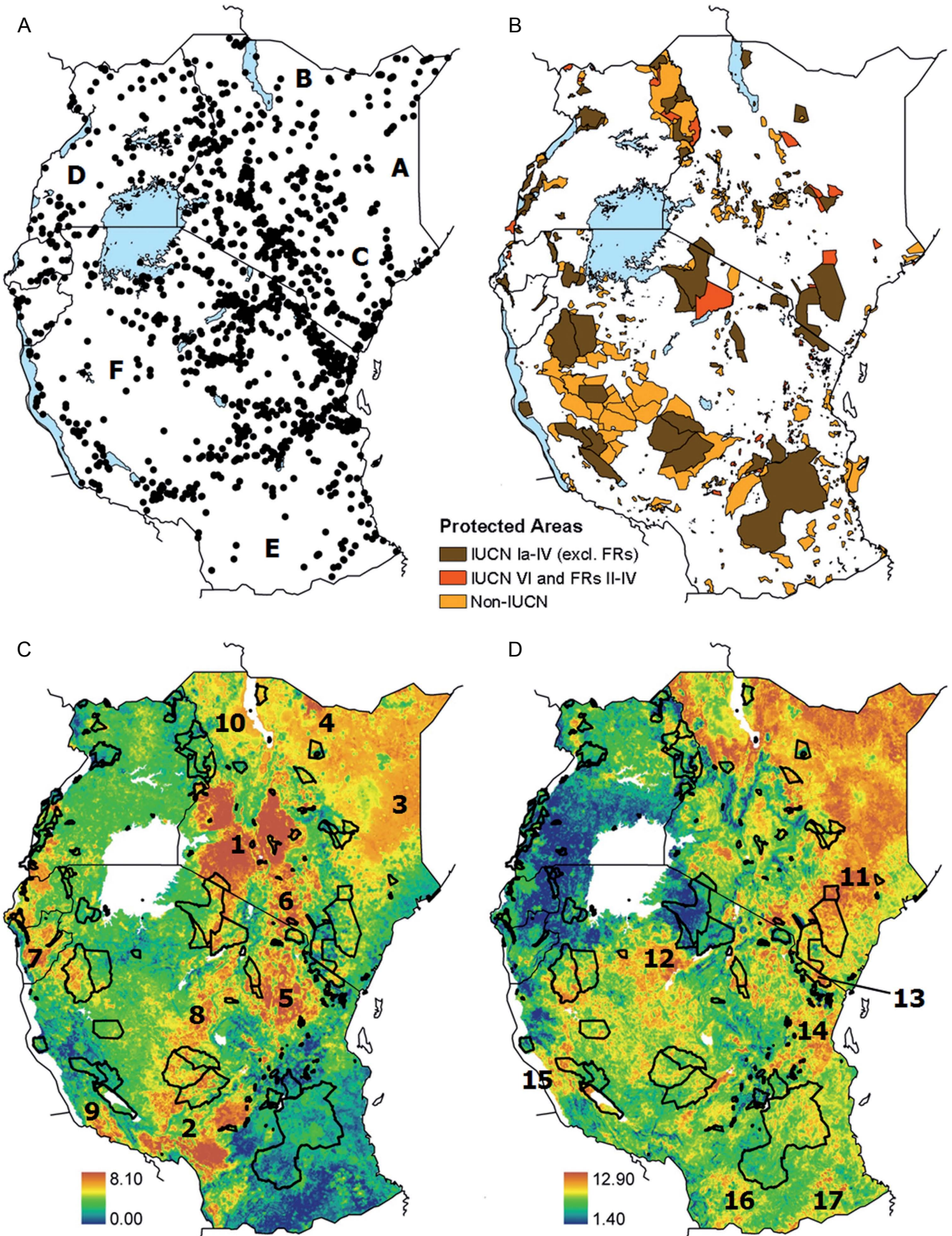
Figure 3 – Location of: A, *Acacia* collection records and B, protected areas in East Africa. Predicted biodiversity of the genus *Acacia* is shown in relation to IUCN protected areas I-VI for: C, sixteen taxa with excellent fit to known distributions and D, 36 taxa including the same sixteen taxa plus twenty taxa showing minor range extensions to known distributions. Letters A–F (in A) indicate geographic areas under-represented in the herbarium record and numbers 1–17 (in C & D) indicate *Acacia* biodiversity hotspots (table 2). Scale bars indicate the predicted number of *Acacia* taxa per 1 arc-minute (1.85 km) grid cell averaged across ten model runs.

Table 2 – Summary of the 17 geographic areas identified as high priorities for research and conservation of the genus *Acacia* in East Africa (see fig. 3C & D).
Letters A–F refer to areas under-represented in the herbarium record (see fig. 3A).
*Protected areas coverage defined as low (< 10%), moderate (10–30%) or high (> 30%).
**Saadani National Park established in 2005 has protected status equivalent to IUCN class I/II, but had not been assessed for the World Database of Protected Areas (UNEP-WCMC 2009).

Code Fig. 3	Location	Protected Area Coverage*	Collection Record	Biodiversity Importance	
				Best 16 taxa	Best 36 taxa
1	Southwest Kenya	Low	Good	High	Moderate
2	Central-south Tanzania	Moderate	Moderate	High	Moderate
3 / A	East Kenya	None	Poor	High	High
4 / B	Marsabit, Kenya	Low	Poor	High	High
5	West Manyara / Maasai Steppe, Tanzania	Low	Moderate	High	Moderate
6	South-central Kenya	Low	Good	High	High
7	South-west Uganda to Kigoma, Tanzania	Moderate	Moderate	High	Low
8	Singida, Tanzania	Low	Moderate	High	Moderate
9	South Rukwa to south-west Mbeya, Tanzania	Very Low	Moderate	High	Low
10	Turkana, Kenya	Nil	Moderate	Mod-High	High
11 / C	Tana River, Kenya	Moderate	Poor-Mod	Moderate	High
12	Central Shinyanga / north-east Tabora, Tanzania	Low	Moderate	Low-Mod	High
13	Mkomazi	High	Low	Moderate	High
14	North Pwani / south Tanga, Tanzania	Low**	Good	Moderate	High
15	West Rukwa, Tanzania	Moderate	Moderate	Low	High
16	Central Ruvuma, Tanzania	Very Low	Poor	Moderate	Mod-High
17	West Mtwara / south-west Lindi, Tanzania	Low	Moderate	Low	Mod-High
D	East Uganda	Moderate	Poor	Moderate	Low
E	South Tanzania (includes Central Ruvuma, 16)	Moderate	Poor	Low	Moderate
F	East-central Tanzania	High	Poor	Moderate	Mod-High

level of protection is no more than would be expected by randomised placement (Binomial test: $\chi^2 = 0.74$, $p = 0.39$). A mean of 11.2% of the predicted range of each species was protected within the highest category of protected area (IUCN I-IV, excluding forest reserves). *Acacia* taxon ranges are marginally more often conserved in IUCN protected areas (12.6%) than non-IUCN protected areas (8.9%; table 3). Five *Acacia* taxa [*A. horrida* (L.) Willd. subsp. *benadirensis* (Chiov.) Hillc. & Brenan, *Acacia gerrardii* var. *latisiliqua* Brenan, *A. reficiens* Wawra subsp. *misera* (Vatke) Brenan, *A. turnbulliana* and *A. zanzibarica* S. Moore var. *microphylla* (Taub.) Brenan] have less than 10% of their predicted range included within a protected area, four of which occurred predominantly in north-east Kenya.

Climate change

Climate change projections suggest a decline in climatic suitability up to 80.0 % (163,574 km² declining to 32,630 km²; scenario A1B) or 65.2 % (56,848 km²; scenario B1) by 2090 for *Acacia abyssinica* subsp. *calophylla* (fig. 4A, electronic appendix 5A). This tree is typically found at high elevation, where the atmosphere is moist and temperatures are cool. Accordingly, the various DM runs for *A. abyssinica* subsp. *calophylla* identified negative relationships with tempera-

ture (annual mean and PET, %D 30.4, contributing to all ten forward-backward models runs), and positive relationships with the annual moisture index (%D 52.9, 6/10 runs). The future projection for *A. abyssinica* subsp. *calophylla* predicts a progressive movement to higher elevation, where the most common protected areas are forest reserves (2090: 18.3% of range protected under IUCN reserve versus 27.4% non-IUCN; fig. 4A). Because of the steep predicted range decline, the proportion of area protected is predicted to increase (21.4 % increasing to 52.4% [A1B] or 37.9% [B1] in 2090; fig. 4A).

The lowland tree *Acacia turnbulliana* is predicted to increase in range by 77.0% (122,395 km² increasing to 532,675 km²; scenario A1B) or 63.1% (331,414 km²; scenario B1) by 2090 (fig. 4B; appendix 5B [online material]). The increase resulted from a positive relationship with temperature (annual mean and PET, %D 59.4, 7/10 runs; temperature range, %D 28.2, 6/10 runs) and a negative relationship with the moisture index (%D 67.2, 3/10 runs). However, these (monotonic) relationships (fig. 4B) were extrapolated up to 12.7% (A1B, 2090) beyond present-day temperatures in East Africa, and thus the projected range-expansion in north-east Kenya is subject to envelope distance up to 18.3% for mean temperature (electronic appendix 3). From being the least

Table 3 – Mean (± 95% bootstrapped confidence limit) of the predicted range of 36 *Acacia* taxa within protected areas in East Africa (total area 1,711,585 km².)
*There are no IUCN class V protected areas in the region.

	Area of predicted range protected (thousand km²)	% of predicted range protected
IUCN I-IV (excluding Forest Reserves)	35.6 (28.4–42.8)	11.2 (9.8–12.7)
IUCN VI and IUCN Forest Reserves*	4.1 (3.3–4.8)	1.4 (1.1–1.8)
IUCN total (I-VI)	39.7 (32.3–47.1)	12.6 (12.2–14.1)
Non-IUCN protected areas	28.5 (21.2–35.6)	8.9 (7.3–10.6)
All protected areas	**68.2 (55.5–83.7)**	**21.6 (18.6–24.4)**
Unprotected	**237.0 (204.6–269. 4)**	**78.4 (75.8–81.1)**

protected *Acacia* taxon based on distribution models (0.4 % range within protected areas; electronic appendix 4), the projected range increase predicts an expansion into protected areas (16.7% [A1B] or 7.3% [B1] of predicted range in 2090; fig. 4A).

DISCUSSION

Acacia distribution and biodiversity

Many of the high *Acacia* diversity areas identified have not previously been highlighted as being of major importance for conservation of the genus. Botanists working in East Africa agree that these areas are likely to be important for *Acacia* species (N. Dharani, World Agroforestry Centre, Kenya, pers. comm.; R.E. Gereau pers. obs.), providing support for model outputs that were both robust and had good agreement with collection localities (fig. 3, table 2, electronic appendix 2).

Identification of biodiversity hotspots can help managers prioritise future conservation efforts (Myers et al. 2000). In determining conservation priorities for a taxon, the degree of protection of the overall range is more important than information on the location of isolated records. Thus, while many *Acacia* taxa have been collected from protected areas, there is discordance between protected areas and predicted *Acacia* diversity hotspots, low protection of predicted ranges (mean 78.4% unprotected; table 3) and extremely weak protection for taxa restricted to north-east Kenya. An increasing demand in East Africa for natural resources such as charcoal (Ahrends et al. 2010), fuelwood, honey, etc., leaves species outside of protected areas at risk. The designation of Africa's national parks and game reserves based on declining animal populations (Balmford et al. 1992) might therefore be failing to protect one of Africa's most iconic plant groups, which could in turn impact on East Africa's globally important vertebrate assemblage *via* the supporting function that *Acacia* species provide for habitat, herbivores and biogeochemical cycling.

Discordances between biologically rich areas and the protected area network in Africa have also been documented for threatened mammals (Fjeldså et al. 2004), birds (De Klerk et al. 2004) and threatened and/or range-restricted plants (Burgess et al. 2005). It is appropriate, therefore, to question the extent to which the genus *Acacia* is a suitable surrogate for overall biodiversity in the East African region. Pratt & Gwynne (1977) delineated six eco-climatic zones in Kenya, Tanzania and Uganda based on moisture indices derived from monthly rainfall and evaporation. These eco-climatic zones are well correlated with vegetation and land-use classes, and each one is represented by a number of characteristic species, many of which belong to the genus of *Acacia* (Pratt & Gwynne 1977). We therefore assume that the distribution of these indicators represents a significant proportion of regional biodiversity. For example, bird assemblages in East Africa are dependent on the structure and diversity of woody plants for food and shelter (Kissling et al. 2010), while the interactions between *Acacia* trees, large herbivores, beetles, ants and other invertebrates are also well documented (New 1984). Predominantly associated with East African woodlands, wooded grasslands and bushlands, the genus *Acacia* is perhaps less representative of biodiversity in moist forest habitats, such as the Eastern Arc Mountains of Tanzania and Kenya. In addition, while hotspots 6 and 10 in fig. 3C conform to known biodiversity of woody vegetation in Kenya, more northern areas may not (Kissling et al. 2010). Nevertheless, this charismatic genus can be added to a growing body of evidence for hotspots of diversity situated outside of Africa's protected areas.

Many of the predicted *Acacia* climate suitability maps (electronic appendix 2) show reasonable fit to known distributions. However, as is typical for DMs, limiting factors beyond the scope of the models, combined with geographic gaps in the herbarium record, resulted in some degree of extension beyond known ranges (cf. Dharani 2006). Future botanical collection would be most beneficial in areas where *Acacia* diversity is predicted to be high, but which are lacking in collection records (fig. 3, table 2). Hotspots in the north-east of Kenya and in southern and west-central Tanzania have been poorly collected, despite several *Acacia* observations from these areas in the literature (Dharani 2006). Ground-truthing could verify predicted range extensions (table 1, electronic appendix 2) and improve parameterisation of temperature as a limiting factor for species such as *A. turnbulliana*.

Biodiversity assessments are highly dependent on the data available, thus affecting conservation prioritisation (Platts et al. 2010, Ahrends et al. 2011). Here, for example, some *Acacia* hotspots vary according to the subset of taxa considered: north-east Kenya in particular is more clearly emphasised by the subset of 36 taxa, which includes predictions of minor range extension, than by the set of 16 (excellent fit to known
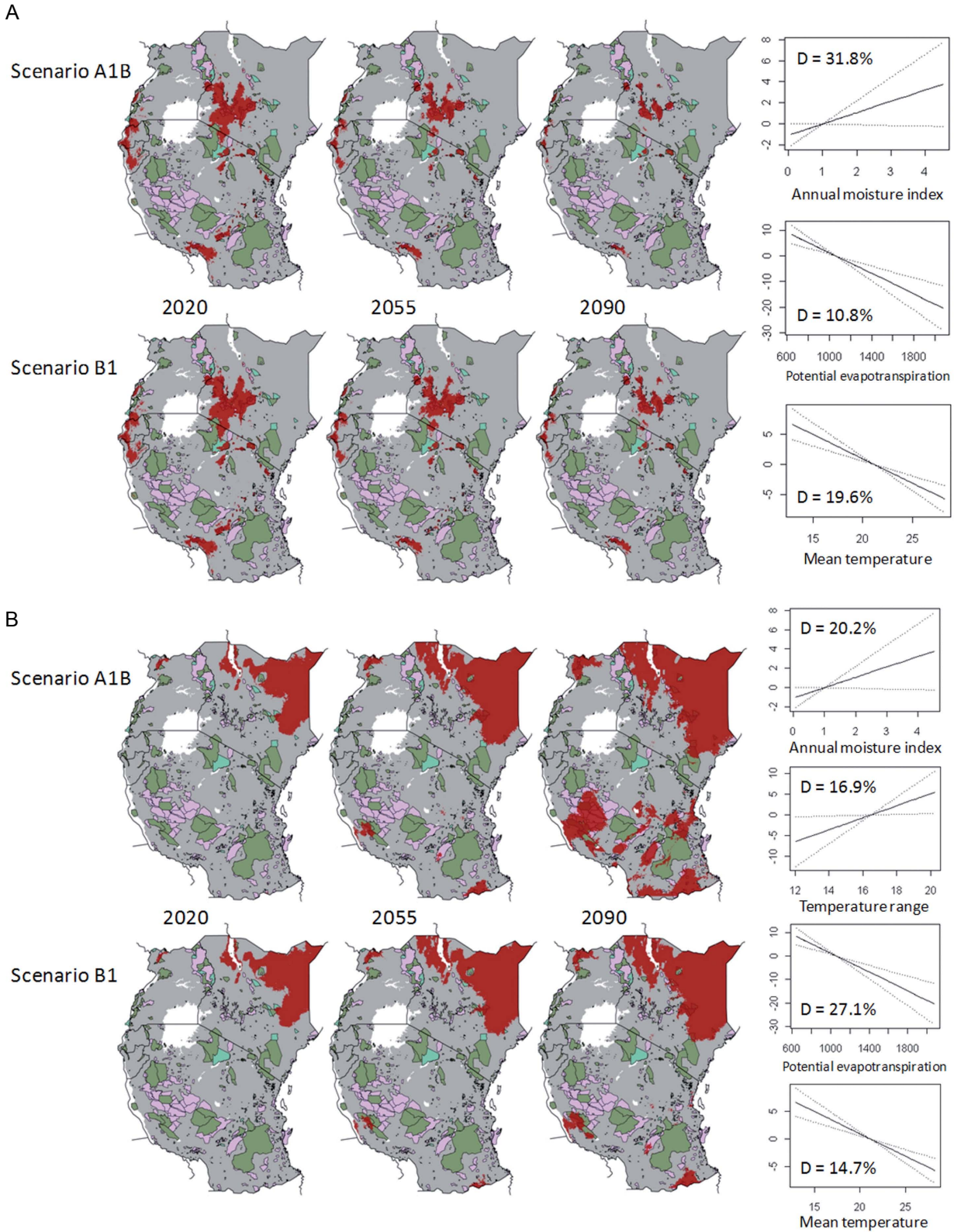
Figure 4 – Future range predictions for: A, *Acacia abyssinica* subsp. *calophylla*, and B, *Acacia turnbulliana* in relation to protected areas in East Africa. Red areas indicate predicted presence based on climatic suitability. Protected areas are shown in green (IUCN Ia-IV excluding Forest Reserves), blue (IUCN VI and Forest Reserves II-VI) and pink (non IUCN). Surfaces were derived from present day distribution model response curves (as shown, ± s.e., including predictor contribution, D). Straight line responses indicate either a preference for climatic extremes, or undersampling towards range limits.

distributions only). This discrepancy corresponds to a gap in the collection record, which necessarily renders occurrence predictions in north-east Kenya 'range extensions beyond-' rather than 'excellent fits to-' known distributions.

Climate change

Our application of a regional climate model, as opposed to a coarser, native resolution global circulation model, for predicting species distributions in the inter-tropical convergence zone has great potential to assist conservation planning. While sensitivity analysis would benefit from consideration of additional model calibrations (e.g. Jones et al. 2004) and scenarios (IPCC 2007), our results nonetheless highlight the potential for contrasting responses within a particular genus. The different ecological requirements of our two focal taxa resulted in very different responses to climate change: xerophytic taxa such as *Acacia turnbulliana* may benefit initially, whereas montane taxa such as *A. abyssinica* subsp. *calophylla* are predicted to reduce in range and become more dependent on weaker protected areas (fig. 4A). As montane taxa track changing climatic conditions (particularly rising temperatures) up the elevational gradient, the available space decreases, competition for resources increases, and eventually some may become locally extinct (La Sorte & Jetz 2010). If the predicted reduction in climatic suitability for *A. abyssinica* subsp. *calophylla* causes a reduction in the range of this taxon by the projected 65–80% by 2090, it could qualify as Endangered under criterion A3 of the IUCN Red List (≥ 50% population reduction projected or suspected over three generations, up to a maximum of 100 years; IUCN 2001). High elevation specialists may therefore be the group most threatened by rising global temperatures (Laurance et al. 2011), except in cases where complex topography provides climatic refugia – pockets of climatic stability undetected at the landscape scale (Austin & Van Niel 2011).

The behaviour of taxa in relation to both present and future climates is uncertain. For example, DMs rarely account for adaptability, dispersal or biotic interactions with competitors, food sources or predators (Guisan & Thuiller 2005). While the effects of climate change can be projected, direct human influences are more palpable. Habitat removal and overexploitation have been responsible for the inclusion of 80% of globally threatened species on the global Red List (IUCN 2011). Moreover, human influence has shaped the world's ecosystems through a complex interaction with biotic factors (Hoekstra et al. 2005, Ellis & Ramankutty 2008). Conversely, *Acacia* distribution in Turkana (Kenya) has been shown to be more closely related to rainfall and elevation gradients than to long-term anthropogenic disturbances (Coughenour & Ellis 1993). Hence, while incorporation of land-use into DM outputs will help to improve accuracy, climatic and topographic factors will likely remain central to estimates of both current and future *Acacia* diversity.

Policy implications

Continued human pressure on habitats and species has led to the incorporation of biodiversity as the central theme of management planning of protected areas in East Africa. All five East African countries have ratified the Convention on Biological Diversity (1992) and were party to the new Convention on Biodiversity Strategic Plan (2011-2020; UNEP 2010), which includes a commitment to achieve at least 15% coverage of "... comprehensive, ecologically representative and well-connected systems of effectively managed protected areas...". Recent protected area designations based on biodiversity importance demonstrate this commitment in practice in East Africa (Davenport 2002, Marshall et al. 2007).

The question for managers is how best to deal with the potential mismatch between biodiversity and the current protected area network, both now and in the future. The strongest and most effective means of biodiversity conservation has consistently resided in the establishment of protected areas (Lockwood et al. 2006). In the future, this strategy could be strengthened by designating corridors as "stepping-stones" for wildlife between the existing fixed network designs. Repositioning of protected areas is out of the question due to the inherent uncertainties of both DMs and climate forecasts (Hunter et al. 2010), not to mention cultural, logistical and financial considerations.

Small-scale community initiatives underway in East Africa aim to encourage sustainable use of natural resources and the conservation of biodiversity-rich areas, including north-eastern Kenya. New conservation efforts do not necessarily have to follow the traditional format of protected areas and should work closely with local people, but ultimately must be based on solid science underpinned by verifiable and consistently collected data. Previous studies in the region have demonstrated the need for lower-level protected areas, such as forest reserves, to augment the biodiversity conserved by national parks and nature reserves (Burgess et al. 2007, Gardner et al. 2007). Our future range projection for a montane specialist emphasises the importance of high elevation climate refuges, where forest reserves are the most common form of protected area. While we emphasise that approximately half of the *Acacia* range predictions that are within protected areas correspond to levels of protection not recognised on the IUCN scale of I-VI, these sites do at least offer some legislated protection that may be built upon in the future.

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