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Developing conservation strategies for endemic tree species when faced with time and data constraints: *Boswellia* spp. on Socotra (Yemen)

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Abstract Many endemic tree species have important scientific, ecological and economic value but the scarcity of information about their biological and ecological features makes it difficult to develop conservation strategies for them. A four-step approach is presented to address this problem, based on the analysis of data collected in a limited-duration field study: (1) Data collected are used to analyse the ecological niche, population structure and regeneration status of the species in question. (2) Several IUCN Red List (RL) parameters, useful for assessing the species' risk of extinction, are measured, including population counts, number of locations, extent and area of occurrence. (3) The IUCN RL parameters are used together with the other information gathered to set preliminary conservation priorities. (4) The analysis of utilization pattern is used to develop conservation actions specific to the environmental and socio-economic context. To test the applicability of this approach *Boswellia* spp. of Socotra island were analysed. Ground-rooted species (*B. ameero*, *B. elongata* and *B. socotrana*) were the most abundant and widespread and, according to the spatial analysis, were characterised by a geo-altitudinal zonation. However, the Weibull functions fitted on their stem diameters, and the absence or presence of only a small number of saplings highlighted a poor regeneration status. In the absence of conservation actions, these species will probably be subject to a progressive decline because of uncontrolled grazing. Of the four cliff-rooted species, which grow in sites that are less accessible to livestock, two (*B. popoviana* and *B. dioscorides*) were of lower

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conservation priority and may become the most numerically abundant. Conversely, the other two (*B. nana* and *B. bullata*), which may be threatened by stochastic events because of their reduced populations and small number of locations, were considered of very high priority. Different conservation actions were then identified for each species. In particular, for *Boswellia* species producing gum, the conservation-through-use action was discussed as a potential option.

Keywords IUCN Red List · Ecological niche modelling · Random Forest · Soil parameters · Weibull function

Introduction

Socotra is part of a continental archipelago comprising four islands and a few islets in the Indian Ocean between 12°06′–12°42′ N and 52°03′–54°32′ E; Abd al Kuri, the westernmost island, lies about 80 km from Cape Guardafui in Somalia, and Socotra about 380 km south of the Arabian Peninsula (Fig. 1). The island is characterised by an undulating plateau ranging from 300 to 900 m composed of a thin stratum of Cretaceous and Tertiary limestone that overlies an igneous and metamorphic basement (Socotra Platform), which is exposed in three areas (Beydoun and Bichan 1970). On the coastal plains and in the inner depressions, Quaternary and recent deposits of marine, fluvial and continental origin overlie the older substrata.

Local climate is influenced by large-scale weather phenomena, particularly the seasonally reversing monsoon: the NE (winter) monsoon, which lasts from November to

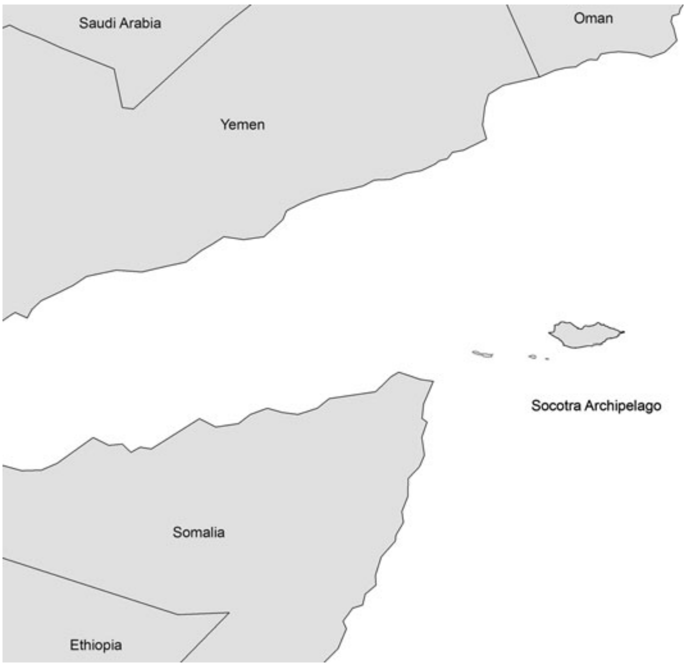

Fig. 1 Study area

March, and the SW (Indian or summer) monsoon, which blows from May to September. Mean annual rainfall and temperature are 216 mm and 28.9°C respectively, but the former varies across the island with exposure and elevation: on the coastal plains the annual precipitation may be as little as 125 mm or it may even be absent altogether, while in the mountains it can reach exceptional levels of 1,000 mm, of which preliminary measurements suggest that fog-derived moisture may constitute over two-thirds of the total (Scholte and De Geest 2010).

The long isolation of the Socotra archipelago has contributed to the creation of a unique flora (Miller and Morris 2004), and the sustainable traditional land practices have allowed such a "hot spot" of biological diversity to be conserved: Socotra hosts 308 endemic flowering plant species out of an estimated 825, a 37.3% level of endemism (Miller and Morris 2004). The semi-arid climate has favoured frankincense tree species belonging to *Boswellia* genus (Thulin and Al-Gifri 1998), which comprises 20 species distributed in the semi-arid regions of tropical Africa, the Arabian Peninsula and India (Gillet 1991; Vollesen 1989). *Boswellia* genus represents one of the most interesting examples of adaptive radiation on Socotra (Turelli et al. 2001) and this process has led to the evolution of seven endemic species, giving the relatively small island the highest concentration of frankincense tree species in the world (Thulin and Al-Gifri 1998).

Boswellia species of Socotra have two distinct growth forms (Miller and Morris 2004; Mies et al. 2000): the so-called cliff-rooted species (*B. bullata*, *B. dioscorides*, *B. nana*, *B. popoviana*); and the ground-rooted species (*B. ameero*, *B. elongata*, *B. socotrana*). Since early historical times, frankincense has been produced mainly from two ground species, *B. elongata* and *B. socotrana*, and then used for house cleansing and in traditional and veterinary medicine, or exported like other valuable natural products such as aloe and cinnabar, the resin of the well-known Dragon's blood tree, *Dracaena cinnabari*.

Grazing by livestock, mainly goats, has been recognised as the main factor hindering the regeneration of *Dracaena cinnabari* (Adolt and Pavlis 2004; Attorre et al. 2007a; Habrova et al. 2009), and the same impact could be expected for *Boswellia* species. Moreover, foliage loping by herders in the dry months to feed their livestock can further stress the trees, making them less resistant to the predicted increasing drought (Miller and Morris 2004). The decline of *Boswellia* species may not only increase their risk of extinction, but also lead to the disappearance of a potential source of income for the rural population, an increase in soil erosion processes and a reduced appeal for eco-tourism.

The scientific, ecological and economic importance of these endemic tree species motivates conservation biologists to develop specific management strategies. However, such a pursuit can be severely hampered by the scarcity of information about their distribution, ecological characteristics, population structure, growth, sexual reproduction and dispersal mechanisms, genetic characteristics and isolation and past trends. The current generalised dearth of such detailed knowledge is primarily due to the relatively long time needed to collect relevant data. Trees, for example, account for the majority of plant species assessed in the IUCN Red List (RL), but this assessment has been carried out mainly according to the B Criterion on geographic range size (Newton and Oldfield 2008). The generalised tendency to gather information from herbarium data, which also explains the abovementioned bias towards trees, limits the possibility for analysis to carrying out mere preliminary evaluations on species' conservation status (Lughadha et al. 2005).

In this context, *Boswellia* spp. of Socotra are of particular interest because their different growth forms and uses make comparative analysis a useful tool for testing the validity of a methodological approach for developing appropriate conservation strategies when time for data collection is limited.

Materials and methods

The methodological approach developed in the present study was based on a four-step procedure:

- Analysis of the ecological niche (even spatially explicit), population structure, regeneration status of tree species.
- Assessment of the extinction risk according to a set of IUCN parameters that are applicable when data about past population trends are unavailable: population counts, determination of the number of locations, measure of extent and area of occurrence.
- Setting of conservation priorities by integrating the abovementioned information; this step is needed because of intrinsic limitations in the IUCN RL classification, namely while tree species can be classified under the same extinction risk category they may differ in actual conservation priority given their population structure and regeneration status (de Grammont and Cuaron 2006; Mace et al. 2008).
- Identification of conservation actions that are specific to the ecological characteristics of each species and to the environmental and socio-economic context.

Moreover, the results of our analyses were compared with those obtained by several recent studies on the relationship between the spatial distribution, population structure and regeneration processes of *Boswellia papyrifera* and environmental factors and land use practices in the Horn of Africa (Ogbazghi et al. 2006a, b; Rijkers et al. 2006; Negussie et al. 2008).

Data set

In order to analyse the ecological niche and the population structure of *Boswellia* spp., all known areas characterised by the species were sampled in February–March 2007 using bibliographical information (Miller and Morris 2004; Mies et al. 2000; Thulin and Al-Gifri 1998) and indications provided by the local staff of the Environmental Protection Authority of Socotra. 108 sample plots, with a spatial resolution of 20 $\times$ 20 m for the cliff species and 50 $\times$ 50 m for the ground species, were identified using GPS coordinates. Dendrometric surveys were then carried out by measuring with a tape the circumference at breast height (1.30 m) of all the trees with a diameter equal to or over 2 cm. For *B. nana* which, due to the combined effects of strong wind and grazing, grows prostrate, stem diameter was measured at the base. The number of saplings was also recorded.

As a measure of abundance the Importance Value (IV) was calculated according to the following formula:

$$\text{Importance Value (x)} = \text{Density (x)} + \text{Dominance (x)}$$

$$\text{Density (x)} = 100 * \text{NS (x)}/\text{NS(all species)}$$

$$\text{Dominance (x)} = 100 * \text{BA (x)}/\text{BA(all species)}$$

where x is one of the considered species, NS is the number of stems of a plot and BA is the basal area of the plot calculated using the diameter at breast height of each individual stem. In monotypic stands, the IV could reach a maximum of 200.

Limited to ground species, in each plot five soil samples were collected from the upper layer, one at the centre and four at random distances from the centre in different perpendicular directions. The soil samples were then pooled and stored in plastic bags for the chemical-physical analyses. In the laboratory, the samples were oven-dried, crushed in a mortar and passed through a 2-mm mesh sieve before being analysed using standard techniques (MIPAAF 2000): pH with the potentiometric method in a 1:2.5 (v/v) soil:water suspension; organic carbon with the Walkley–Black wet combustion method and organic matter, by multiplying values for organic carbon by the Van Bemmelen factor of 1.724; and total nitrogen (N) with the Kjeldahl method. To estimate available phosphorus (P), the Bray and Kurtz method was used for soils with pH < 6.5 and the Olsen method for soils with higher pH values. Exchangeable bases (sodium, potassium, calcium and magnesium) were measured by atomic absorption spectrophotometry, using ammonium acetate as the extractant. Electrical conductivity was determined in a 1:5 soil:water suspension. Finally, the particle size analysis was performed with the hydrometer method.

Data analysis

Abundance and spatial distribution

In order to investigate the effect of the environmental parameters on the abundance and distribution of *Boswellia* species two separate analyses were performed. In the first, limited to ground species, the relationship between abundance and environmental factors such as topographical, climatic and pedological parameters was investigated by means of a forward stepwise multiple linear regression. In the second, the most important environmental variables influencing the current spatial distribution of *Boswellia* species were identified in order to produce maps of their potential distribution. IVs were used as dependent variables, while climatic, topographical and geological data, in GRID format with a spatial resolution of 100 m, were used as independent variables. Climatic maps were obtained by interpolating precipitation and temperature data recorded in 10 manual meteorological stations and calculating the average data for the 2000–2008 period (Attorre et al. 2007b). Besides mean annual temperature and annual precipitation, a moisture index (Mi) was used. Mi is based on: Mi = P/PET, where P is the mean annual precipitation and PET is the potential evapotranspiration. A simplified geological map, including granitic, limestone, alluvial and sand substrata, was used as a surrogate for a pedological map, which still does not exist for the whole area.

For the statistical method a Random Forests (RF) model was used since it has proved to be efficient in predicting the spatial distribution of tree species (for technical details see Benito Garzòn et al. 2006; Prasad et al. 2006; Scarnati et al. 2009). Since RF requires records of absences, the use of presence-only data would bias the analysis and lead to overoptimistic predictions of the potential distribution. However, in the case of rare tree species such as *Boswellia*, absence data are difficult to obtain: a given location may be classified in the 'absence' set both when for historical reasons the species is absent even though the habitat is suitable and when the habitat is truly unsuitable; and only the latter is relevant for predictions. When no true absence data are available, one approach is to generate 'pseudo-absences' and to use them in the model as absence data for the species. In this case the method proposed by Engler et al. (2004) for rare and endangered species was chosen: first a suitability map was produced through the ecological niche factor analysis (ENFA) implemented in the BIOMAPPER package (Hirzel et al. 2002), then for each species a number of pseudo-absences equal to that of presences was randomly chosen in areas whose ENFA prediction was lower than the lowest one associated with observed presences.

Population structure

To examine the population structure of *Boswellia* species a Weibull distribution curve was fitted on pooled stem diameters (DBH). This function has proved to be very flexible and suitable in fitting stem-size distribution data for ecological applications (Bailey and Dell 1973; Tanouchi and Yamamoto 1995) and it is popular with modellers dealing with uneven-age stands (Kamziah et al. 2000; Zhang and Liu 2006).

It was calculated as follows:

$$f(x) = \frac{\gamma}{\alpha} + \left(\frac{x-\mu}{\alpha}\right)^{\gamma-1} \exp\left(-\left(\frac{X-\mu}{\alpha}\right)^{\gamma}\right)$$

where x is the observed variable, in this case the DBH, γ is the shape parameter, α is the scale parameter and μ is the location parameter. In this study, the parameters of the Weibull distribution function were estimated using the statistical package STATISTICA 8.0 by means of linear regression and maximum likelihood methods, and the disparity between the observed and the predicted distribution was explained by the responsible environmental factors (Lykke 1998; Swaine 1998).

The scale parameter is approximately equal to the median DBH while the shape parameter controls the skewness of the distribution. When $0 < \gamma < 1$, the curve approaches an inverse J-shape distribution, indicating abundant young individuals and a very good regeneration status of the species; for $1 < \gamma < 2.6$, a positively skewed distribution with a right tail is expressed, meaning a few young individuals compared to the individuals of average age and indicating a medium regeneration status; for $2.6 < \gamma < 3.7$, the coefficient of skewness approaches zero and the distribution approximates the normal with no tail, while for $\gamma < 3.7$ the distribution is negatively skewed to the left, indicating in both cases a poor regeneration status.

Conservation assessment

The conservation assessment was performed by measuring/calculating several IUCN RL parameters: population counts, number of locations, extent of occurrence (EOO) and area of occurrence (AOO).

The number of locations was calculated by applying the circular buffer method to the georeferenced plots. A radius of 1/10th of the maximum plot distance was used as suggested by Rivers et al. (2010) in a comparative study of the endemic species of the genus *Delonix* s.l. in Madagascar. Here the term locations rather than subpopulations was used because of the current lack of knowledge about the reproductive isolation and dispersal ability of *Boswellia* species.

EOO was estimated using the α-hull method (Burgman and Fox 2003), which provides a more detailed representation of the space contained by the sample plots than the traditional convex hull method. AOO, which is the part of EOO occupied by a taxon, was calculated using two methods. In the first it was estimated using a grid square of 2 km as recommended by IUCN (2010). In the second only the suitable area as estimated by the spatial modelling within EOO was considered. The use of spatial modelling to estimate range parameters is not new (see Sérgio et al. 2007) and in our study it is proposed as a way of avoiding the need to identify the appropriate resolution scale for AOO, which is a potential source of inconsistency and bias (IUCN 2010).

Results

Abundance and spatial distribution

The most abundant species on Socotra were two ground ones, *B. elongata* with 826 individuals observed and *B. socotrana* with 378, while the rarest species were two cliff ones, *B. nana* and *B. bullata* (Table 1): *B. nana* was found in only one location on the Hamaderoh mountain in the northeast of Socotra, at an altitudinal range of between 650 and 700 m (Fig. 3e), while *B. bullata* was found only in the western part of the island, where the most abundant population (88 individuals) grows on a sea rock (Fig. 3b). Cliff species had a smaller distribution but a higher density than ground species. *B. elongata* was the only ground species with a mean cover comparable to that of cliff species.

The results of the soil analyses for the three ground species are presented in Table 2. Analysed soils belonged to different textural classes ranging from sandy to silty, with silt and sand varying considerably among the plots, while clay percentages were generally low (<10%). PH values were slightly to strongly alkaline, but measurements of electrical conductivity showed very low levels of soluble salts for all species. The majority of topsoils were characterised by low organic matter content, with only a few exceptions with higher levels (>6% and up to 11%). Available phosphorous turned out to be rather variable among the plots, ranging from low to high. The content of total exchangeable bases was high to very high, with Ca always being the dominant cation.

The stepwise multiple linear regression analysis suggests that the abundance of *B. ameero* is only influenced by pedological parameters, with the clay and sand content of soil being respectively positively and negatively correlated (Table 3). For the other two species (*B. elongata* and *B. socotrana*), slope is the main factor negatively influencing the measure of abundance.

The spatial modelling analysis was not performed for *B. nana* and *B. bullata* due to their small number of plots. For the other species, the potential distribution maps were produced according to the minimal predicted area (MPA), which is particularly useful when modelling the potential distribution of rare species. In fact, a model that predicts species presence everywhere might give the best evaluation results (because all presences would then be effectively predicted as presences), but such a map would be of no use for conservation purposes. On the contrary, consistently with the MPA criterion, the model should predict the smallest possible potential area while still covering a maximum number of species' plots. To calculate the MPA, for each species the threshold of predicted IV

Table 1 Altitudinal range, annual precipitation, mean annual temperature, number of plots, number of trees sampled, mean tree density and cover of *Boswellia* species

Species	Growth form	Altitude range (m)	Tot. prec. (Mm)	Mean temp. (°C)	No. of plots	No. of trees	Mean density n. tree/100^2	Mean cover ($m^2/100^2$)
B. ameero	Ground	458–906	226–358	23–27	13	126	0.1	0.03
B. elongata	Ground	172–690	157–329	24–29	32	826	0.94	0.12
B. socotrana	Ground	39–698	93–329	24–31	29	378	0.52	0.03
B. bullata	Cliff	20–526	95–260	26–30	5	164	7.65	0.05
B. dioscorides	Cliff	54–651	126–311	25–30	17	189	2.78	0.12
B. nana	Cliff	663–698	282–321	24–26	3	23	1.92	0.01
B. popoviana	Cliff	7–244	115–146	26–30	9	126	3.81	0.11

Table 2 Physical and chemical soil properties of ground-rooted *Boswellia* species (*B. ameero, B. elongata, B. socotrana*)

Environmental variable	*B. ameero*		*B. elongata*		*B. socotrana*	
	Mean	Range	Mean	Range	Mean	Range
Slope (°)	18.3	12–25	8.4	2–16	11.6	0–32
Sand (%)	50.2	9.6–92.6	41.1	10.0–84.2	60.2	3.7–96.7
Silt (%)	39.8	5.4–81.8	50.5	11.5–82.0	34.6	1.3–85.9
Clay (%)	10.0	2.0–20.2	8.4	1.0–26.4	5.2	0.0–12.9
pH	7.9	7.5–8.3	8.1	7.2–8.6	8.3	7.2–9.0
Organic matter (%)	5.9	1.2–11.0	3.7	1.3–7.2	2.8	0.7–6.7
Available P (ppm)	9.9	3.3–17.4	10.7	0.0–39.8	8.2	0.0–21.2
Na (me/100 g)	0.5	0.4–1.0	0.9	0.5–1.5	0.7	0.2–1.6
K (me/100 g)	1.6	0.1–3.4	2.2	0.9–3.7	1.2	0.2–3.4
Tot exch. bases (me/100 g)	64.0	13.1–136.5	40.1	20.6–64.9	50.5	20.5–141.7
Soluble salts (me/100 g)	3.3	1.8–5.8	3.7	2.7–5.9	3.0	1.4–5.0

Table 3 Results of the forward stepwise linear regression analysis to assess the importance of environmental factors on the abundance of ground-rooted species measured as IVs

	Intercept	First	Second	r^2	*N*
B. ameero	−92.3	Clay 12.8**	Sand −1.4*	0.86	12
B. elongata	−17.6	Slope −7.1***	Prec. 0.7*	0.58	20
B. socotrana	104.0	Slope −2.2**	Silt −0.6*	0.58	21

r^2 Coefficient of determination; *N* number of sample plots

Only significant variables are reported. * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$

scores was identified that encompassed 90% of species' plots (rule of parsimony), below which predictions were set as zero.

It is worth noting that the three ground species show a stratified distribution linked to a geo-altitudinal gradient, with *B. socotrana* being potentially more widespread in the alluvial basal areas, *B. elongata* in the upper hill limestone plateau and *B. ameero* in the central mountain areas of the Hagghier characterised by a granitic substratum (Fig. 3a, d, g). Of the cliff species, *B. dioscorides* has the widest potential distribution while *B. popoviana* is more localised and restricted (Fig. 3c, f).

Climate and altitude emerge as the most important environmental variables influencing the distribution of ground species (Table 4), while slope and potential evapotranspiration are more significant for cliff species (*B. dioscorides* and *B. popoviana*). For all the modelled species the contribution of lithological variables appears to be minimal, probably because the spatial resolution of data is too coarse or because of the variables' correlation with altitude.

Population structure

Due to their relatively different growth conditions, ground species have a larger DBH than cliff species (Table 5). Of the latter, *B. nana* and *B. bullata* have the smallest mean DBH because of the very harsh environmental conditions that limit their growth. The shape (γ) and

Table 4 Variable importance predicted by RF for the *Boswellia* spp.

Variable	*B. ameero*	*B. elongata*	*B. socotrana*	*B. dioscorides*	*B. popoviana*
Altitude (m)	100 (1)	76.8 (3)	100 (1)	27.9 (6)	37.4 (4)
Temperature (°C)	80.1 (5)	40.1 (5)	34.9 (6)	17.0 (7)	18.6 (7)
Precipitation (mm)	81.3 (3)	100.0 (1)	88.4 (3)	31.1 (5)	47.1 (3)
Moisture Index	99.7 (2)	93.6 (2)	96.6 (2)	36.0 (4)	32.8 (5)
PET (mm)	79.5 (4)	59.0 (4)	65.4 (4)	79.7 (2)	100 (1)
Slope (°)	66.9 (6)	31.7 (6)	49.1 (5)	100 (1)	96.4 (2)
Limestone	2.0 (8)	12.8 (7)	18.4 (7)	35.6 (3)	20.9 (6)
Alluvial	1.7 (9)	0.9 (8)	7.2 (8)	2.6 (8)	4.7 (8)
Sand	0.0 (10)	0.0 (9)	1.9 (9)	0.0 (10)	0.1 (9)
Granitic	5.3 (7)	0.0 (10)	0.5 (10)	0.5 (9)	0.0 (10)

Table 5 Population structure and regeneration status: descriptive statistics and Weibull distribution function parameters γ (shape) and α (scale) of *Boswellia* sp. stem diameters

Species	Growth form	Mean	S.D.	Min.	Max	γ	α	No. of saplings
B. ameero	Ground	31.4	9.7	8	48	3.6***	34.8***	–
B. elongata	Ground	36.5	10.1	13	75	3.7***	40.3***	–
B. socotrana	Ground	22.6	13.2	1	82	1.7***	25.3***	19
B. bullata	Cliff	6.0	5.3	1	30	1.2**	6.4***	34
B. dioscorides	Cliff	19.8	11.2	1	50	1.7***	21.8***	22
B. nana	Cliff	5.3	4.3	2	15	1.4*	5.9***	–
B. popoviana	Cliff	12.7	9.5	1	48	1.3**	13.6***	18

Asterisks indicate statistically significant parameters, respectively * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$

scale (α) parameters of the Weibull functions are statistically significant at different probability levels (Table 5). In particular, all the cliff species are characterised by a γ of between 1 and 2.6, meaning a right-skewed distribution (Fig. 2b) that indicates a medium regeneration status. Of the ground species only *B. socotrana*, with a γ value of 1.7, shows a medium regeneration status. In turn, the γ values of *B. elongata* and *B. ameero*'s of 3.6 and 3.7 respectively indicate an almost normal distribution (Fig. 2a) that suggests a poor regeneration status.

B. dioscorides had the largest number of saplings, while *B. socotrana* was the only ground species for which small trees and saplings were observed, albeit only in rocky fissures or under the protection of spiny shrubs.

Conservation assessment

All the IUCN RL parameters used to assess the conservation status of *Boswellia* spp. highlight their restricted range and limited number of locations (Table 6). The spatial modelling analysis could not be performed for *B. bullata* and *B. nana* due to the very small number of plots and so only AOO, calculated with a 2 km grid resolution, is reported. Of the other species, two ground ones, *B. socotrana* and *B. ameero*, show respectively the largest and the smallest AOO, EOO and number of locations. It is worth noting that AOO measured considering the suitable area within EOO is always bigger than that measured with the grid method.

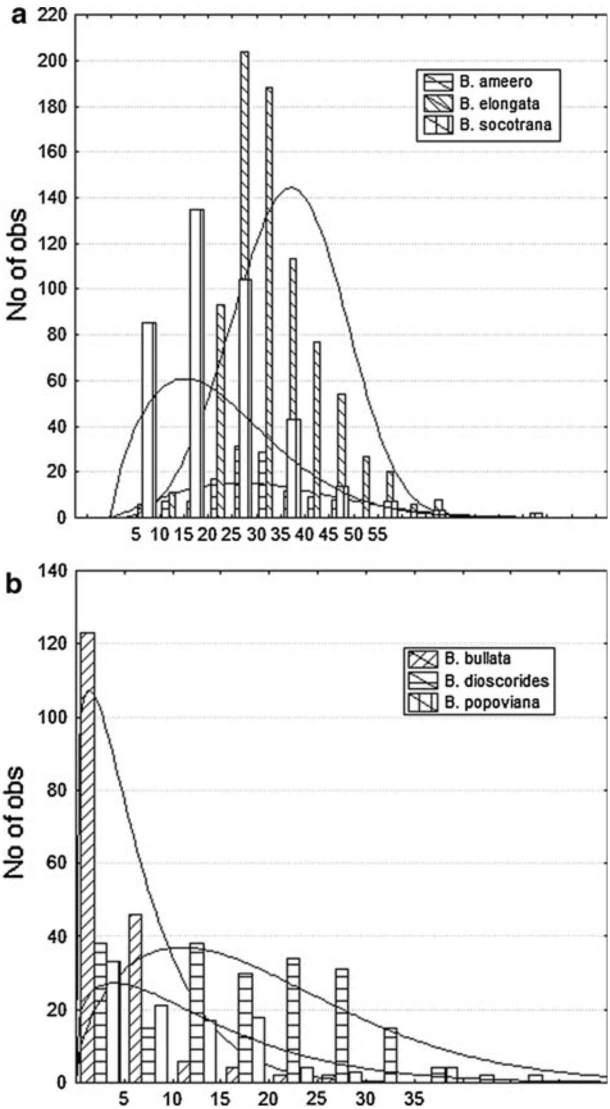

Fig. 2 **a**, **b** Stem diameter distributions of ground-rooted species (**a**) and of cliff-rooted species (**b**). Weibull distribution curves. Data about *B. nana* are not reported due to the small number of samples available

Discussion

Abundance, distribution and population structure

The results of our study indicate that *Boswellia* spp. on Socotra tend to segregate ecologically or geographically in line with the hypothesis of their adaptive radiation origin. In particular, according to the ecological niche spatial analysis, the three ground species show a geo-climatic zonation: *B. socotrana* is potentially more widespread in the basal alluvial areas, *B. elongata* in the hilly limestone plateau and *B. ameero* in the upper granitic

Table 6 *AOO* area of occurrence (km^2) calculated with a 2 km grid resolution, *AOO** area of occurrence considering only the potential area within the extent of occurrence (km^2), *EOO* extent of occurrence measured with the α hull method (km^2), No. of locations estimated with a buffer radius of 1/10th of the maximum sample distance

Species	AOO	AOO* (EOO-HS)	EOO α hull	No. locations
B. ameero	20	32.3	36.7	3
B. elongata	68	328.4	567.8	4
B. socotrana	72	436.2	741.8	5
B. bullata	20	–	–	3
B. dioscorides	40	90.7	406.7	4
B. nana	4	–	–	1
B. popoviana	24	35.3	50.3	3

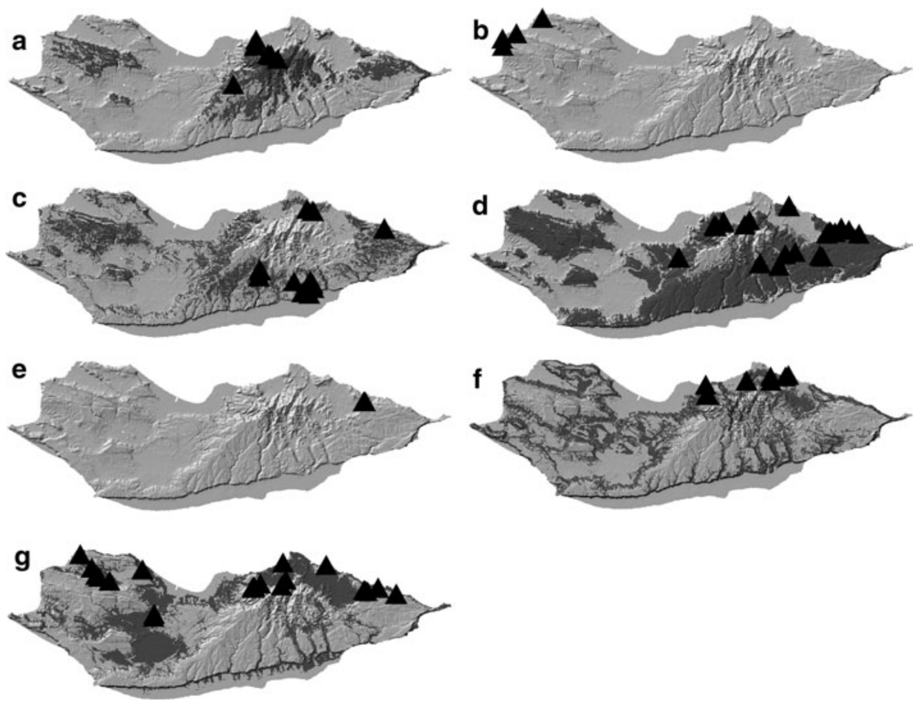

Fig. 3 **a–g** Current potential distribution (*dark grey*) and sample areas of *B. ameero* (**a**), *B. bullata* (**b**), *B. dioscorides* (**c**), *B. elongata* (**d**), *B. nana* (**e**), *B. popoviana* (**f**) and *B. socotrana* (**g**)

Hagghier mountain (Fig. 3a, d, g). In these areas ground species can characterise the landscape, at times forming almost monospecific stands. Soil factors are of no or only minor importance in determining the abundance of *B. socotrana* and *B. elongata*, which generally grow in very flat areas (Table 1), their abundance being negatively influenced by increasing slope (Table 2). *B. ameero*, found mainly in the Hagghier mountain on steeper slopes (Table 1), appears to be influenced by the water retention capacity of soils as indicated by their increasing clay and decreasing sand content (Table 2).

Despite being currently more abundant and widespread, ground species show signs of decline: *B. ameero* and *B. elongata* have a population structure characterised by a poor regeneration status. *B. socotrana* is the only ground species that shows a medium regeneration status with several small trees and saplings recorded, albeit solely in sub-vertical slopes or surrounded by thorny shrubs and thus inaccessible to livestock (Tables 1, 5 and Fig. 2a). This result supports the suggestion that, as for *Boswellia papyrifera* stands in the Horn of Africa (Negussie et al. 2008; Ogbazghi et al. 2006a), grazing is one of the most important human-induced factors affecting the population structure of ground *Boswellia* species of Socotra.

Grazing can have a significantly negative impact on the regeneration of ground species, leading to the removal of whole plants or parts of their vegetative or reproductive structures; in addition, trampling of the soil surface by animals can result in seedling mortality and soil compaction that limits recruitment and seedling establishment. Moreover, seedlings are vulnerable to grazing: being succulent and palatable, they are attractive to grazers and they also grow too slowly to escape them. Grazing by livestock has been taking place on Socotra for thousands of years and it is widespread throughout the island. The traditional semi-nomadic pattern, with livestock populations fluctuating markedly in accordance with periodic droughts, has probably allowed several populations of *Boswellia* ground species to survive by mass regeneration in the aftermath of droughts, when grazing pressure has remained low while rainfall has re-established (Scholte and De Geest 2010). This has also been hypothesised for the dragonblood tree based on the analyses of the fairly homogenous forest stands (Adolt and Pavlis 2004; Attorre et al. 2007a; Habrova et al. 2009). However, road construction and the spread of such practices as purchasing and stocking grain and fodder may lead to a reduction of the spatial and temporal grazing dynamics (Scholte et al. 2008), exacerbating the effects of grazing on the regeneration of ground species.

Land clearing and tapping trees for resin are the other factors that can cause the decline of *Boswellia* species, but they were negligible in Socotra.

Land clearing is the most extreme case as trees are removed from cultivated land, but it does not seem to have ever occurred on Socotra where agricultural activities are very limited and also in decline due to the increased access to food following the opening of the airport in 2001.

Tapping is reported to have a severe impact on the natural regeneration of *B. papyrifera* (Rijkers et al. 2006). In fact the hypothesised competition between the investment of carbohydrates in sexual reproductive structures and the synthesis of frankincense may cause over-exploited trees to produce fewer flowers, fruits and seeds than those that are exempt from tapping. On Socotra frankincense is produced mainly from *B. elongata* and *B. socotrana*, but tapping was observed only in one tree of the latter species. The reduced economic interest in this non-timber forest product has led to the collapse of traditional silvicultural activities; consequently, the harvest of frankincense gum is much less regulated and droplets of resin are collected freely and sold in the local market and to tourists (Miller and Morris 2004).

Of the cliff species, two show a geographical segregation: *B. nana*, which was found only in one location in the eastern Hamaderau mountain with only 23 individuals counted in three plots; and *B. bullata*, which was only recorded in three locations on the western part of the island (Table 6, Fig. 3b). The other two (*B. dioscorides* and *B. popoviana*) are more widespread and share the same habitat, their distribution being mainly limited to limestone cliffs and escarpments and determined by slope and potential evapotranspiration (Fig. 3c, f and Table 4).

All cliff species have a shape parameter (γ) of the Weibull function of between 1 and 2.6 and a clear right-skewed distribution curve and so can be attributed a medium regeneration status (Table 5, Fig. 2b). This result may be explained by the fact that they are able to germinate and grow in rocky fissures in sub-vertical escarpments inaccessible to goats. However, *B. nana* has unusual characteristics, including a limited distribution, a small number of individuals and no saplings, which make it much more vulnerable to extinction.

Conservation assessment and priorities

The assessment of the extinction risk of *Boswellia* spp., based on the IUCN RL criteria (Table 6), suggested to move almost all the species to a higher risk category than that ascribed by the 2004 assessment (Miller 2004). Such a move is justified by greater knowledge rather than a recorded worsening of their conservation status (Table 7). Moreover, from a methodological point of view, our results support the use of the spatial modelling method rather than the grid method for measuring the AOO. In fact, an adequately robust spatial model may provide a better measurement of this parameter as it reflects not only the spatial distribution of the species but also its ecological requirements.

Conservation priorities were then set by analysing all the above information. In particular, *B. nana*, *B. bullata* and *B. ameero* are considered of very high priority for conservation because they are more prone to threats from environmental factors and stochastic events. The first two species are characterised by small populations and very localised distributions, while *B. ameero* has a poor regeneration status, a more specialised environmental niche and the smallest AOO and EOO of the ground species. The two remaining ground species, *B. elongata* and *B. socotrana,* though classified respectively as endangered and vulnerable, are considered only of high priority because they have relatively large populations even though they are strongly affected by grazing. *B. popoviana* and *B. dioscorides* are ranked of medium priority because of their relative abundance, medium regeneration status and comparatively large number of saplings. This corroborates the hypothesis that, in the absence of any effective conservation actions, they are likely to become the most numerous *Boswellia* species on the island.

Table 7 Assessment of the conservation status, priority for conservation and conservation actions for *Boswellia* spp.

Species	Current IUCN RL category	Proposed IUCN RL category	Priority/actions for conservation
B. nana	VU D2	CR D1	Very high/plant nursery, seed bank
B. ameero	VU B2ab(ii, iii)	EN B2ab(v)	Very high/plant nursery, seed bank
B. bullata	VU D2	EN D1	Very high/plant nursery, seed bank
B. elongata	VU B2ab(iii)	EN B2 ab(v)	High/Enclosure programs conservation-trough-use, seed bank
B. popoviana	VU D2	EN D1	Medium/Seed bank
B. dioscorides	VU D2	VU D1	Medium/Seed bank
B. socotrana	VU D2	VU D2	High/Enclosure programs, conservation-trough-use, seed bank

Conservation actions

Specific conservation actions are ascribed to each of the species based on their particular ecological features, environmental context and economic value. These include the establishment and running of a seed bank, a plant nursery, enclosures and conservation-through-use programmes. Some such conservation actions have already been implemented and include carrying out a field study to collect seeds according to internationally agreed standards, growing saplings of all the species from cuttings in a plant nursery and implementing enclosure projects to verify the effect of grazing on the regeneration of *B. elongata*: one of these, implemented in 2008 in the Homil plateau by the GEF-UNDP "Socotra Conservation and Development Programme", resulted in high seed production and germination during the rainy season, but none of the seedlings survived the dry summer monsoon (Nadim Taleb pers. comm.). This outcome, which was probably due to the excessive hardness of the eroded soil, was similar to that of Negussie et al. (2008), who recorded a high seedling mortality even after years of successfully establishing enclosures, and calls for additional types of intervention, from appropriate soil preparation to shading seedlings.

The conservation-through-use option is considered only for *B. elongata* and *B. socotrana,* the two ground species producing a quality of gum that is valued as a potential source of extra income for rural populations (Newton 2008). However, in order to effectively pursue this conservation option several activities need to be undertaken which, given the current limited skills of local agencies and institutions, require the support of the international scientific community. These include tapping and collection trials, chemical analyses of the extracts, application of agroforestry improvement techniques (time of seed collection, nursery practices, choice of appropriate planting sites and post-planting care), value-adding processing practices, international and domestic market analyses (Gebrehiwot et al. 2003).

Moreover, the progressive collapse of the traditional system of land management means that local communities need to be involved in forest protection and management activities; their participation can be ensured by providing incentives, including in the form of ownership/user rights and benefit-sharing mechanisms.

Concluding remarks

The methodological approach developed in the present study specifically addresses analytical difficulties that recur when the scarcity of information hinders the identification of conservation strategies and actions for endemic tree species. This applies particularly when, due to their relatively short duration, field studies aimed at improving the effectiveness of a given conservation action only allow a limited amount of information to be collected for use in a structured way.

Our operational context made it possible to sample all the known areas characterised by endemic *Boswellia* spp. and, therefore, to further knowledge about several important topics including their actual and current potential distribution, regeneration status and the environmental and human-induced factors influencing them. However, even in larger or more inaccessible areas where favourable conditions such as those found on Socotra cannot be met, this approach could be fruitfully applied if supported by a statistically defined sampling procedure.

Moreover, the data and information obtained in this study provide a strong basic framework for further research that can only be carried out at a later stage and with more time available, such as into pollination and dispersal mechanisms, phylogenetic relationship and genetic isolation of the identified populations. By increasing the knowledge of the ecological and biological characteristics of the species, this research could support the further refinement of the conservation strategies and options set out in the present study.

The results of the present study highlight the effectiveness of the method developed particularly when faced with time constraints, and suggest that it can be fruitfully consolidated through application to other endemic tree species and different contexts, particularly when preceded by cost-benefit analyses and factual estimates of the prospects of success versus logistical constraints.

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