Conservation Area Networks for the Indian Region: Systematic Methods and Future Prospects

Sahotra Sarkar[1*], Michael Mayfield[2], Susan Cameron[3], Trevon Fuller[1], and Justin Garson[4]

1.Biodiversity and Biocultural Conservation Laboratory, Section of Integrative Biology, University of Texas at Austin, 1 University Station C0930, Austin, Texas, USA 78712

2.Wello Horld, Inc., 195 Morgan Avenue, Brooklyn, New York, USA 11237

3.Graduate Group in Ecology, Department of Environmental Science and Policy, University of California at Davis, Davis, California, USA 95616

4.Department of Philosophy, University of Texas at Austin, 1 University Station C3500, Austin, Texas, USA 78712

*To whom correspondence should be addressed. E-mail: sarkar@mail.utexas.edu

Conservation Area Networks for the Indian Region: Systematic Methods and Future Prospects

Abstract

A framework for systematic conservation planning for biodiversity is presented with an emphasis on the Indian context. The use of this framework is then illustrated by the analysis of two data sets from the Indian region consisting of environmental and physical parameters that serve as surrogates for biodiversity. The first data set included the entire region while the second was limited to the eastern Himalayas. For different ecoregions, the surrogate sets that were used achieve different levels of representation when they are used to select conservation area networks. Tentative results indicate that these surrogates are successful in selecting most areas known from fieldwork to have high biodiversity content such as the broadleaf and subalpine conifer forests of the Eastern Himalayas. However, areas not known to be high in biodiversity content are also selected such as the coast of the Arabian Sea. Areas selected to satisfy a 10 % target of representation for the complete surrogate set provide representation for 46.03 % of the ecoregions in the entire study area. A disproportionately small number of cells is selected in the Western Ghats, a hotspot of vascular plant endemism. At the same target level, restricted surrogate sets represent 33.33 % of the ecoregions in the entire study area and 46.67 % of the ecoregions in the Eastern Himalayas. Finally, it is pointed out that any more sophisticated use of such systematic methods will require the assembly of Geographical Information Systems (GIS)-based biogeographical data sets on a regional scale.

Keywords: Indian biodiversity; Eastern Himalayas; complementarity; area prioritization; reserve selection; surrogacy.

1. Introduction.

The Indian subcontinent is a region of moderate to very high biodiversity including two of the global hotspots of vascular plant endemism in the Western Ghats and the Eastern Himalayas (Myers et al. 2000). It has also had a long cultural history of biological conservation, going back almost 2 500 years in recorded history. Since independence in 1947, and particularly since 1970, India has been one of the international leaders in setting aside land for biodiversity conservation. In spite of strong local interest, a highly developed scientific infrastructure, and considerable political will for conservation, it is surprising that systematic conservation planning methods from contemporary conservation biology have rarely been used in any Indian context (see, however, Pawar et al. 2007). Our purpose here is to provide a brief introduction to these methods with particular attention to the Indian context, and then apply them to two Indian data sets. However, the data sets we use were generated using publicly available coarse-grained data from the World Wide Web. The only geographical data that are thus available for India are for environmental features. No geographical distributional data for biota were available. Consequently, we could only test the adequacy of using environmental features by assessing what fraction of each ecoregion was selected when these features are used to prioritize places for conservation. However, the surrogates we used have been shown to be effective in other areas (Sarkar et al. 2005; Margules and Sarkar [2007]). Because of these limitations, our results should be regarded as indicative of what can be achieved when adequate data are compiled in appropriate form as part of the ongoing Indian ecoinformatics projects. They should not be used as a guide for policy formulation. In the future, we hope to repeat this analysis with more adequate data sets and provide policy recommendations. However, for one case in peninsular India our results suggest a new program of investigative research.

Section 2 of this paper describes a systematic conservation planning and management framework that has previously been used for conservation planning in many countries including Australia, Canada, Papua New Guinea, and South Africa. (For details, see Margules and Sarkar [2007]; for a historical review, see Justus and Sarkar [2002].) Our discussion is tailored to the Indian context. In Section 3 we describe the data sets, algorithms, and software tools we use. In Section 4 we provide our initial results and discuss their implications in Section 5.

2. Systematic Biodiversity Conservation Planning and Management.

The aim of biodiversity conservation planning is to select conservation area networks (CANs) and to devise methods for their adequate management. A conservation area is defined as an area in which some conservation action is implemented. Such actions include the designation of traditional reserves with human exclusion, but they also include sustainable human use and management. (This is why the term "conservation area" is preferable to the more traditional "reserve.") **Table 1** details the framework for systematic conservation planning and management as an eleven-stage process which is described in detail by Margules and Sarkar (2007; see also Margules and Pressey [2000]). The first stage is the identification of stakeholders for a region and a discussion of process and general goals. The next stage is that of data collection. It is critical that the data be georeferenced and recorded in a Geographical Information System (GIS) model. As part of this stage, the biological entities that are of the most interest for conservation must also be identified. These obviously include species that are at risk and also those that are endemic or rare. The quality of the data must also be assessed. Even though no techniques as yet exist to quantify uncertainties in the data, and how these propagate through the analysis, the best possible assessment of the quality of the data must nevertheless guide how results are interpreted. The last point will be illustrated as we discuss our own results.

The third stage of conservation planning consists of selecting surrogates to represent general biodiversity. In this context, there is an operationally useful distinction between "true" and "estimator" surrogates for biodiversity (Sarkar and Margules 2002; Margules and Sarkar 2007). The former must represent biodiversity in general. However, since general biodiversity has so far proved impossible to define, some convention must be used. Though there are many plausible alternatives, the most common convention has been to regard the set of all species as a true surrogate set (Sarkar 2002). Unfortunately, complete distributions of such comprehensive true surrogate sets are almost always impossible to obtain in practice: consequently, estimator surrogates have to be used. Whereas true surrogates have general biodiversity as their target of representation, estimator surrogates have true surrogates as their target. Estimator surrogates must be landscape features that are easily and accurately quantified and assessed. These surrogates may be sets of species or higher taxa, as well as environmental parameters such as climatic variables and land classes. The question as to whether an estimator surrogate set adequately represents an explicitly specified true surrogate set is an empirical one that must be determined in the field. The extent to which an estimator surrogate set represents a true surrogate set can be evaluated in two ways: (i) estimator surrogate distributions may be used to predict the true surrogate distributions, for instance, through niche modeling; or (ii) results of planning using estimator surrogates may be compared to those obtained using the true surrogates. Method (i) has so far never been successfully implemented for large complements of biota at the landscape scale. However, method (ii) has been used with some success (Ferrier and Watson 1997; Garson et al. 2002a; Sarkar et al. 2007). Typically, a small, suitably randomized, set of sites must be surveyed for both the true and potential estimator surrogates. Places must then be prioritized using both true and estimator surrogate sets (see the discussion of the sixth stage below) and the results compared. The subset of potential estimator surrogates that achieves the closest level of representation of the true surrogate set is the best to use for the entire region for which the full distributions of true surrogates is not known.

At the fourth stage, explicit targets and goals must be established for the conservation area network. Without explicit targets and goals, it would be impossible to assess the success (or failure) of a conservation plan. However setting such targets and goals provides ample scope for controversy. Typically, two types of targets are used: (i) a level of representation for each surrogate within a conservation area network (CAN); or (ii) the area of land that can be put under a conservation plan. A common target of type (i) is to set the level of representation at 100 % for species at risk and 10 % for all other surrogates. A common target of type (ii) is 10 % of the total area of a region, as originally proposed by the World Wide Fund for Nature (WWF) and the International Union for the Conservation of Nature and Natural Resources (IUCN) (Dudley et al. 1996). However, the actual numbers used are not entirely determined by biological criteria. Rather, they represent conventions arrived at by educated intuition. Similarly, while it is generally accepted on ecological grounds that larger conservation areas are better than smaller ones, ecology does not specify how large is good enough. The question of connectivity also remains controversial: while connectivity might help species migrate to find suitable habitat, *etc.*, it may also enable the spread of infectious disease.

At the fifth stage, the performance of existing conservation areas in satisfying the targets and goals of the third must be assessed. This will determine what conservation action (if any) should be taken. Because systematic conservation planning has never been implemented in India, it is unknown whether, and to what extent, the existing network of protected areas adequately represents India's biodiversity. It is only in the southern region (Kerala, southern Karnataka, and Tamil Nadu) that close to 10 % of the land is under some form of protection. However, it is not known whether the areas under protection have been economically selected, that is, selected so as to represent biodiversity maximally in the area of land that has been put under protection.

The sixth stage consists of prioritizing places for conservation action to satisfy the stated targets and goals of the third stage. The result is a potential CAN. This problem corresponds to the traditional problem of reserve network selection. The term "place prioritization" is intentionally being used instead of the more traditional "reserve selection" to emphasize that systematic conservation planning envisions a variety of conservation actions including, but not limited to, the designation of reserves. A wide variety of algorithms and other methods are available for place prioritization (Cabeza and Moilanen 2001). The algorithm used here will be discussed in Section 3. It is designed to construct a CAN as economically as possible, that is with the least number of areas put under management for biodiversity conservation.

However, the current representation of biodiversity in a CAN does not solely ensure its persistence: the level of threat from ecological and anthropogenic factors must also be taken into account. The seventh stage of systematic conservation planning consists of assessing such risks (Gaston et al. 2002). This is often a difficult task, and much more remains uncertain than what is known. Techniques for coping with risk include population and habitat-based viability analysis, as well as threat estimation (Boyce 1992; Boyce et al. 1994). None of these has ever been carried out for any Indian region.

In the eighth stage, areas with poor prognosis for relevant biodiversity features are dropped and place prioritization is repeated excluding these areas. Biodiversity conservation is not the only possible use of land. Competing uses such as agriculture, recreation, or industrial development, place strong socio-economic constraints on environmental policy. The ninth stage consists of attempting to synchronize all these criteria. Many interesting conceptual and practical problems are encountered at this stage, the main one being whether all these criteria can be compounded in one utility function to be maximized (Jannsen 1992; Faith 1995; Sarkar and Garson 2003; Moffett and Sarkar 2005). Systematic conservation planning in India has never reached this stage.

The end of the ninth stage produces a plan for implementation. An attempt at implementation constitutes the tenth stage of the conservation process. If implementation is impossible, as it sometimes is because of the constraints encountered, new plans must be formulated. This requires a return to the sixth stage. Finally, conservation action is not a one-time process. The status of biological entities changes over time. Consequently, the last stage consists of repeating the entire process after a period of time. This period of time may be set in absolute terms (a specified number of years, once again chosen by convention) or determined by keeping track of explicitly specified indicators of the health of a conservation area network. This iterative process is sometimes referred to as adaptive management.

3. Materials and Methods.

3.1. Data Sets.

Our starting point is the map of terrestrial ecoregions of the world produced by the WWF (http://www.worldwildlife.org/ecoregions/; Olson et al. 2001). In **Figure 1**, all of the ecoregions that partly or fully overlap the political map of India are overlaid to produce the region of analysis. The first part of our analysis encompasses the entirety of this region which will be referred to as the “Indian region.” We divided this region into cells at a resolution of 0.1° × 0.1° of longitude and latitude, resulting in 63 954 cells which varied in size from 94.6 -123.6 sq. km. (The variation in area is due to the fact that the distance between lines of longitude decreases away from the equator.) The total area of the region is 6 987 279.29 sq. km. There are 63 ecoregions represented.

As estimator surrogates we used climatic parameters (annual mean temperature, the minimum temperature during the coldest period, the maximum temperature during the hottest period, and precipitation), slope, elevation, aspect, and soil classes. Since we had no access to biogeographical distributional data, the adequacy of our surrogate set was judged on the basis of its ability to select representative fractions of the ecoregions, which are partly defined using coarse-grained biological features. However, this estimator surrogate set has previously been shown to be adequate in representing biota for two widely different data sets from Queensland and Québec (Sarkar et al. 2005).

Elevation data were obtained from the GTOPO30 DEM which is a 30 arc-second DEM available from the United States Geological Survey (USGS) (USGS 1988; http://edcdaac.usgs.gov/gtopo30/gtopo30.html). Slope and aspect layers were created using the Spatial Analyst extension in ArcGIS 8.1 (ESRI 2002) from the DEM as specified in the Hydro 1K elevation derivative database methodology (http://edcdaac.usgs.gov/gtopo30/hydro/index.html) also available from USGS.

The annual precipitation, mean temperature, minimum temperature of the coldest period, and maximum temperature of the coldest period layers were created from the GTOPO30 DEM and the FAOCLIM worldwide agroclimatic database (FAO 2000; http://www.fao.org/sd/2001/EN1102_en.htm) using the ANUSPLIN 4.1 (Hutchinson 2000; http://cres.anu.edu.au/outputs/anusplin.html) and ANUCLIM 5.1 (Houlder et al. 2000; http://cres.anu.edu/outputs/anuclim.html) software packages available from the Centre for Resource and Environmental Studies at the Australian National University. Procedures used for running ANUSPLIN and ANUCLIM were identical to those used in the Australian BioRap analysis (Hutchinson 1991; Hutchinson et al. 1996). In ANUSPLIN, the SELNOT and SplineB programs were used with the same default values as in the BioRap analysis.

Soil classifications for India were obtained from the world soil resources map (http://www.fao.org/sd/eidirect/gis/chap7.htm) created by the Food and Agriculture Organization of the United Nations (FAO 1993). There were only 13 associations of soil types, making this the most coarse-grained (and least satisfactory) of our estimator surrogate sets.

The annual mean temperature data (range: -19° –29° C) and annual precipitation data (range: 15 –7 873 mm) were divided into 10 equal interval classes. The minimum temperature of the coldest period of the year (range: -40° –24°C) and the maximum temperature of the warmest period of the year (range: 0° –45°C) were divided into four equal interval classes. No significance should be attached to the exact number of classes used: the choices used here reflect the intuition that mean temperature matters more for biodiversity than the annual high and low temperatures. However, there is an important reason why equal intervals should be used: this attempts to ensure that biotic features found in rare temperature regimes (for instance, species found in hot desert and cold tundra environments) are adequately represented by a conservation plan.

Slope was divided into five classes based on standard deviations (range: 0° –52° below the horizon). The use of standard deviations reflects an assumption that mid-range slopes are more important for biodiversity than extremes. This assumption is based on the fact that the two biodiversity hotspot regions in the Indian region (the Western Ghats and the Eastern Himalayas) are in mountains that have most of their biota in the mid-range of slope. However, this assumption may introduce an unjustified bias against the plains, which are also important for Indian biodiversity. To guard against this bias, elevation (1 –8752 m) was divided into 25 classes based on quantiles. The use of quantiles gives preference to flatter regions. The soil data were divided into 13 classes based on the 13 soil association types that occur within the region (FAO 1993). Aspect was divided into eight classes based on the cardinal directions (N, NE, E, SE, S, SW, W, NW).

Thus, there were a total of 79 estimator surrogates. We also repeated our analysis without using slope, aspect, and elevation since these were used to calculate the climatic parameters. There were then a total of 41 estimator surrogates in the repeated analysis.

For our second data set, we partitioned the Eastern Himalayas at the finer scale of 0.01° × 00.1° of longitude and latitude to obtain some preliminary indicative results because we plan to do further work on this region. We overlaid the 15 ecoregions that intersected with the Eastern Himalayas and then eliminated non-mountainous terrain using an elevation threshold of 400 m. There were 365 347 cells which varied in area between 1.06 and 1.18 sq. km. The total area of the region was 401 834.03 sq. km.

In the Eastern Himalayas, there are 15 ecoregions. We only used the truncated estimator surrogate set in order to keep the computations tractable. The annual mean temperature data (range: -19° –25°C) and annual precipitation data (395- 7873 mm) were divided into 10 equal interval classes. Minimum temperature of the coldest period of the year (-40° –14°C) and maximum temperature of the warmest period of the year (0° –36°C) were divided into four equal interval classes. Soil data were divided into four classes, corresponding to the four soil association types that occur in the region. Elevation, aspect, and slope data were not included in this analysis. Thus, there were a total of 32 estimator surrogates.

3.2. Algorithms and Software.

All computations were performed using the ResNet Ver. 1.2 software package initialized with rarity (Garson et al. 2002b). This software package implements a CAN selection algorithm fully described by Sarkar et al. (2002). Targets of five % and 10 % of the total distribution of surrogates were used. To initiate the construction of a CAN, the first cell was selected by the presence of the rarest surrogate in the data set. Then the CAN was iteratively augmented by adding cells using rarity again and, if there were ties, breaking them by complementarity. (The complementarity value of a cell is the number of surrogates in it that have not yet achieved their targets.) Remaining ties were broken by a random selection of a cell. Finally, redundant cells were removed. It is well-established that such rarity-complementarity algorithms lead to very economical CANs, that is, those that achieve all the prescribed targets with as few cells as possible (Csuti et al. 1997; Pressey et al. 1997). Such economy is important because the addition of a unit to a CAN imposes costs, including the cost of acquisition and the cost of forgone opportunities (Sarkar et al. 2006).

4. Results.

Figure 2a shows the selected cells for the entire Indian region when all 79 surrogates are used with a target of representation of five %; **Figure 2b** is the result when the target is set at 10 %. 3 223 cells with an area of 353 991.82 sq. km. or 5.07 % of the total area are selected in **Figure 2a**; 6 472 cells with an area of 688 047.22 sq. km. or 10.32 % of the total area in **Figure 2b**. **Table 2** shows the percentage of the area selected for each of the 63 ecoregions. These results permit some assessment of the adequacy of our estimator surrogates. When a target of five % representation of surrogates is used, only 20 out of 63 ecoregions have at least five % of their area selected; at a 10 % surrogate representation, 29 ecoregions achieve a 10 % area representation. With very few exceptions, the areas selected at the 10 % representation augment those selected at the five % representation.

In **Figures 3a**, **b**, the result of using only 41 surrogates is superimposed on those of using all 79 surrogates for five % and 10 % targets for the Indian region. This exercise was motivated by the observation that a very high percentage of cells was selected in the Himalayan region. It is possible that the selection of these cells is an artifact of the fact that these mountain ranges have extremes of slope and elevation. Moreover, slope, aspect, and elevation were used in our calculation of the climatic layers. Thus these three parameters and the climatic parameters are not independent of each other and it is at least intuitively plausible—though it has never been proved—that the best estimator surrogate sets are those that include only independent parameters. In this case, no ecoregion achieves five % area representation with five % surrogate representation. However, 21 ecoregions achieve a 10 % area representation with a target of 10 % surrogate representation. Thus, at least at the five % level, results obtained with the truncated surrogate set should not be used for policy development. However, the results shown in **Figures**

3a, **b** are not qualitatively different from those in **Figures 2a**, **b** though, as expected, with fewer surrogates, less cells are selected. In **Figure 3a**, 2 816 cells with an area of 308 219.26 sq. km. or 4.41 % of the total area are selected; in **Figure 3b**, 5 637 cells with an area of 618 275.36 sq. km. or 8.85 % of the total area.

Figures 4a shows the selected cells for the entire Eastern Himalayas at a 0.1° × 0.1° longitude × latitude scale when 32 surrogates, ignoring slope, aspect, and elevation, are used with a target of representation of five %; **Figure 2b** is the result when the target is set at 10 %. As noted before, the truncated set was used for computational efficiency. It will be shown below that it does not perform as poorly for the Eastern Himalayas as it does for the entire Indian region. This exercise was motivated by the fact that conservation planning in the Indian region takes place at the regional rather than the subcontinental level. The question asked is whether there is a significant loss of economy if targets of (local) representation must be met within the confines of each region. In **Figure 4a**, 17 985 cells with an area of 19 745.31 sq. km. or 4.91 % of the total area are selected; in **Figure 4b**, 35 945 cells with an area of 39 386.67 sq. km. or 9.8 % of the total area. **Table 3** shows the shows the percentage of the area selected for each of the 15 ecoregions.

At both the five % and the 10 % surrogate representation level, seven out of the 15 ecoregions achieved the corresponding level of area representation (five % or 10 %). That the truncated surrogate set performs relatively well for the Eastern Himalayas is probably a result of their being fewer ecoregions present compared to the entire Indian region (15 versus 63). (It is unlikely that this difference in percentage is due to the change in the spatial scale of analysis. In general, surrogates perform better at larger spatial scales [Garson et al. 2002a], and this effect is likely to be enhanced when there are fewer surrogates present.)

5. Discussion.

With the increasing population and *per capita* resource use in India, the near future will see an increase in anthropogenic demands on habitats. Consequently, systematic conservation planning and management is a necessity, not a luxury. However, going beyond the preliminary and incomplete results of this analysis will require the availability of GIS-based biogeographic data on as many taxa and habitat types as possible at regional or larger scales. The creation of such databases must be regarded as one of the highest priorities for biodiversity conservation in India. This will require large-scale collaborative efforts between governmental and non-governmental institutions including those involved in education and environmental advocacy. These efforts must begin with an assessment of what data are available in computerized and non-computerized forms, and also of the data quality. This was the first stage of the framework presented in Section 2. Collaborative biodiversity conservation programs would be beneficial in South Asia because participant countries could work together to solve funding, infrastructure, and training problems (Gupta et al. 2002). International collaborations of this sort have proven fruitful for mangrove conservation in South Asia (Clüsener-Godt 2002; WWF and ICIMOD 2005), bioprospecting for marine natural products (Berlinck et al. 2004), and research in medicinal botany supported by the International Cooperative Biodiversity Group (Lewis 2003). In addition, a larger proportion of the biodiversity content of the Indian region could be surveyed if several countries participate in the conservation planning process (Wikramanayake et al. 2001; CEPF 2005). Collaborative conservation programs will require the establishment of common standards for the representation of data, a problem that is yet to be fully solved anywhere. Until the creation of databases conservation planning in India can only be *ad hoc*, a procedure that is known to be uneconomical (Pressey 1994; Pressey and Cowling 2001). Such *ad hoc* CAN selection often leads to the inclusion of biologically irrelevant areas in CANs, and thus the illegitimate exclusion of human economic and other interests. For obvious political reasons, this is a situation that is best avoided.

With respect to the entire Indian region, the Himalayas are over-represented in our nominal CANs (**Table 2**, **Figures 2a**, **b**). This should come as no surprise because elevation, slope, and aspect were used along with climatic parameters derived using them. This region is known to have high biodiversity content. However the selection of a large number of cells in the coastal region along the Arabian Sea west of India may be entirely an artifact of the data set used. The variation in environmental parameters selected by our analysis does not correspond to known variation in biodiversity content. It is also surprising that relatively few cells in the Western Ghats are selected. We conjecture that while environmental estimator surrogates may adequately capture biological diversity, they do not perform well at capturing endemism which is much more dependent on the biogeographic history of a place. Similarly, the Sunderbans and Nicobar

Island rain forests are not adequately represented. In peninsular India, cells along fronts simultaneously separating soil association types and climatic regimes are also selected. These have generally been ignored in conservation decisions in this region. Our results suggest that these areas should be systematically investigated for their biodiversity content: this is the only case where our results are more than merely illustrative and may have practical use.

For the Eastern Himalayas, the most interesting result is that the selected cells are fairly evenly distributed across most of the Eastern Himalayas. If this result continues to hold when demonstrably adequate surrogate sets are used, and across spatial scales, it will have an important implication for conservation planning for the Eastern Himalayas: conservation planning must pay attention to the entire region, and not only to a small set of large conservation areas. Our results are partially discordant with those obtained by Pawar et al. (2007) who found priority areas to be somewhat more concentrated towards the higher elevation regions of the landscape (rather than the low elevation Brahmaputra valley). However, that study used modeled amphibian and reptile distributions as surrogates and explicitly noted that the results should not be interpreted to identify priority areas for all biota.

Finally, it should again be emphasized that the analysis presented here is intended to be illustrative and not to be used to guide policy. We have shown how many conclusions with implications for conservation planning can be drawn even from limited data so long as those data are represented as a GIS model. However, for such an analysis to have even partial relevance for policy formulation, at the very least, accurate vegetation maps must be included. If, as a first step, such maps were made available, then the adequacy of the surrogates used here could be tested. Vegetation maps can often be created using remotely sensed data (that is, satellite imagery). However, our results do suggest that the fronts separating soil association types and climatic regimes in peninsular India should be systematically investigated for their biodiversity features. We end with the suggestion that the creation of GIS-based vegetation maps for India’s two recognized hotspots of vascular plant endemism, the Western Ghats and the Eastern Himalayas, be made an immediate priority.

Software Availability

The software used for this analysis, ResNet Ver. 1.2, can be freely downloaded from http://uts.cc.utexas.edu/~consbio/Cons/Labframeset.html.

References

Berlinck RGS, E Hajdu, RM da Rocha, JHHL de Oliveira, ILC Hernandez, MHR Seleghim, AC Granato, EVR de Almeida, CV Nunez, G Muricy, S Peixinho, C Pessoa, MO Moraes, BC Cavalcanti, GGF Nascimento, O Thiemann, M Silva, AO Souza, CL Silva and PRR Minarini. 2004. Challenges and rewards of research in marine natural products chemistry in Brazil. *Journal of Natural Products* **67**(3): 510-522

Boyce MS. 1992. Population viability analysis. *Annual Review of Ecology and Systematics* **23**: 481-506

Boyce MS, JS Meyer and L Irwin. 1994. Habitat-based PVA for the Northern Spotted Owl. In: Fletcher DJ and BFJ Manly, (eds), *Statistics in ecology and environmental monitoring*. Dunedin: University of Otago Press, p 63-85

Cabeza M and A Moilanen. 2001. Design of reserve networks and the persistence of biodiversity. *Trends in Ecology and Evolution* **16**(5): 242-248

CEPF [Critical Ecosystem Partnership Fund] 2005. *Ecosystem profile: Indo-Burman hotspot, Eastern Himalayan region*. Washington: WWF US-Asian Program. 97 p

Clüsener-Godt M. 2002. Asia-Pacific cooperation for the sustainable use of renewable natural resources in Biosphere Reserves and similarly managed areas. *Trees-Structure and Function* **16**(2-3): 230-234

Csuti B, S Polasky, PH Williams, RL Pressey, JD Camm, M Kershaw, AR Kiester, B Downs, R Hamilton, M Huso and K Sahr. 1997. A comparison of reserve selection algorithms using data on terrestrial vertebrates in Oregon. *Biological Conservation* **80**(1): 83-97

Dudley N, D Gilmour and J.-P. Jeanrenaud (eds). 1996. *Forests for life: the WWF/ IUCN forest policy book*. Gland: WWF and IUCN. 62 p

Environmental Systems Resource Institute (ESRI). 2002. *ArcMap 8.1*. Redlands, California: ESRI

Faith DP. 1995. Biodiversity and regional sustainability analysis. Lyneham: CSIRO Division of Wildlife and Ecology. 30 p

Ferrier S and G Watson. 1997. An evaluation of the effectiveness of environmental surrogates and modelling techniques in predicting the distribution of biological diversity. Arimidale: Environment Australia. Consultancy report to the Biodiversity Convention and strategy section of the Biodiversity Group, Environment Australia. 184 p

Food and Agriculture Organization of the United Nations (FAO). 1993. World soil resources: an explanatory note on the FAO World Soil Resources Map at 1: 25 000 000 scale. Rome: FAO. World soil resources report no. 66, rev. 1

Food and Agriculture Organization of the United Nations (FAO) Agrometeorology Group. 2000. FAOCLIM 2: a worldwide agroclimatic database. Rome: FAO. Environment and natural resources working paper no. 5.

Garson J, A Aggarwal and S Sarkar. 2002a. Birds as surrogates for biodiversity: an analysis of a data set from southern Québec. *Journal of Biosciences* **27**(S2): 347-360

Garson J, A Aggarwal, and S Sarkar. 2002b. *ResNet ver 1.2 manual*. Austin: University of Texas Biodiversity and Biocultural Conservation Laboratory. 44 p

Gaston KJ, RL Pressey and CR Margules. 2002. Persistence and vulnerability: retaining biodiversity in the landscape and in protected areas. *Journal of Biosciences* **27**(S2): 361-384

Gupta BM, UM Munshi and PK Mishra. 2002. S&T collaboration of India with other South Asian countries. *Current Science* **83**(10): 1201-1209

Houlder D, M Hutchinson, H Nix and J McMahon. 2000. *ANUCLIM user's guide, version 5.1*. Canberra: Centre for Resource and Environmental Studies, Australian National University

Hutchinson MF. 1991. The application of thin plate smoothing splines to continent-wide data assimilation. In: JD Jasper (ed), *Data assimilation systems*. Melbourne: Bureau of Meteorology. Bureau of meteorology research report no. 27. p 104-113

Hutchinson MF. 2000. *ANUSPLIN user's guide, version 4.1*. Canberra: Centre for Resource and Environmental Studies, Australian National University

Hutchinson MF, L Belbin, AO Nicholls, HA Nix, JP McMahon and KD Ord. 1996. *BioRap. Volume two. Spatial modeling tools*. Canberra: The Australian BioRap Consortium. 142 p

Janssen R. 1992. Multiobjective decision support for environmental management. Dordrecht: Kluwer. 248 p

Justus J and S Sarkar. 2002. The principle of complementarity in the design of reserve networks to conserve biodiversity: a preliminary history. *Journal of Biosciences* **27**(S2): 421-435

Lewis WH. 2003. Pharmaceutical discoveries based on ethnomedicinal plants: 1985 to 2000 and beyond. *Economic Botany* **57**(1): 126-134

Margules CR and RL Pressey. 2000. Systematic conservation planning. *Nature* **405**(6783): 242-253

Margules CR and S Sarkar. 2007. *Systematic conservation planning*. Cambridge, UK: Cambridge University Press. 270 p

Moffett A and S Sarkar. 2005. Incorporating multiple criteria into the design of conservation area networks: a minireview with recommendations. *Diversity and Distributions* **12**(2): 125-137

Myers N, RA Mittermeier, CG Mittermeier, GA da Fonseca and J Kent. 2000. Biodiversity hotspots for conservation priorities. *Nature* **403**(6772): 853-858

Olson DM, E Dinerstein, ED Wikramanayake, ND Burgess, GVN Powell, EC Underwood, JA D'Amico, I Itoua, HE Strand, JC Morrison, CJ Loucks, TF Allnutt, TH Ricketts, Y Kura, JF Lamoreux, WW Wettengel, P Hedao and KR Kassem. 2001. Terrestrial ecoregions of the world: a new map of life on Earth. *BioScience* **51**(11): 933-938

Pawar S, MS Koo, C Kelley, MF Ahmed, S Chaudhuri and S Sarkar. 2007. Conservation assessment and prioritization of areas in Northeast India: priorities for amphibians and reptiles. *Biological Conservation* **136**(3): 346-361

Pressey RL. 1994. *Ad hoc* reservations: forward of backward steps in developing representative reserve systems. *Conservation Biology* **8**(3): 662-668

Pressey RL and RM Cowling. 2001. Reserve selection algorithms and the real world. *Conservation Biology* **15**(1): 275-277

Pressey RL, HP Possingham and JR Day. 1997. Effectiveness of alternative heuristic algorithms for approximating minimum requirements for conservation reserves. *Biological Conservation* **80**(2): 207-219

Sarkar S. 2002. Defining "biodiversity": assessing biodiversity. *Monist* **85**(1): 131-155

Sarkar S, A Aggarwal, J Garson, CR Margules and J Zeidler. 2002. Place prioritization for biodiversity content. *Journal of Biosciences* **27**(S2): 339-346

Sarkar S and J Garson. 2003. Multiple criterion synchronization (MCS) for conservation area network design: the use of non-dominated alternative sets. *Conservation and Society* **2**(2): 433-448

Sarkar S, J Justus, T Fuller, C Kelley, J Garson and M Mayfield. 2005. Effectiveness of environmental surrogates for the selection of conservation area networks. *Conservation Biology* **19**(3): 815-825

Sarkar S and CR Margules. 2002. Operationalizing biodiversity for conservation planning. *Journal of Biosciences* **27**(S2): 299-308

Sarkar S, RL Pressey, DP Faith, CR Margules, T Fuller, DM Stoms, A Moffett, KA Wilson, KJ Williams, PH Williams and S Andelman. 2006. Biodiversity conservation planning tools: present status and challenges for the future. *Annual Review of Environment and Resources* **31**: 123-159

United States Geological Survey. 1998. *GTOPO30 Global 30 Arc-second Digital Elevation Model.* Sioux Falls, South Dakota, USA: Center for Earth Resources Observation and Science

WWF and ICIMOD. 2001. Ecoregion-based conservation in the Eastern Himalaya: identifying important areas for biodiversity conservation. Kathmandu: WWF Nepal. 178 p

Table 1

Systematic Conservation Action

1. **Identify stakeholders for the planning region**: • Stakeholders include: (a) those who have decision-making powers; (b) those who will be affected by conservation plans for region; (c) those with expertise about the region and (d) those who may commit resources for conservation plans; • Include both local and global stakeholders; • Ensure transparency in the involvement of all stakeholders from the beginning.
2. **Compile, assess, and refine biodiversity and socio-economic data for the region**: • Compile available geographical distribution data on as many biotic and environmental parameters as possible at every level of organization; • Compile available socio-economic data, including values for alternate uses, resource ownership and infrastructure; • Collect relevant new data to the extent feasible within available time; remote sensing data should be easily accessible; systematic surveys at the level of species (or lower levels) will usually be impossible; • Assess conservation status for biotic entities, for instance, their rarity, endemism, and endangerment; • Assess the reliability of the data, formally and informally; in particular, critically analyze the process of data selection; • When data do not reflect representative samples of the landscape, correct for bias and model distributions.
3. **Select biodiversity surrogates for the region**: • Choose true surrogate sets for biodiversity (representing general "biodiversity") for part of the region; be explicit about criteria used for this choice; • Choose alternate estimator surrogate sets (for representing true surrogate sets in the planning process); • Prioritize sites using true surrogate sets; prioritize sites using as many combinations of estimator surrogate sets as feasible, and compare them;

• Potentially also use other methods of surrogacy analysis to assess estimator-surrogate sets, including measures of spatial congruence between plans formulated using the true and estimator surrogate sets; • Assess which estimator surrogate set is best on the basis of (i) economy and (ii) representation.
4. **Establish conservation targets and goals**: • Set quantitative targets for surrogate coverage; • Set quantitative targets for total network area; • Set quantitative targets for minimum size for population, unit area, *etc*.; • Set design criteria such as shape, size, dispersion, connectivity, alignment, and replication; • Set precise goals for criteria other than biodiversity, including socio-political criteria.
5. **Review the existing conservation area network (CAN)**: • Estimate the extent to which conservation targets and goals are met by the existing set of conservation areas; • Determine the prognosis for the existing CAN; • Refine the first estimate.
6. **Prioritize new areas for potential conservation action**: • Using principles such as complementarity, rarity, and endemism, prioritize areas for their biodiversity content to create a set of potential conservation area networks; • Starting with the existing CAN, repeat the process of prioritization to compare results; • Incorporate socio-political criteria, such as various costs, if desired, using a trade-off analysis; • Incorporate design criteria such as shape, size, dispersion, connectivity, alignment, and replication, if desired, using a trade-off analysis. • Alternatively, carry out last three steps using optimal algorithms.
7. **Assess prognosis for biodiversity within each newly selected area**:

• Assess the likelihood of persistence of all biodiversity surrogates in all selected areas. This may include population viability analysis for as many species using as many models as feasible; • Perform the best feasible habitat-based viability analysis to obtain a general assessment of the prognosis for all species in a potential conservation area; • Assess vulnerability of a potential conservation area from external threats, using techniques such as risk analysis.
8. **Refine networks of areas selected for conservation action**: • Delete the presence of surrogates from potential conservation areas if the viability of that surrogate is not sufficiently high; • Run the prioritization protocol again to prioritize potential conservation areas by biodiversity value; • Incorporate design criteria such as shape, size, dispersion, connectivity, alignment, and replication.
9. **Examine feasibility using multi-criteria analysis**: • Order each set of potential conservation areas by each of the criteria other than those used in Stage 6; • Find all best solutions; discard all other solutions; • Select one of the best solutions.
10. **Implement a conservation plan**: • Decide on most appropriate legal mode of protection for each targeted place; • Decide on most appropriate mode of management for persistence of each targeted surrogate; • If implementation is impossible return to Stage 5; • Decide on a time frame for implementation, depending on available resources.
11. **Periodically reassess the network**: • Set management goals in an appropriate time-frame for each protected area; • Decide on indicators that will show whether goals are met; • Periodically measure these indicators; • Return to Stage 1.

Table 2

Representation of Ecoregions among Selected Cells for the Indian Region

Ecoregion	All Surrogates 5 %	All Surrogates 10 %	Restricted Surrogates 5 %	Restricted Surrogates 10 %
Andaman Islands rain forests	0.00	42.88	0.00	0.00
Baluchistan xeric woodlands	4.26	14.11	0.04	7.76
Brahmaputra Valley semi-evergreen forests	0.39	0.78	0.00	0.20
Central Afghan Mountains xeric woodlands	6.04	15.71	0.03	10.11
Central Deccan Plateau dry deciduous forests	4.70	7.45	0.05	6.06
Central Tibetan Plateau alpine steppe	1.42	3.37	0.02	2.84
Chhota-Nagpur dry deciduous forests	9.10	11.21	0.07	8.83
Chin Hills-Arakan Yoma montane forests	12.20	28.65	0.13	23.68
Deccan thorn scrub forests	4.62	6.36	0.02	11.54
East Afghan montane conifer forests	0.00	0.00	0.00	7.47
East Deccan dry-evergreen forests	0.00	0.00	0.00	0.00
Eastern highlands moist deciduous forests	4.71	12.13	0.04	10.38
Eastern Himalayan alpine shrub and meadows	6.68	9.79	0.07	10.26
Eastern Himalayan broadleaf	14.77	26.69	0.10	28.66

forests				
Eastern Himalayan subalpine conifer forests	24.64	28.34	0.30	37.78
Goadavari-Krishna mangroves	0.00	1.92	0.02	1.92
Himalayan subtropical broadleaf forests	6.12	26.78	0.01	3.20
Himalayan subtropical pine forests	7.37	15.28	0.05	10.20
Hindu Kush alpine meadow	0.00	7.74	0.02	14.04
Indus River Delta-Arabian Sea mangroves	13.76	19.88	0.00	25.85
Indus Valley desert	0.00	0.00	0.00	0.00
Karakoram-West Tibetan Plateau alpine steppe	4.00	14.19	0.05	6.60
Khathiar-Gir dry deciduous forests	2.57	5.59	0.03	10.55
Kuh Rud and Eastern Iran montane woodlands	0.42	10.02	0.00	0.42
Lower Gangetic Plains moist deciduous forests	3.50	5.98	0.04	6.27
Malabar Coast moist forests	1.32	2.33	0.00	0.98
Meghalaya subtropical forests	7.18	17.02	0.05	11.42
Mizoram-Manipur-Kachin rain forests	4.41	11.72	0.01	2.08
Myanamar Coast mangroves	0.00	0.00	0.00	0.00
Myanmar coastal rain forests	5.07	22.79	0.04	8.76
Narmada Valley dry deciduous forests	3.39	8.15	0.04	8.38
Nicobar Islands rain forests	10.01	0.00	0.00	0.00
North Tibetan Plateau-Kunlun Mountains alpine desert	3.69	7.40	0.03	7.39

North Western Ghats moist deciduous forests	5.86	15.09	0.03	7.83
North Western Ghats montane rain forests	14.09	22.59	0.06	16.78
Northeast India-Myanmar pine forests	1.15	3.47	0.00	2.31
Northeastern Himalayan subalpine conifer forests	2.34	5.83	0.02	6.05
Northern dry deciduous forests	0.20	2.76	0.00	0.60
Northern Triangle temperate forests	0.00	0.00	0.03	4.04
Northwestern Himalayan alpine shrub and meadows	9.15	18.19	0.07	17.55
Northwestern thorn scrub forests	3.70	5.83	0.01	5.76
Orissa semi-evergreen forests	3.17	16.89	0.00	4.22
Pamir alpine desert and tundra	3.34	4.86	0.03	4.52
Rann of Kutch seasonal salt marsh	4.51	16.45	0.07	7.39
Registan-North Pakistan sandy desert	4.93	11.13	0.06	10.67
Rock and ice	11.69	23.74	0.12	23.42
South Deccan Plateau dry deciduous forests	0.00	5.44	0.00	5.87
South Iran Nubo-Sindian desert and semi-desert	21.16	32.18	0.24	35.02
South Western Ghats moist deciduous forests	3.08	7.19	0.07	1.03
South Western Ghats montane rain forests	11.04	24.19	0.09	4.22
Sri Lanka dry-zone dry	0.00	3.30	0.00	0.00

evergreen forests				
Sri Lanka lowland rain forests	0.00	9.81	0.03	0.00
Sri Lanka montane rain forests	4.17	12.50	0.21	12.50
Sulaiman Range alpine meadows	0.00	2.58	0.00	1.74
Sundarbans freshwater swamp forests	0.00	0.00	0.00	0.00
Sundarbans mangroves	0.00	0.00	0.00	4.22
Terai-Duar savanna and grasslands	0.00	5.77	0.03	6.14
Thar desert	4.25	6.85	0.03	5.50
Upper Gangetic Plains moist deciduous forests	1.57	1.86	0.00	0.67
Western Himalayan alpine shrub and meadows	11.93	22.04	0.08	22.34
Western Himalayan broadleaf forests	14.85	21.54	0.16	25.00
Western Himalayan subalpine conifer forests	12.56	18.22	0.13	23.03

Table 3

Representation of Ecoregions among Selected Cells for the Eastern Himalayas

Ecoregion	**Restricted Surrogates 5 %**	**Restricted Surrogates 10 %**
Brahmaputra Valley semi-evergreen forests	1.49	10.82
Chin Hills-Arakan Yoma montane forests	4.20	4.59
Eastern Himalayan alpine shrub and meadows	5.00	11.02
Eastern Himalayan broadleaf forests	6.59	15.55
Eastern Himalayan subalpine conifer forests	4.70	6.67
Himalayan subtropical broadleaf forests	8.45	48.99
Himalayan subtropical pine forests	4.50	4.69
Lower Gangetic Plains moist deciduous forests	0.90	70.25
Meghalaya subtropical forests	5.53	10.19
Mizoram-Manipur-Kachin rain forests	3.81	5.40
Northeast India-Myanmar pine forests	5.74	6.74
Northeastern Himalayan subalpine conifer forests	4.84	7.51
Northern Triangle temperate	3.41	8.65

forests		
Rock and ice	2.50	3.66
Terai-Duar savanna and grasslands	6.42	13.30

Figure Captions

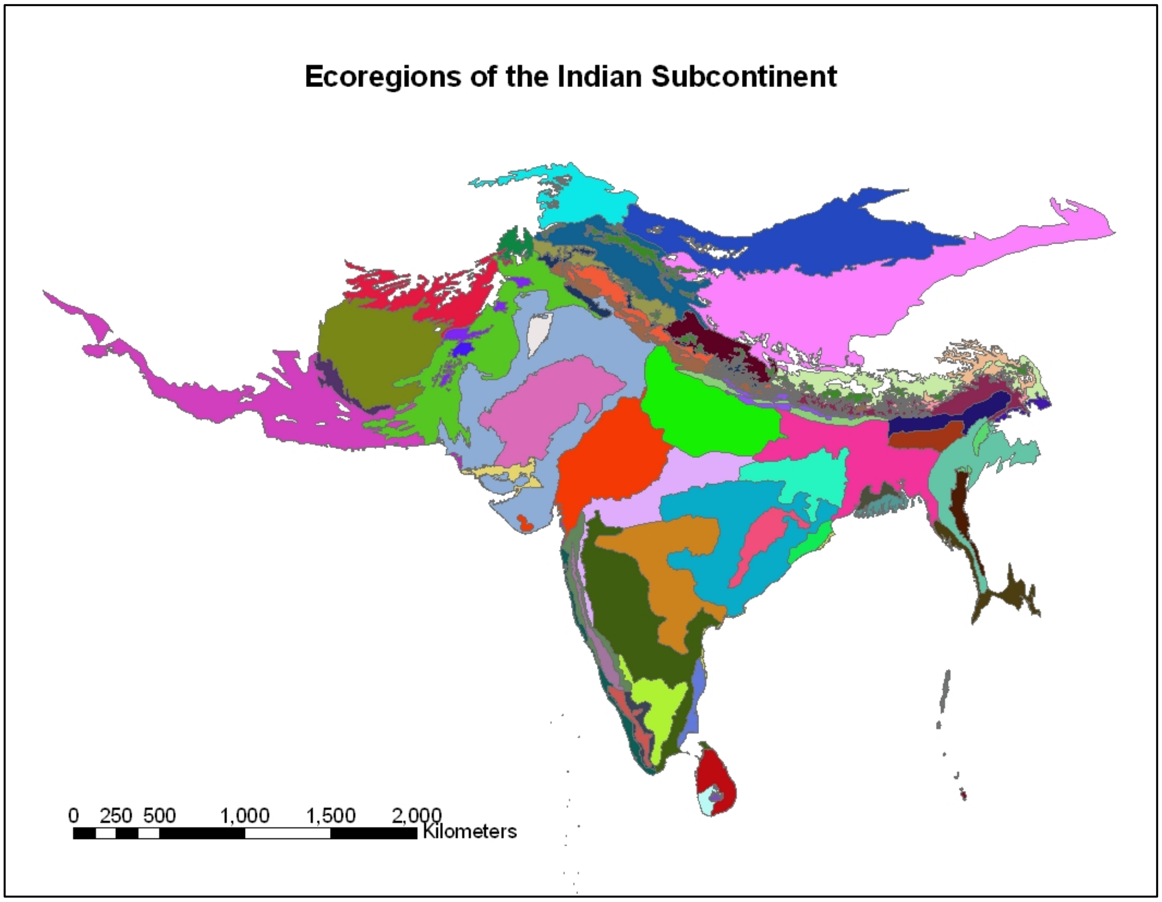
Figure 1. **The Ecoregions of India**. Note that all ecoregions that intersect India are included. Thus the map extends well beyond the political boundaries of India.

Figure 2. **Selected Areas in the Indian Region**: (a) Target of Representation of five %; (b) Target of Representation of 10 %. The selected cells are shown in dark blue.

Figure 3. **Effect of Surrogate Set Composition on Selected Areas**: (a) **Target of Representation of five %**; (b) **Target of Representation of 10%**. When all 79 surrogates are used, the areas selected are shown in light blue. When only the 41 surrogates are used (excluding slope, aspect, and elevation), the selected cells are super-imposed in dark blue. (What appears visible in light blue are the additional cells selected when there are 79 surrogates.)

Figure 4. **Selected Areas in the Eastern Himalayas**: (a) **Target of Representation of five %**; (b) **Target of Representation of 10 %**. The selected cells are shown in dark blue. Inset: Countries bordering the eastern Himalayan ecoregion. The blue box in the inset shows the eastern Himalayas.

Figure 1


Ecoregions of the Indian Subcontinent
0 250 500 1,000 1,500 2,000
Kilometers

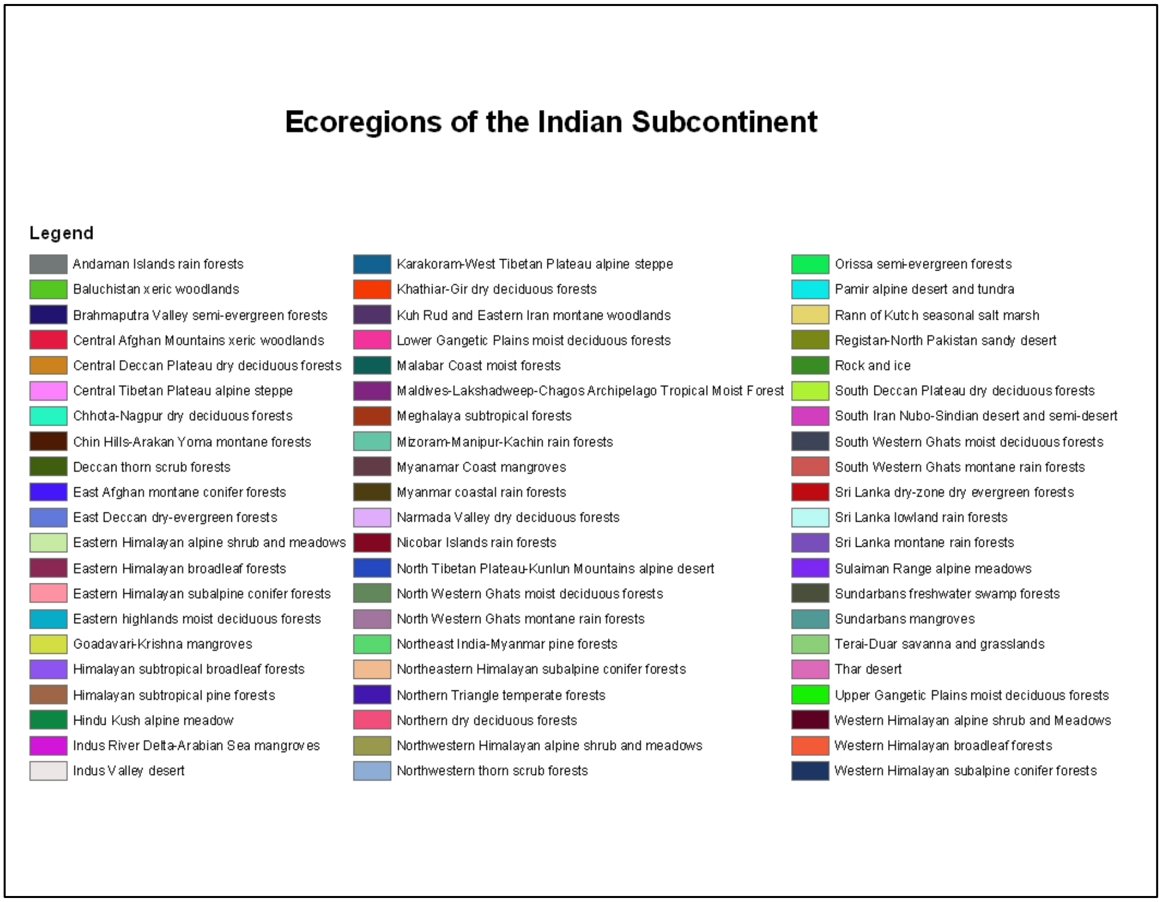

Ecoregions of the Indian Subcontinent
Legend
Andaman Islands rain forests
Baluchistan xeric woodlands
Brahmaputra Valley semi-evergreen forests
Central Afghan Mountains xeric woodlands
Central Deccan Plateau dry deciduous forests
Central Tibetan Plateau alpine steppe
Chhota-Nagpur dry deciduous forests
Chin Hills-Arakan Yoma montane forests
Deccan thorn scrub forests
East Afghan montane conifer forests
East Deccan dry-evergreen forests
Eastern Himalayan alpine shrub and meadows
Eastern Himalayan broadleaf forests
Eastern Himalayan subalpine conifer forests
Eastern highlands moist deciduous forests
Goadavari-Krishna mangroves
Himalayan subtropical broadleaf forests
Himalayan subtropical pine forests
Hindu Kush alpine meadow
Indus River Delta-Arabian Sea mangroves
Indus Valley desert
Karakoram-West Tibetan Plateau alpine steppe
Khathiar-Gir dry deciduous forests
Kuh Rud and Eastern Iran montane woodlands
Lower Gangetic Plains moist deciduous forests
Malabar Coast moist forests
Maldives-Lakshadweep-Chagos Archipelago Tropical Moist Forest
Meghalaya subtropical forests
Mizoram-Manipur-Kachin rain forests
Myanamar Coast mangroves
Myanmar coastal rain forests
Narmada Valley dry deciduous forests
Nicobar Islands rain forests
North Tibetan Plateau-Kunlun Mountains alpine desert
North Western Ghats moist deciduous forests
North Western Ghats montane rain forests
Northeast India-Myanmar pine forests
Northeastern Himalayan subalpine conifer forests
Northern Triangle temperate forests
Northern dry deciduous forests
Northwestern Himalayan alpine shrub and meadows
Northwestern thorn scrub forests
Orissa semi-evergreen forests
Pamir alpine desert and tundra
Rann of Kutch seasonal salt marsh
Registan-North Pakistan sandy desert
Rock and ice
South Deccan Plateau dry deciduous forests
South Iran Nubo-Sindian desert and semi-desert
South Western Ghats moist deciduous forests
South Western Ghats montane rain forests
Sri Lanka dry-zone dry evergreen forests
Sri Lanka lowland rain forests
Sri Lanka montane rain forests
Sulaiman Range alpine meadows
Sundarbans freshwater swamp forests
Sundarbans mangroves
Terai-Duar savanna and grasslands
Thar desert
Upper Gangetic Plains moist deciduous forests
Western Himalayan alpine shrub and Meadows
Western Himalayan broadleaf forests
Western Himalayan subalpine conifer forests

Figure 2a

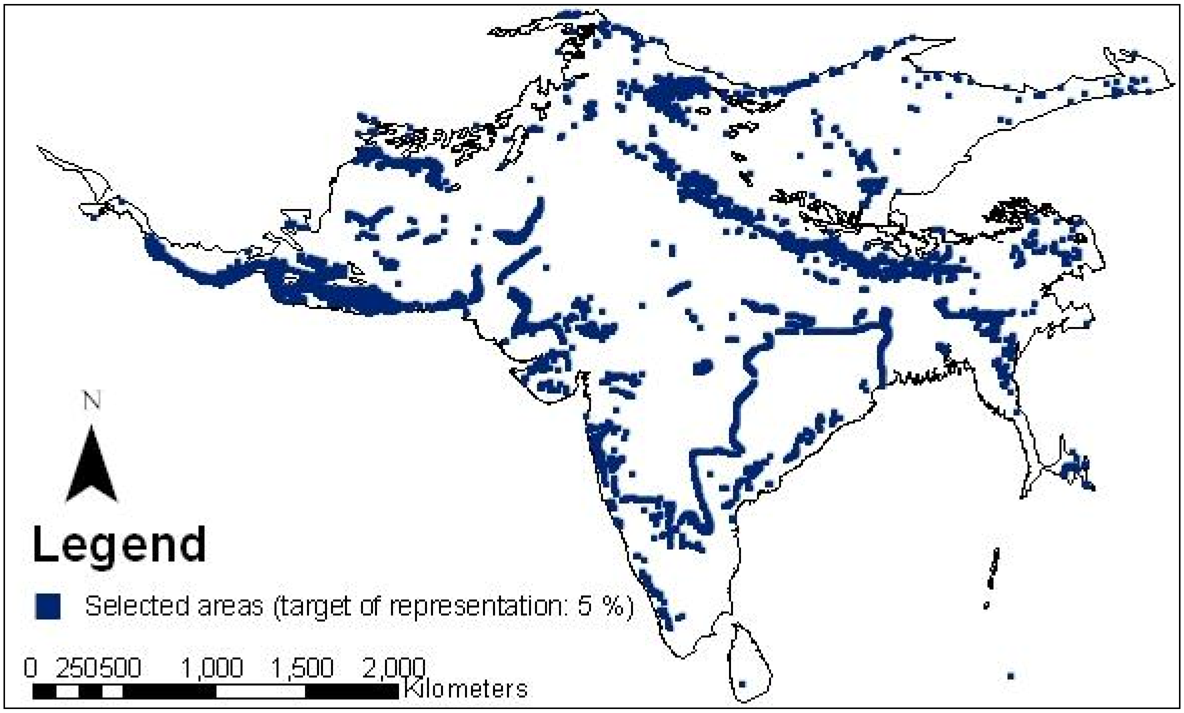

N
Legend
Selected areas (target of representation: 5 %)
0 250500 1,000 1,500 2,000
Kilometers

Figure 2b

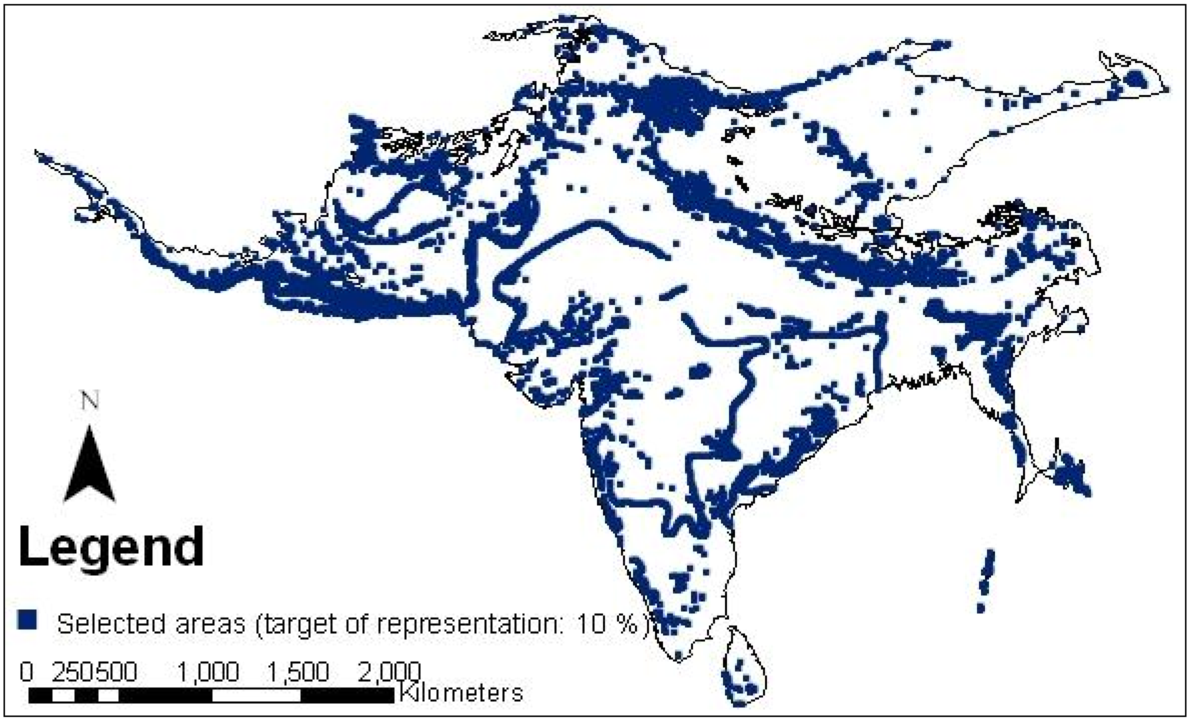

N
Legend
Selected areas (target of representation: 10 %)
0 250500 1,000 1,500 2,000
Kilometers

Figure 3a

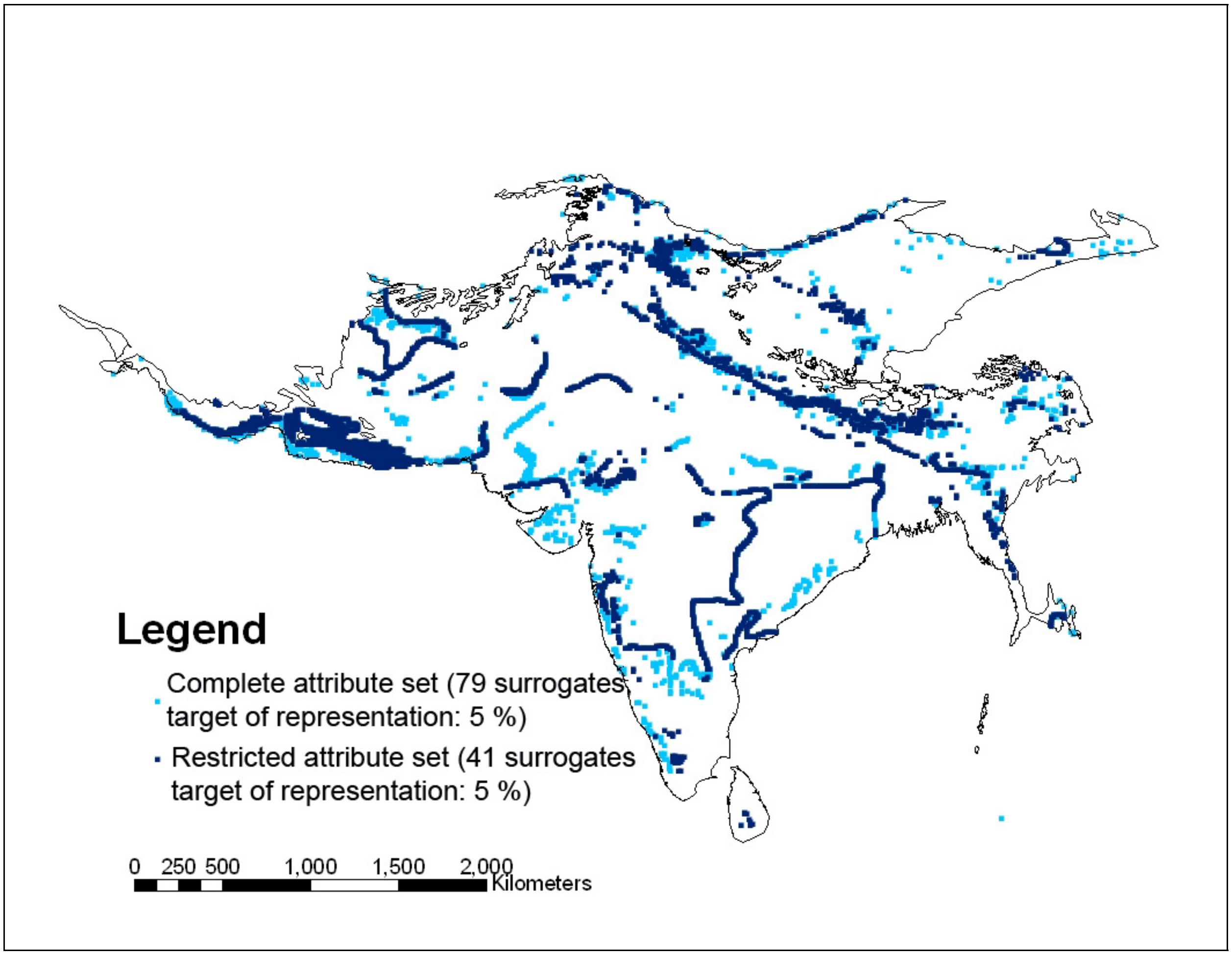

Legend
Complete attribute set (79 surrogates
target of representation: 5 %)
Restricted attribute set (41 surrogates
target of representation: 5 %)
0 250 500 1,000 1,500 2,000
Kilometers

Figure 3b

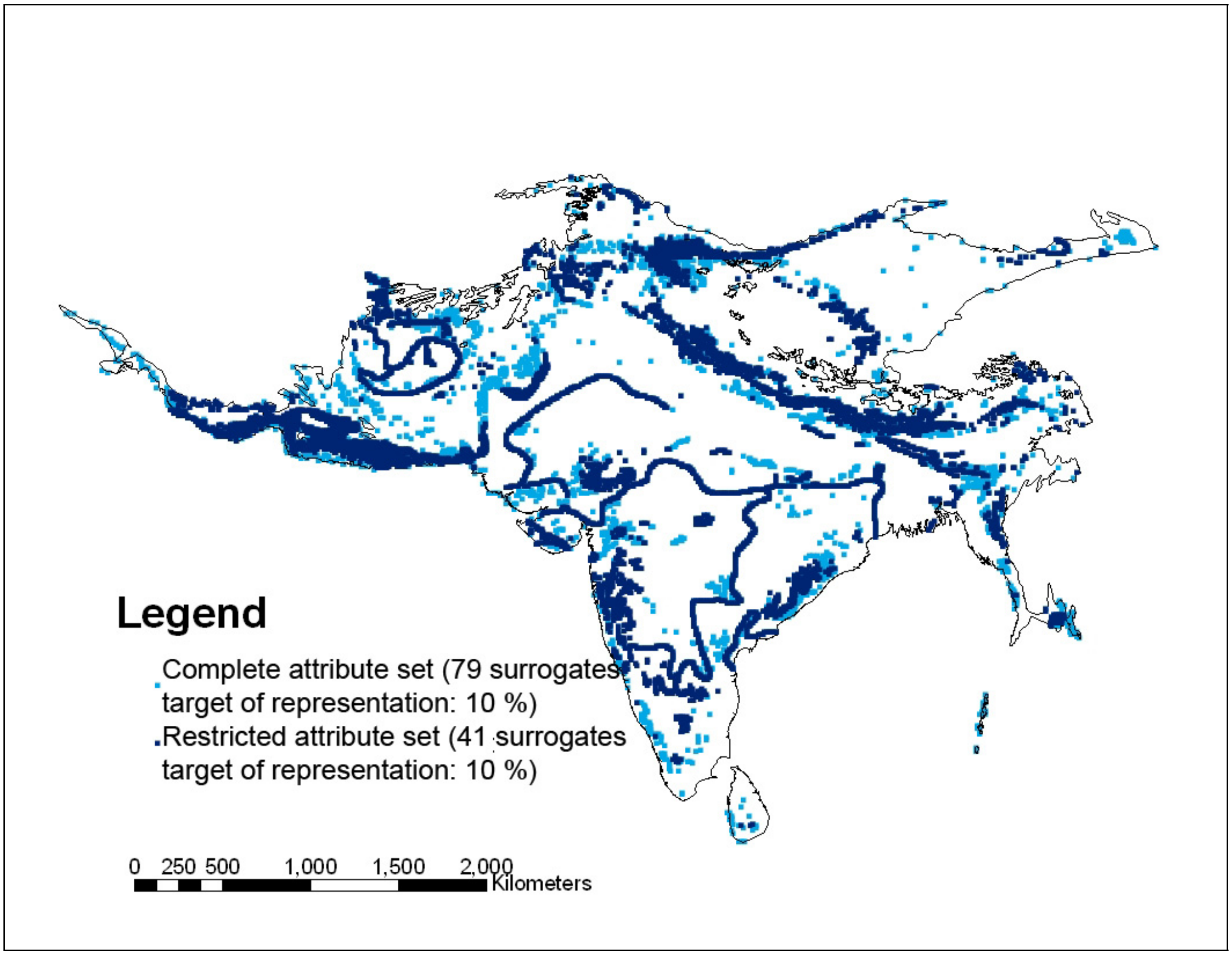

Legend
Complete attribute set (79 surrogates
target of representation: 10 %)
Restricted attribute set (41 surrogates
target of representation: 10 %)
0 250 500 1,000 1,500 2,000
Kilometers

Figure 4a

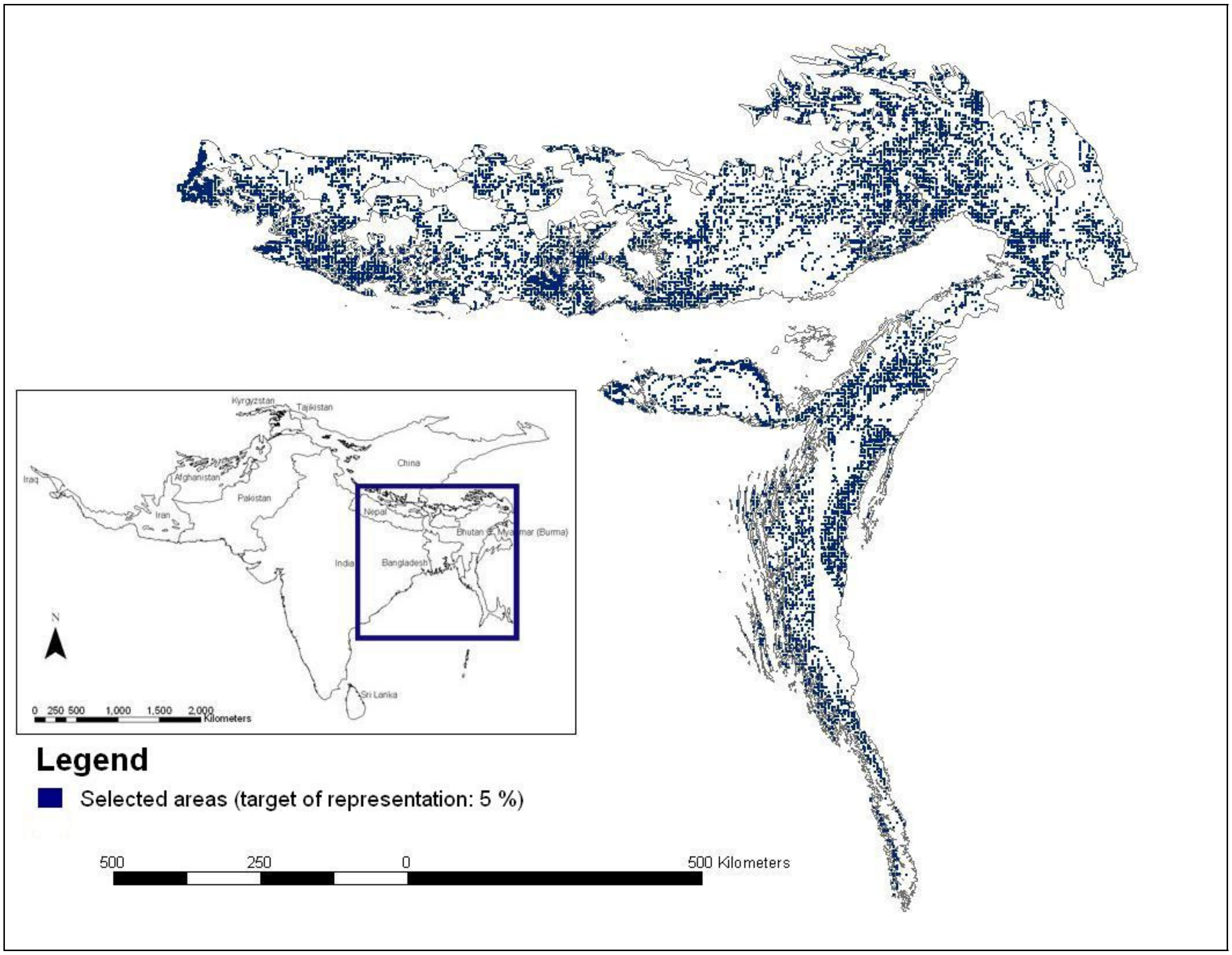
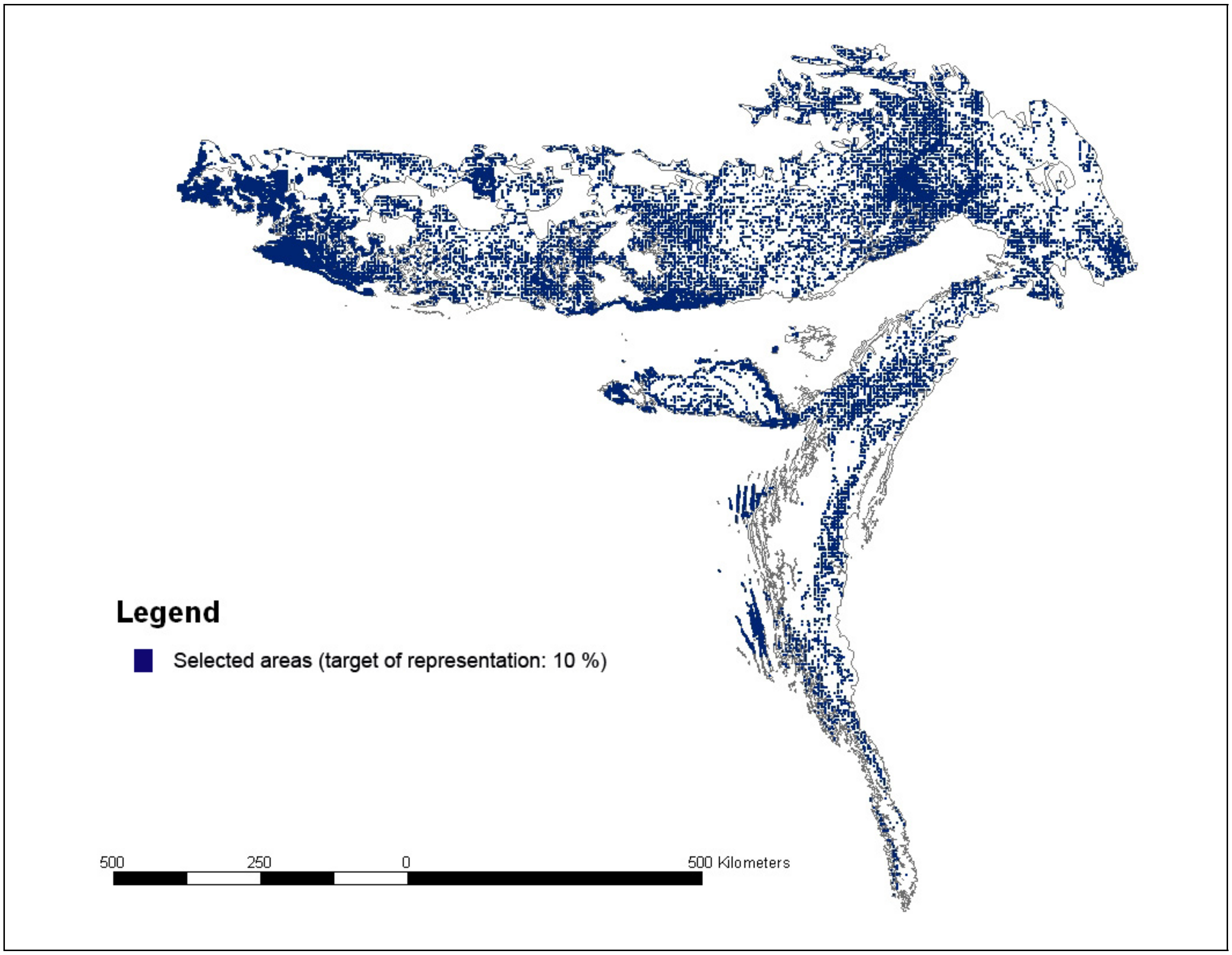

Kyrgyzstan
Tajikistan
China
Iraq
Afghanistan
Pakistan
Iran
Nepal
Bhutan
Myanmar (Burma)
India
Bangladesh
Sri Lanka
N
0 250 500 1,000 1,500 2,000 Kilometers
Legend
Selected areas (target of representation: 5 %)
500 250 0 500 Kilometers

Figure 4b


Legend
Selected areas (target of representation: 10 %)
500
250
0
500 Kilometers