Biodiversity Conservation in an Urbanized Insular Landscape: Identifying Priority Areas for Bird Species in Taiwan

CHRISTOPHER D. KELLEY*, PEI-FEN LEE#, TZUNG-SU DING† and SAHOTRA SARKAR*

The performance of Taiwan's national park system in representing populations of native land-breeding birds was assessed and new priority areas for bird conservation were identified. Ecological niche models based on a maximum entropy algorithm were used to predict species' distributions. Areas were prioritized using a rarity—complementarity based algorithm that required satisfaction of explicit representation targets. The impracticability of selecting urbanized areas was incorporated by masking from selection those areas that contained more than a specified (threshold) percentage of modified land cover. Four modelling parameter sets differentiated by land-use land-cover (LULC) measures were used to model species' distributions. The areas selected using the different modeling parameter sets, varying representation targets for bird species presence, and different modified land cover percentage thresholds were compared to the existing national park system of Taiwan. Standard techniques of systematic conservation planning were adapted for a situation in which biodiversity conservation must take place in an insular, highly urbanized landscape. There were two surprising conclusions: (i) even though urbanization leads to declines in species' ranges, including urbanized areas leads to as spatially economical a representation of species in conservation area networks as not including them; and (ii) using a large array of LULC parameters to model species' distributions also leads to more economical solutions.

Key words: Conservation area networks; Reserve selection; ResNet; Taiwan; Urban biodiversity.

INTRODUCTION

THE main island of Taiwan contains extensive coastal lowlands and a mountainous interior. It is host to a broad array of taxa including many endemic species. The high endemism makes the protection of Taiwan's biodiversity an international priority. The government of Taiwan has established five major national parks on the main island and one on a smaller island, together covering more than 8% of the country's areas, besides several other smaller reserves. Extensive anthropogenic modification, mainly due to rapid urbanization, threatens most species' habitats. A major goal of this study was to examine how well the five national parks represent bird species distributions, besides identifying other priority areas for bird conservation in Taiwan's main island.

Birds were chosen as the focus of this study because they are an important component of biodiversity, and bird records are often relatively complete and reliable. Birds may also sometimes be effective surrogates for other taxa. Garson *et al.* (2002a) found some evidence for this in Québec. However, in general, taxonomic surrogate sets have performed poorly compared to abiotic environmental surrogates and have shown different patterns from other taxonomic sets (Prendergast *et al.* 1993; Lund and Rahbek 2002; Sarkar *et al.* 2005, 2006; Margules and Sarkar 2007). Thus, while this study establishes priorities for birds, the analyses must be extended to other taxa for a comprehensive biodiversity assessment.

When biota are used as biodiversity surrogates, the lack of adequate distribution data is a problem that must be addressed through data treatment (Margules and Sarkar 2007). Ecological niche models, which enable prediction of distributions of species from limited observational data, are being increasingly used to address this problem (Sánchez-Cordero *et al.* 2005). Numerous papers in recent years have discussed the relative costs and benefits of various niche-modelling methods for predicting both species' presences and absences (see Scott *et al.* [2002] and Elith *et al.* [2006] for reviews).

In this study, predicted distributions of breeding bird species across Taiwan were modelled from limited occurrence records and island-wide climatic, topographic, and land-use land-cover (LULC) data, using a maximum entropy algorithm (Phillips *et al.* 2004, 2006). The use of climatic and topographic data as predictor variables in niche models is standard (Peterson *et al.* 2002; Sánchez-Cordero *et al.* 2005; Elith *et al.* 2006). However, extensive anthropogenic transformation of the landscape suggested the development of a new protocol for building models using LULC measures as additional predictive variables (for discussion of previous work, see Margules and Sarkar [2007]).

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This protocol incorporates the likely fact that birds have modified behaviours to survive in urban and semi-urban habitats different from their historical habitats. Different combinations of LULC features were comparatively analysed, allowing an exploration of niche modelling choices for urban planning contexts.

Ecological niche models predict the potential distribution of species (Sóberon and Peterson 2005). To predict the geographical distribution of a species, these distributions must be restricted to realized distributions. This restriction was carried out by excluding areas that had a specified degree of anthropogenic transformation. This choice was also motivated by the extensive urbanization of Taiwan's landscape. The predicted distributions were then used to prioritize areas for conservation using the ResNet software package (Garson *et al.* 2002b; Sarkar *et al.* 2002). Anthropogenic transformation was again incorporated into the analysis in a standard way by excluding from consideration sites with a specified degree of transformation (Fuller *et al.* 2007a, b; Margules and Sarkar 2007). Results were then used to assess the performance of the existing protected areas of Taiwan and identify new possibilities for conservation.

The analysis thus had four objectives: (i) construction of ecological niche models for predicted bird species' distributions for Taiwan; (ii) area prioritization for conservation using these models; (iii) an assessment of the performance of Taiwan's existing protected areas with respect to the representation of bird species; and (iv) the identification of high priority areas for potential inclusion in a conservation area network.

METHODS

Study Area

Taiwan is a Pacific island of approximately 36 000 km² which contains a diverse array of flora and fauna, with identified species including more than 4 200 vascular plants (≥ 1 100 endemic), around 80 species and subspecies of mammal (≥ 40 endemic species and subspecies), 543 bird species (83 endemic species and subspecies), 45 snake species (eight endemic), 31 lizard species (two endemic) and five turtle and tortoise species, 32 amphibian species (nine endemic), over 160 freshwater fish species (≥ 30 endemic species and subspecies), and an estimated 45 000 to 200 000 insect species (Taiwan Endemic Species Research Institute 2008).

The main island of Taiwan contains five national parks: Yangmingshan (11 455 ha), Yushan (105 490 ha), Kenting (18 085 terrestrial ha), Shei-Pa (76 850 ha), and Taroko (92 000 ha) (Figure 1). These five national parks, together with a sixth on a separate island, cover 8.43% of the terrestrial area of Taiwan (Yang and Su 2002).

In recent decades, rapid economic growth and high population density (> 600 persons per km²; Population Reference Bureau 2003) has fuelled rapid urbanization in Taiwan. Land use change has tended towards urban sprawl. Because of the insular nature of the landscape, urban corridors have developed along transportation lines in the coastal lowlands, restricted in part by the island's mountainous interior (CIESIN and CIAT 2004). The extent and distribution of such development in Taiwan poses potential threats to biodiversity in terms of habitat loss and alteration (Koh *et al.* 2006). Continuing development also makes it difficult to design adequate conservation area networks with good long-term prognosis for the persistence of biota.

Data

Land-breeding native bird species data were compiled by Lee *et al.* (2004) from museum records and surveys between 1980 to 2000. Data consisted of 31 616 georeferenced species' occurrence records for 142 species collected from 288 bird census reports (Lee *et al.* 2004). These records occur on a grid of 9 388 sites (each cell or site was 2 × 2 km²) covering the island. Of these 142 species, 95 were included in this analysis. (Appendix lists the 142 species. For species inclusion criteria, see below.)

Environmental data for 19 global climatic parameters, obtained from the WorldClim site (Hijmans *et al.* 2005), quantify various aspects of global seasonal temperature and precipitation variation during 1950–2000. Elevation data were obtained from the GTOPO30 DEM, a 30" digital elevation map (DEM) from the U.S. Geological Survey (USGS 1998). Slope and aspect data were derived from the DEM. (Table 1 lists the layers used for this analysis.) Because the species data had a 2 × 2 km² resolution, the entire analysis used that resolution.

Land and tree cover LULC data, derived from global AVHRR satellite observations (Hansen *et al.* 1998; DeFries *et al.* 2000), were obtained from the University of Maryland's Global Land Cover Facility (GLCF). The land cover data were grouped into 14 interpolated classes representing predicted land type (such as urban area and agricultural land) (Table 2). The tree cover data were grouped into 74 interpolated classes, representing predicted percentage tree cover below 10 %, at percentage points from 10 % to ≥ 80 %, unvegetated, and water (Table 2).

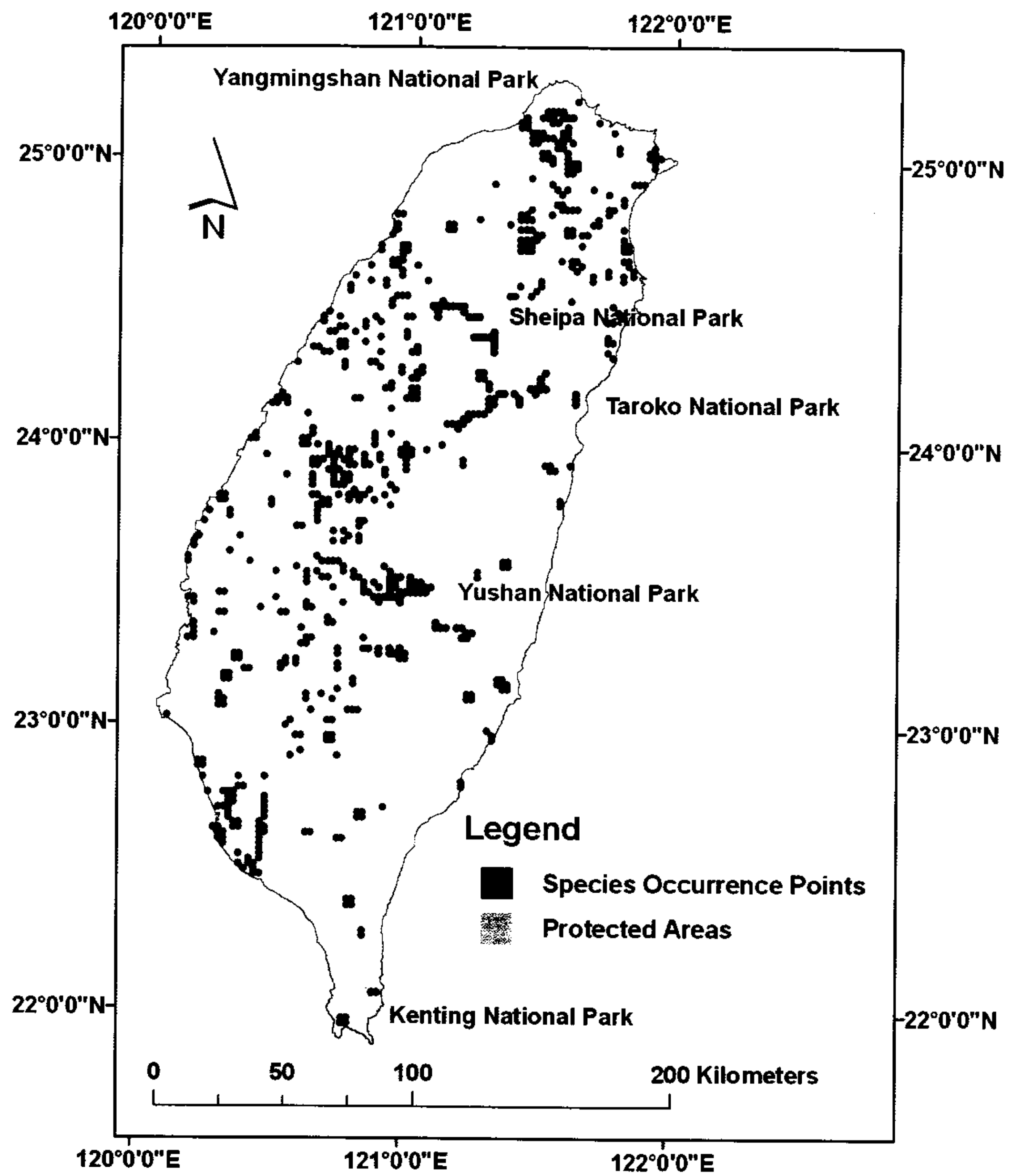


Fig. 1. **Study Area: Taiwan.** This figure is a map of the protected areas and occurrence points of bird species in this analysis.

Maps of Taiwan's national parks (which may be obtained in digital image format from http://econgis.forest.gov.tw/np/index.htm; last accessed 17-03-09) were incorporated as polygon data in UTM Zone 51N coordinates with the Hu Tzu Shan datum.

A critical facet of this analysis was to incorporate fully the effects of extensive anthropogenic transformation of Taiwan's landscape, mainly through urbanization. Lee *et al.* (2004) and Koh *et al.* (2006) reported that road density and human population density both correlate negatively with bird species richness. Here, built areas were progressively masked from the analysis when species' fundamental niches were restricted to their presumed realized niches. This provides a preliminary measure of the effect on conservation of increasing urbanization, as measured by the change in conservation cost incurred when urbanized sites are excluded from nominal conservation areas. Data on existing built areas included polygon and polyline data of developed land and thoroughfares (local and inter-regional roads and railways). These data were developed by the Ministry of the Interior as a 1:25 000 map in 2000 in UTM Zone 51N coordinates with the Hu Tzu Shan datum.

Table 1. **WorldClim Environmental Data Set Layers Used in the Maxent Niche Models.**

Code (for Climate Layers)	Content
1	Annual Mean Temperature
2	Mean Diurnal Range (Mean of monthly (max temp-min temp))
3	Isothermality (Layer 2/Layer 7)*(100)
4	Temperature Seasonality (standard deviation *100)
5	Max Temperature of Warmest Month
6	Min Temperature of Coldest Month
7	Temperature Annual Range (Layer 5 — Layer 6)
8	Mean Temperature of Wettest Quarter
9	Mean Temperature of Driest Quarter
10	Mean Temperature of Warmest Quarter
11	Mean Temperature of Coldest Quarter
12	Annual Precipitation
13	Precipitation of Wettest Month
14	Precipitation of Driest Month
15	Precipitation Seasonality (Coefficient of Variation)
16	Precipitation of Wettest Quarter
17	Precipitation of Driest Quarter
18	Precipitation of Warmest Quarter
19	Precipitation of Coldest Quarter
	Elevation
	Slope
	Aspect

Table 2. **Land and Tree Cover Classes Used in the Maxent Niche Models.**

	Land Cover
1	Water
2	Needleleaf Evergreen Forest
3	Broadleaf Evergreen Forest
4	Needleleaf Deciduous Forest
5	Broadleaf Deciduous Forest
6	Mixed Forest
7	Woodland
8	Wooded Grassland
9	Closed shrublands
10	Open shrublands
11	Grassland
12	Cropland
13	Bare Ground
14	Urban and built up
	Tree Cover
1	Water
2–72	10%–80% tree cover (each percentage is a unique class)
73	Non-vegetated
74	Tree cover is less than 10% of land

Maximum Entropy Niche Models

Predicted bird species' potential distributions for the island of Taiwan were produced using a maximum entropy—based algorithm implemented in the Maxent software package (Phillips *et al.* 2004, 2006). Given a set of occurrence records and environmental variables distributed over geographical space, Maxent estimates a potential distribution by finding the maximum entropy distribution subject to the constraint that the expectation of each "feature" (which is a variable or derived from a variable) under the estimated distribution matches its observed average over sample locations. The resulting model is a relative probability distribution for the presence of a species over all sites in the chosen geographical space which sums to 1 over the landscape. A high value at a site predicts that it has suitable environmental conditions for a taxon. The relative probabilities computed by Maxent were converted to absolute probabilities through normalization by dividing each relative probability by the highest relative probability in the modelled distribution. The normalization assumes that a species is at least present at a site with the highest predicted relative probability. Maxent has been shown to be robust for modelling presence—only occurrence data, outperforming many other techniques (Elith *et al.* 2006).

Environmental data parameter sets were prepared for use with Maxent by projecting (to UTM Zone 51N), georeferencing (to correct for false easting in the biological data coordinates), and resampling data points (to a 2 × 2 km^2 resolution). While environmental data are often correlated, theoretical considerations of algorithm design (Phillips *et al.* 2004, 2006) and extensive tests (Elith *et al.* 2006) have shown that Maxent results remain predictively reliable even when a large number of environmental layers are used, including correlated ones (see, also, Margules and Sarkar [2007]).

The set of sites lacking attribute information for one or more of the data sets described above was then removed from the analysis, restricting the analysis to 8 795 of the original 9 388 sites. Maxent run parameters and result evaluation procedures were those recommended by Pawar *et al.* (2007), with the exception that the maximum number of iterations per run was set to 500 (the default value). Two species were removed from the analysis prior to modelling because they had too few sample occurrences (2 and 3 points, respectively). Modelled distributions of the 140 remaining species were screened for performance relative to random selection, using the threshold-dependent and threshold-independent binomial model validation tests provided within Maxent (Phillips *et al.* 2006).

Land-Use Land-Cover (LULC) Parameter Sets

Models were constructed using different environmental parameter sets as input to investigate the possible effects of using different LULC measures in extensively anthropogenically transformed landscapes. This is important because the ecological salience of different LULC measures remains poorly characterized. Four separate sets of modelled distributions were produced using the compiled point occurrence records and four sets of the environmental data parameters. These sets (each with a shorthand reference used in the remainder of the paper) are: (i) WorldClim, elevation, slope, and aspect layers ("W"); (ii) the layers in "W" and the GLCF land cover layer ("WL"); (iii) the layers in "W" and the GLCF percent tree cover layer ("WT"); (iv) the layers in "W", the GLCF percent tree cover layer, and the GLCF land cover layer ("WTL").

In "natural" landscapes W is typically taken to be the canonical set to be used for niche modelling. However, when study areas are extensively anthropogenically transformed, many species adapt to the changed ecological conditions. The WL, WT, and WTL parameter sets were analysed in an attempt to determine the extent to which the results of planning exercises would be affected by such changes. While the additional data beyond W are explicitly only land cover parameters, since land cover patterns, especially in urbanizing landscapes, are the result of land use changes, these are more appropriately thought of as general LULC parameters.

Area Prioritization

Area prioritization used a rarity- and complementarity—based algorithm incorporated in the ResNet software package (Garson *et al.* 2002b; Sarkar *et al.* 2002). This algorithm attempts to achieve a targeted representation of surrogates such as species in a conservation area network with as few selected sites as possible. It selects an initial set of sites either because they comprise an existing protected area, or *ab initio*, because of the rarity or richness of species at a site. Subsequent sites are selected iteratively on the basis of the rarity of species in them which have not yet achieved their targets. Ties between sites are broken using complementarity, that is, the expected total presence of species that have not yet met their targets. Remaining ties are broken by random selection. Some sites selected during the algorithm's execution may become redundant because of sites selected subsequently. The algorithm removes such sites from selection.

Masking Sites

ResNet input files were created from the four normalized Maxent output files after the predicted fundamental niche models were refined to realized niche models that take into account Taiwan's extensive urbanization. Refinement consisted of the progressive removal of sites that contained built area totaling ≥ 100, 50, 25, 10, 5, 1, and > 0 %. This removed 0, 53, 146, 465, 981, 2 229, and 3 585 sites, respectively.

Finally, representation targets of 10, 20, and 30 percent of the modelled potential distributions (before site exclusion) were set for each of the species. ResNet analyses were performed for each input file with each representation target and with the removal of each built area masking set. Each analysis was initialized in turn by rarity and by all existing protected areas. ResNet produced 168 separate maps of selected sites.

Spatial Analysis

The Hamming distance between two solutions is defined for two sets A and B as $(|A \cup B| - |A \cap B|) / (|A| + |B|)$, and is a measure of how different two sets are. This measure varies from 0 (completely co-extensive) to 1 (completely disjoint). For each combination of target, masking, initialization, and redundancy, the Hamming distance between each pair of modeling parameter sets was calculated. This parameter gives an indication of the extent to which different solutions coincided with each other.

RESULTS

Niche Models

Of the 140 modelled species' distributions, 95 (see Appendix) met the statistical significance criteria of Pawar *et al.* (2007) for each of the four environmental parameter modeling sets (AUC ≥ 0.75; $p \leq 0.05$ for at least one binomial test), and only these were used for the remainder of this analysis.

Table 3. **Selected Areas** Number of sites selected with initialization by rarity (left of comma) and protected areas (right of comma). W – WorldClim, elevation, slope, and aspect layers; WL – the layers in "W" and the GLCF land cover layer; WT – the layers in "W" and the GLCF percent tree cover layer; WTL the layers in "W", the GLCF percent tree cover layer, and the GLCF land cover layer.

Built Area Threshold	Target Percentage	W	WL	WT	WTL
100	10	768, 1196	647, 1046	660, 1052	616, 1015
100	20	1598, 1849	1420, 1659	1426, 1619	1401, 1608
100	30	2416, 2573	2228, 2421	2227, 2360	2232, 2375
50	10	766, 1194	654, 1051	660, 1051	612, 1014
50	20	1592, 1845	1422, 1656	1431, 1616	1399, 1605
50	30	2416, 2571	2229, 2422	2228, 2361	2229, 2376
25	10	762, 1193	652, 1054	659, 1051	620, 1010
25	20	1594, 1843	1413, 1655	1433, 1610	1395, 1603
25	30	2418, 2569	2236, 2421	2230, 2363	2231, 2379
10	10	770, 1191	652, 1056	653, 1055	621, 1021
10	20	1583, 1840	1424, 1662	1443, 1613	1396, 1600
10	30	2392, 2542	2242, 2438	2263, 2380	2236, 2385
5	10	733, 1166	656, 1065	661, 1064	627, 1036
5	20	1526, 1778	1427, 1678	1443, 1630	1419, 1628
5	30	2336, 2499	2271, 2446	2283, 2408	2266, 2425
1	10	737, 1163	699, 1116	700, 1114	669, 1081
1	20	1787, 2076	1557, 1769	1559, 1766	1526, 1725
1	30	6566*, 6566*	6566*, 6566*	2544, 2713	2570, 2720
>0	10	3384, 3488	2752, 2822	2916, 3000	2648, 2712
>0	20	5120*, 5120*	5120*, 5120*	5120*, 5112	5120*, 5120*
>0	30	5120*, 5120*	5120*, 5120*	5120*, 5120*	5120*, 5120*

*Targets could not be met due to built area masking level (see the text for detail).

each species in the study area to meet all representation targets. This means that adequate bird conservation plans can be created while restricting inclusion to sites with < 5% built cover.

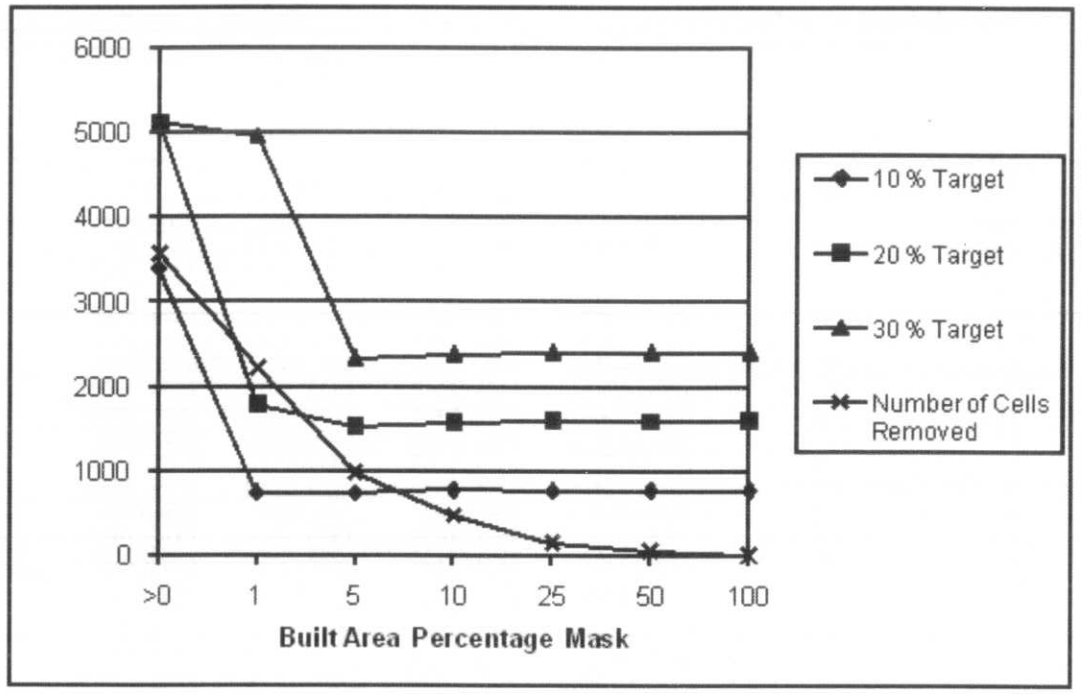
Area Prioritization and Spatial Analysis

ResNet runs were initialized either by choosing the site with the rarest surrogates, or by selecting all existing protected areas. In all cases, initializing with the existing protected areas led to less economical solutions (that is, ones with more selected sites) than initialization with rarity (Table 3). This means that the examined protected areas are not effective for the representation of bird species, a point that will be further discussed below. Removal of redundant sites from solutions initialized by rarity and by protected areas decreased the total area of selected sites on average by 0.6% and 0.7%, respectively. The cardinality of a ResNet solution for a given target varied several-fold depending on the built area threshold mask used to remove sites from the selection process.

Conservation of all bird species at a representation target of ≥ 20% is impossible if only sites with < 1% built area are considered for conservation. Specifically, when including only sites with < 1% built area, 0, 1, and 4 species will fail to meet representation targets of 10%, 20%, and 30%, respectively. When including only sites containing no built area, these figures grow to 7, 16, and 28 species, respectively. For all other built area masks examined, there remain sufficient habitat for

With each area selection, ResNet explicitly tracks the progress of a solution towards representation of given biodiversity surrogates at stated target levels. Thus, using ResNet one can deduce the marginal contribution towards representation targets contributed by selecting existing protected areas. In all cases examined, the set of protected area sites of the existing national parks contributed to some extent towards representation of all 95 bird species. The number of species represented at or above target levels within the national parks was nearly uniform for all modelling parameter sets at each species representation target: across modelling parameter sets, 41.6% to 47.18% of species met 10% representation targets, 23.2% to 24.7% of species met 20% representation targets, and 10.6 % to 11.3% of species met 30% representation targets, within national parks alone. For a given built area mask, representation target, and method of site selection initialization, the area selected generally increased with modeling parameter sets in the following manner: "W" > "WL" > "WT" > "WTL". This means that increasing the number of LULC parameters led to greater spatial economy in the selected conservation area networks. For a given modelling parameter set, built area mask, and method of initialization, the total area of selected sites monotonically increased with the representation target used as expected.

A)



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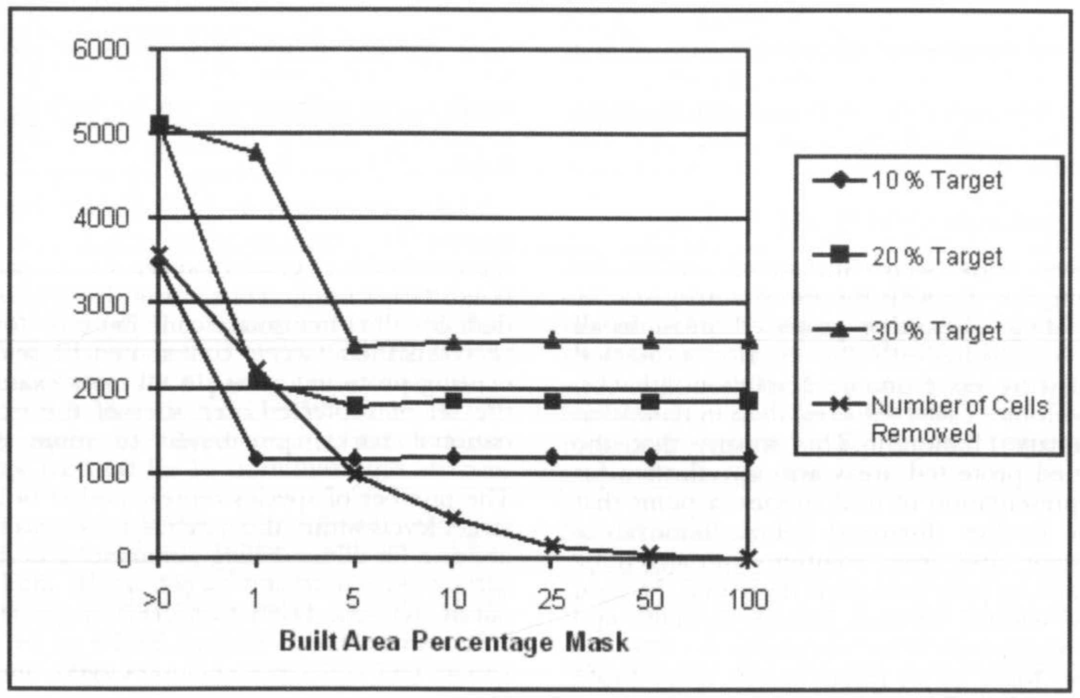
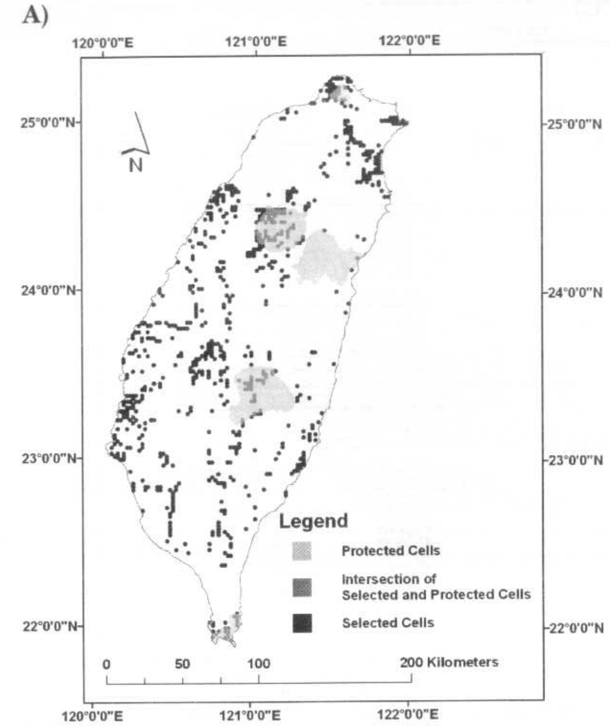


Fig. 2. **Mask Threshold and Selected Area from the W Data Set**. This figure depicts the relationship between masking threshold and total selected area. This graph shows the number of selected sites (y-axis) needed to meet 10, 20, and 30 % species representation targets as the built area percentage threshold (x-axis) removes more sites from the analysis. Species probabilities for the sites represented in this figure were modelled from the "W" environmental parameter set. **a**—ResNet was initialized by rarity.; **b**—ResNet was initialized by the protected areas.

In Figure 2, which shows the relation between the built area masking threshold and total selected area for the "W" model, masking built areas neither tracked nor substantially changed the total area of selected sites at or above the 5% threshold (largest change: 4.3% increase; average maximum change within one masking set: 2.2% increase). At a 1% built area mask threshold, the total selected area increased drastically for the 30 % representation target, compared to a built area mask threshold of 5% or higher. At a > 0% built area mask threshold, the total selected area increased drastically for all input sets at all representation targets compared to a built area mask threshold of 5% or higher. This means that, if these results are used to guide policy discussion, it makes sense to exclude all sites that have more than 5% anthropogenic transformation since including them does not increase spatial economy but may reult in the selection of conservation sites which are anthropogenically so transformed as to be inimical to species' persistence. In particular, this means that all urban areas can be excluded from selection with no loss of economy since they will all have more than 5% transformation.

A)



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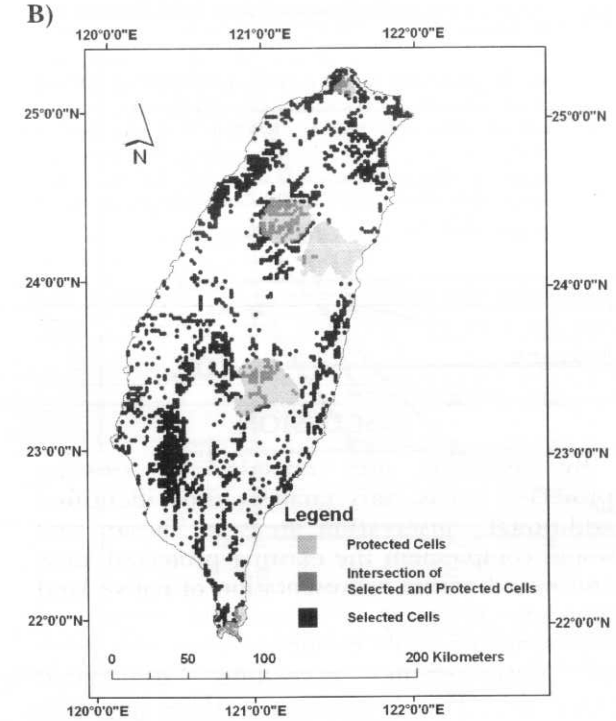

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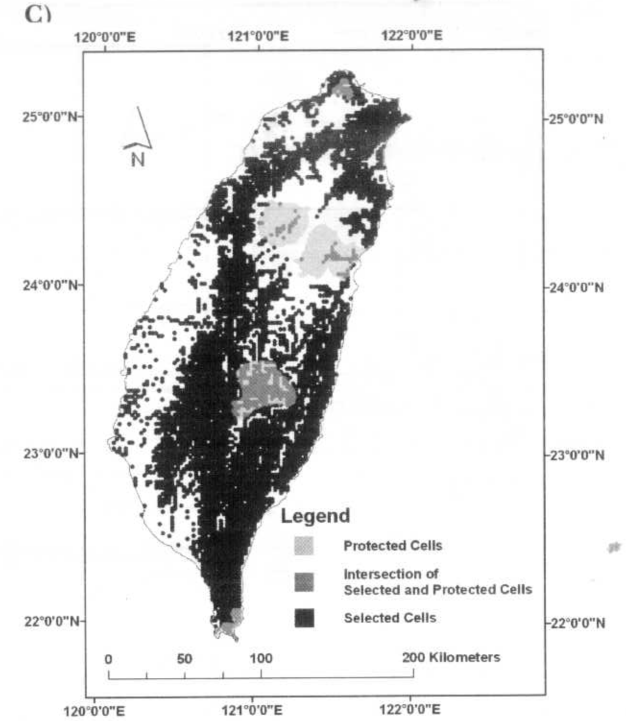
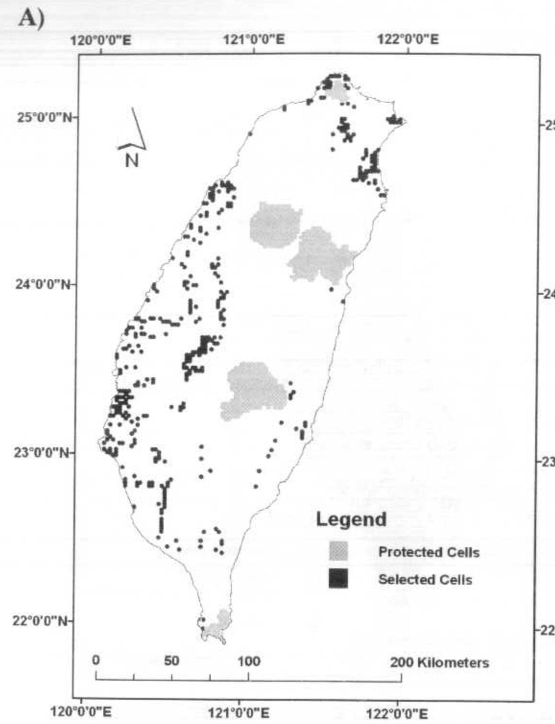


Fig. 3. **Priority Sites with Rarity Initialization and W Parameter Set**. This is a map of sites selected by ResNet from the "W" dataset. ResNet was initialized by rarity. A built area mask of 1% was used. The set of sites within protected areas, and the set of sites selected by ResNet that are within protected areas, are each separately indicated on the map. **a**—Representation target of 10% ; **b**—Representation target of 20%; **c**—Representation target of 30%.

With a 1% mask (Figures 3 and 4), more area is needed but the prognosis for species' persistence is better; these two figures show the geographic locations of the sets of sites selected to represent all 95 bird species using representation targets of 10%, 20%, and 30% of species representation and a 1 % built area mask. In Figure 3 the runs were initialized using rarity; in Figure 4, existing protected areas were used for initialization. Hamming distance values of .07 to .5, and .08 to .42, with averages of .27 and .15, were observed for sets of selected sites when ResNet was initialized by rarity and by protected areas, respectively. This indicates that different sets of sites were selected from input sets modelled with different environmental parameter sets.

Figure 5 corresponds to Figure 2 for the WTL LULC parameter set; the results are qualitatively

A)



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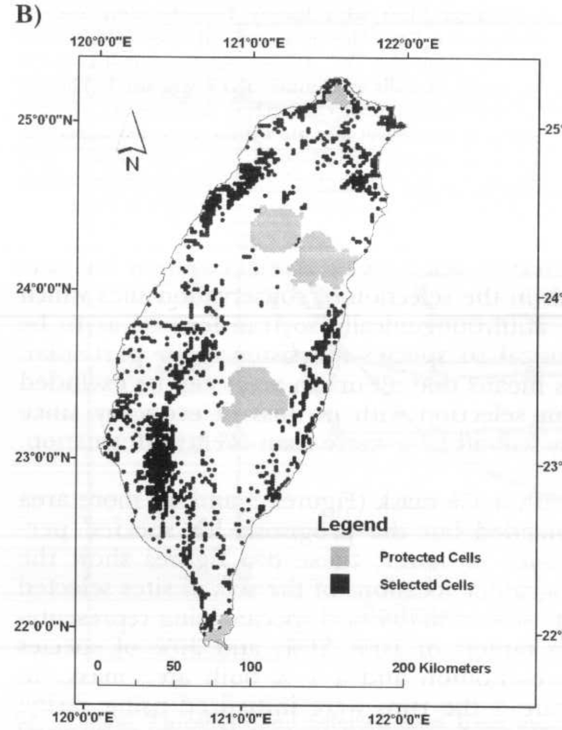

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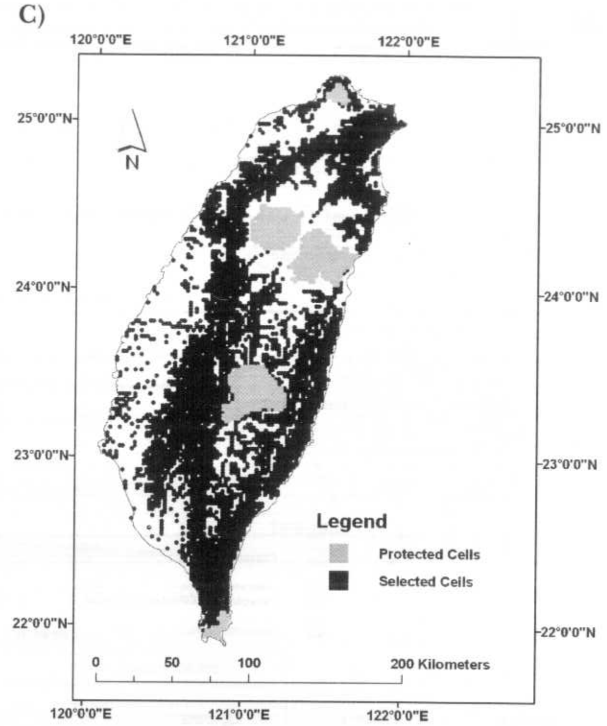


Fig. 4. **Priority Sites with Protected Area Initialization and W Parameter Set**. This is a map of sites selected by ResNet from the "W" dataset. ResNet was initialized by the protected areas. A built area mask of 1% was used. The set of sites within protected areas, and the set of sites selected by ResNet that are within protected areas, are each separately indicated on the map. **a**—Representation target of 10 % ; **b**—Representation target of 20 %; **c**—Representation target of 30 %.

identical except for the 30% representation target. For that target, in this case, there is no drastic change (as discussed above for Figure 2). Similarly, Figures 6 and 7 correspond to Figures 3 and 4 but report results with the WTL parameter set. The spatial economy increased (Table 3) and the areas selected are strikingly different. In Figures 3, 4, 6, and 7, Taiwan's insularity manifests itself through the relative paucity of areas selected near the coast, in particular the southeast coast. This reflects the use of coastal corridors for communication linkages.

DISCUSSION

By selecting sites outside the existing protected areas, this analysis thus identified additional conservation areas in Taiwan that would complement the existing protected areas and would ensure representation of native land breeding birds at the specified targets of representation while excluding areas with levels of development exceeding designated thresholds. The distribution of these new sites merits attention from all those interested in analysing options for future biodiversity conservation in Taiwan and, after more scrutiny and other extensions (see below) from planners.

Differences between LULC parameter sets used to model species' distributions affected whether representation targets could be met in nominal conservation area networks in only two cases (Figure 4). However, they strongly affected which individual sites were prioritized and the total selected area decreased as more LULC parameters were included. This suggests that, in this example, there is a complex relationship between bird habitat and LULC types, which is not surprising: different bird species respond differently to vegetation structure and type. However, the disparate performances of these modelling criteria underscore the recommendation that the model predictions be tested in the field before any implementation is envisioned. If models with a large array of LULC parameters, such as the WTL parameter set-based model, turn out to be predictively successful, they should be used because area selection to satisfy representation targets is done more economically than with models based on fewer LULC parameters. This is an unexpected result. However, birds may be atypical (Margules and Sarkar 2007) and the case of Taiwan may be unique because of its insularity or pattern or urbanization. This issue merits further study.

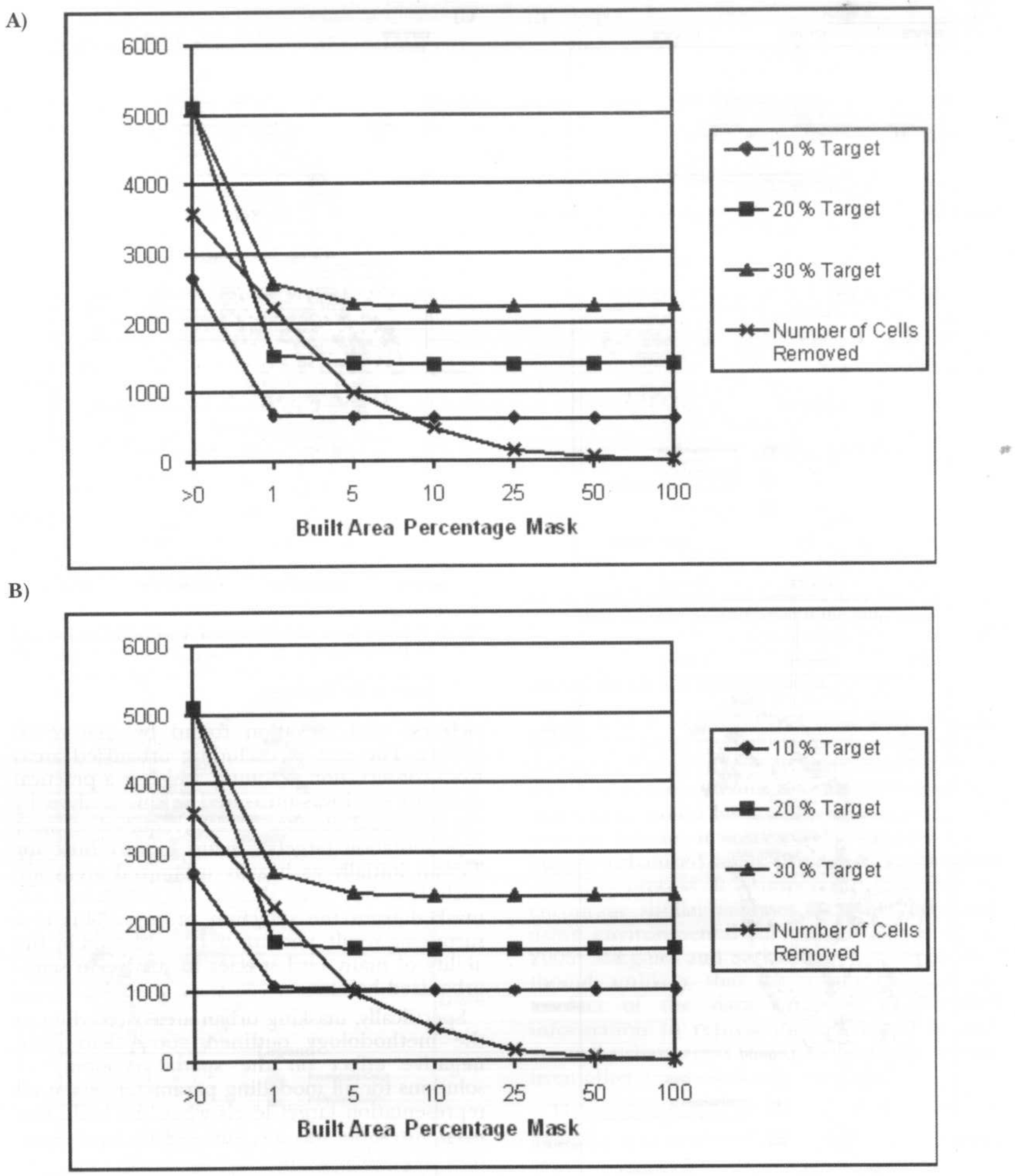
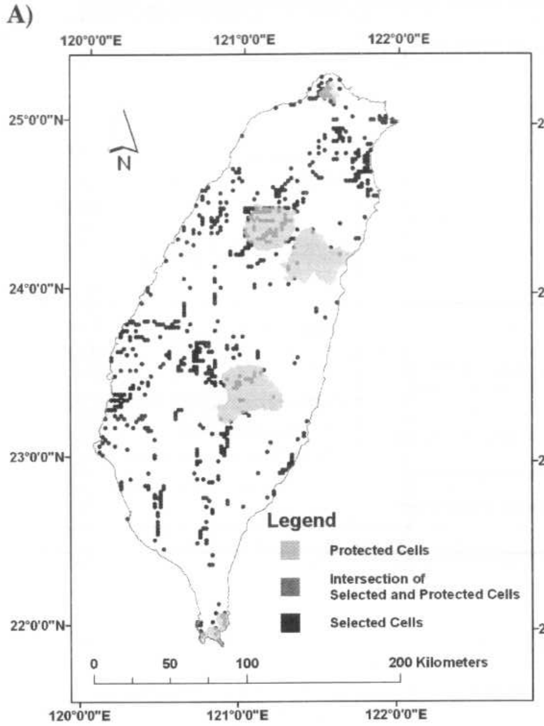
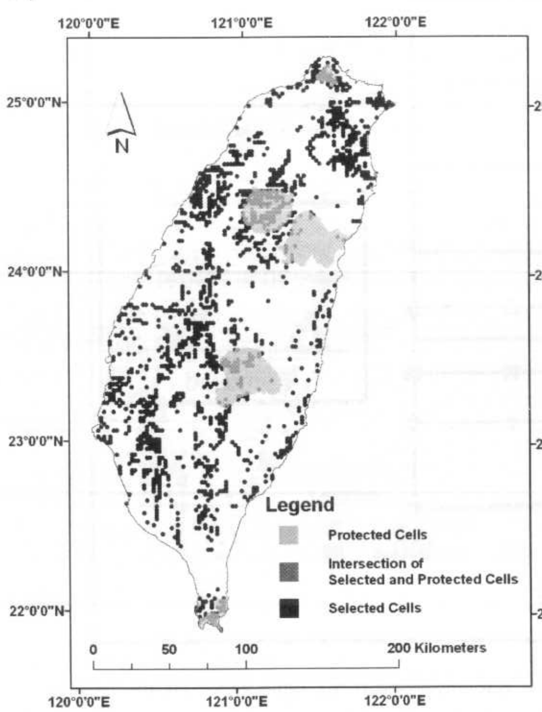


Fig. 5. **Mask Threshold and Selected Area from the WTL Data Set**. The interpretation is the same as for Figure 2.

A)



B)



C)

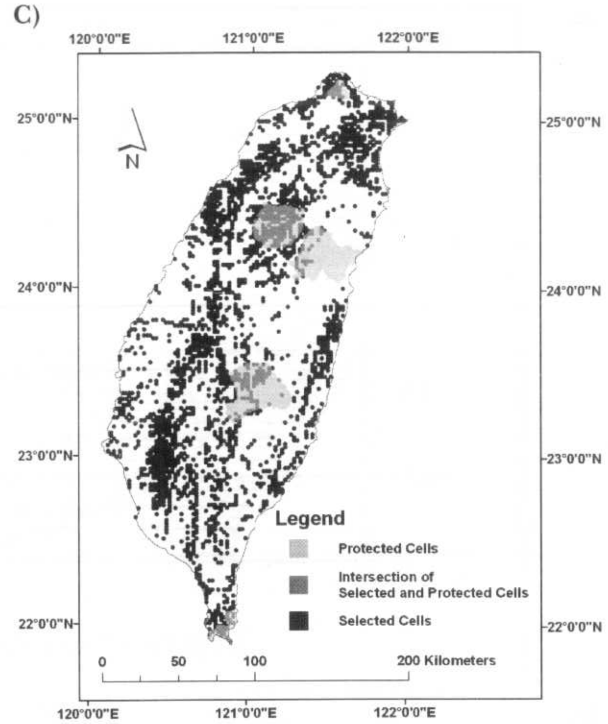


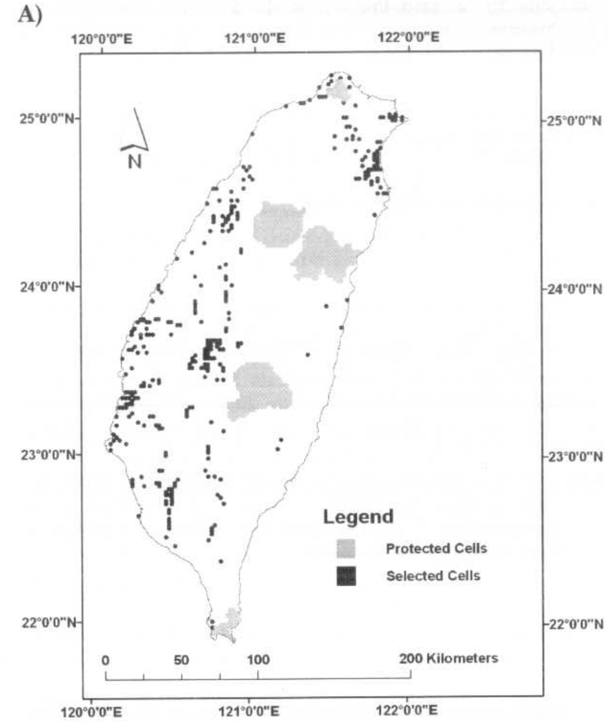
Fig. 6. **Priority Sites with Protected Area Initialization and W Parameter Set.** Mask Threshold and Selected Area from the WTL Data Set. The interpretation is the same as for Figure 3.

Masking urban areas acknowledges that conservation planning does not take place except in the context of human needs and other socio-economic and geographical constraints (Pressey 1998; Sarkar 2005; Pierce *et al.* 2005; Moffett *et al.* 2006). Also, as heavily urban areas in Taiwan are predominantly located in the coastal lowlands, the spatial pattern of the urban area that must be masked complements the bell-shaped relationship between bird species richness and elevation found by Lee *et al.* (2004). The cost of excluding urbanized areas from conservation planning, which is a practical necessity (and was measured in this analysis by the increased number of sites required to meet representation targets), seems to vary little for Taiwan initially as heavily urbanized areas are excluded, but rises sharply as more sites are masked from the selection process. This is a surprising result, perhaps to be explained by the ability of many bird species to survive in semi-urbanized habitat.

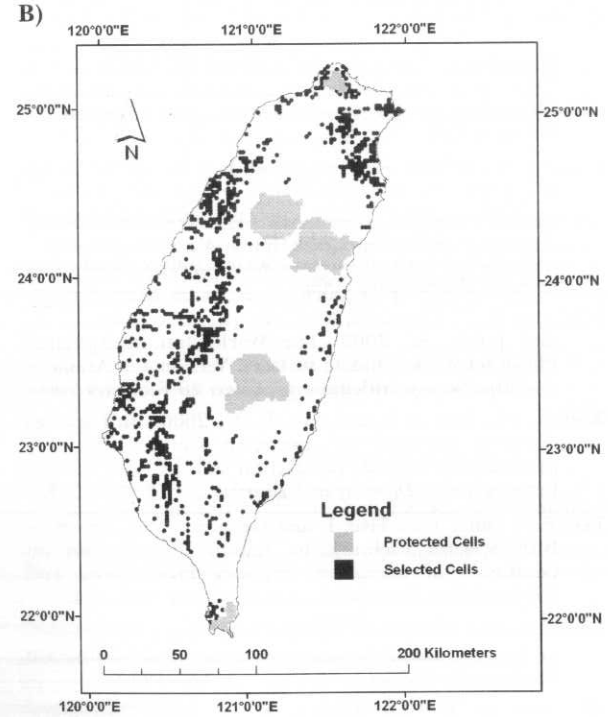
Specifically, masking urban areas according to the methodology outlined above had little negative effect on the spatial economy of solutions for all modelling parameter sets at all representation target levels when the built area mask threshold was 5%, and at 10% representation target levels when the mask threshold was 1%. This means, as noted earlier, that it will in general be possible to devise adequate bird conservation plans for Taiwan using areas with less than 5% built cover; to the extent that 10% is a reasonable representation target (e.g., for common species), it will even be possible to achieve such a goal with land with less than 1 % built cover. This suggests that conservation planning for Taiwan focuses on land with less than 5% built cover.

There were several instances in which additional masking of built areas resulted in a slight reduction in total area selected. This result stems from the masking process itself. As sites are masked out, predicted species presences are masked out to varying degrees, which in turn potentially changes the proportional contribution of each unmasked site with respect to the total predicted presence of each species—so the results obtained here should be treated with caution and replicated before being taken to be definitive about the response of birds—let alone other taxa—to urbanization.

A)



B)



C)

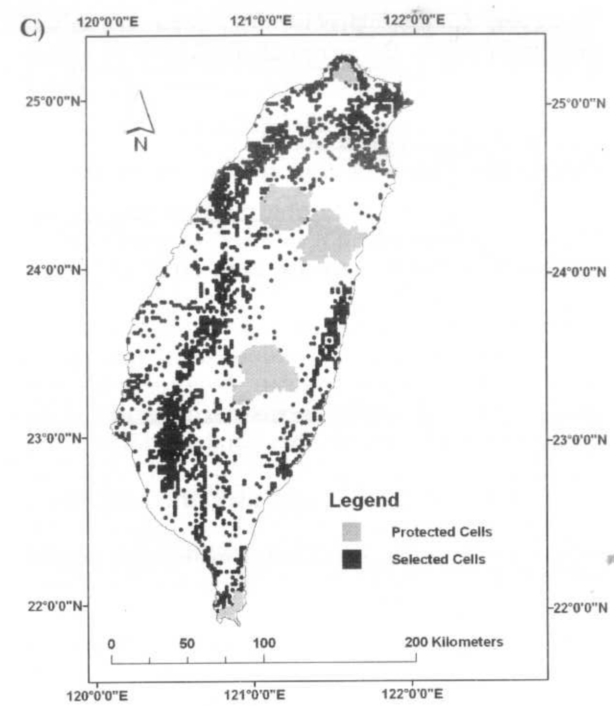


Fig. 7. **Mask Threshold and Selected Area from the WTL Data Set.** The interpretation is the same as for Figure 4.

Implications for Management

The relative invariance of total area selected under different built-area percentage masks during exclusion of heavily transformed areas is an unexpected outcome but, if replicated for other taxa, would be a welcome signal that, at least in Taiwan, it costs little to remove more heavily urbanized areas from the conservation planning process. It is important, therefore, to encourage similar analyses for other taxa and using environmental surrogates (Sarkar *et al.* 2005; Margules and Sarkar 2007). It is possible, though unlikely, that the results here are an artefact of the data providing inadequate information to represent biodiversity in and around urban areas. Congruence with results from other taxa will clarify this issue.

The difference in size between the units of analysis (uniformly 2 × 2 km^2 sites) and individual parcels of developed land within those sites (which can be of practically any size) could potentially allow for greater flexibility in meeting targets than was recognized in this analysis. For instance, masking of built areas could, in principle, be accomplished by masking the built areas directly, rather than by removing entire sites on the basis of built area density within them. Neither politicians nor planners typically think solely in terms of uniform grids (Pressey 1998; Moffett *et al.* 2006), and dividing units of analysis into subsections would easily allow the avoidance of developed areas without masking out large fractions of a landscape.

However, species' precise locations are often uncertain below the original resolution at which data were collected and recorded. Finer application of built area masking would thus also require field verification of species' predicted distribution data at a finer spatial resolution.

It is important to emphasize that the results of this paper should not be used to guide policy until several conditions are met. First, at least a suitably sampled subset of the niche model predictions must be verified in the field. Second, this analysis must be extended to include other conserved areas in Taiwan beyond national parks to see if results remain the same. The quantitative results of this analysis show that requiring the national parks to be included in a set of selected sites increases the total area required to meet a representation target, often substantially. Such a follow-up evaluation might be of little practical value in planning for future conservation of the particular species included in this analysis then, but should be considered in the broader context of biodiversity conservation planning. In general, the performance of the national parks is consistent with what has been found for traditionally selected protected areas around the world (Pressey 1994; Margules and Sarkar 2007).

Finally, adequate niche models could be constructed for only 95 of 142 bird species given the occurrence data that were available for this analysis. Some of the excluded species (e.g., Whistling Green-pigeon (*Treron formosae*)), Tawny Fish Owl (*Ketuva flavipes*), and Fairy Pitta (*Pitta nympha*)) are locally rare and have limited distributions. Of those species not included, the Fairy Pitta is listed as vulnerable in the World Conservation Union (IUCN) Red List. Thus, if implementation is intended, the data set used for area selection must be supplemented: either more occurrence points must be obtained from surveys so that adequate niche models can be constructed for all species of interest, or other distributional models, for instance those based on expert opinion, must be used along with the niche models.

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APPENDIX

Bird Species Screened for Inclusion in Analysis

Protected Areas:
a = Yangmingshan; b = Sheipa; c = Taroko; d = Yushan; e = Kenting
IUCN Status and Endemism:
LC = Least Concern; NT = Near Threatened; VU = Vulnerable; ED = Endemic

Scientific name	Common English name	Included in Analysis?	Protected Areas	IUCN Status and Endemism
Podiceps ruficollis	Little Grebe	yes	e	LC
Bubulcus ibis	Cattle Egret	yes	a, e	LC
Butorides striatus	Striated Heron	no	a, b, c, e	LC
Egretta garzetta	Little Heron	yes	a, c, e	LC
Gorsachius melanolophus	Malayan Night Heron	yes	c	LC
Ixobrychus cinnamomeus	Cinnamon Bittern	yes	a, c, e	LC
Ixobrychus sinensis	Yellow Bittern	yes	e	LC
Nycticorax nycticorax	Black-crowned Night Heron	yes	a, e	LC
Aix galericulata	Mandarin Duck	yes	b, c	LC
Accipiter virgatus	Besra Sparrowhawk	yes	a, b, c, d	LC, ED
Accipiter trivirgatus	Crested Goshawk	no	a, b, c, d, e	LC, ED
Ictinaetus malayensis	Black Eagle	yes	a, b, c, d	LC
Milvus migrans	Black-eared Kite	yes	a, e	LC
Spilornis cheela	Crested Serpent-Eagle	no	a, b, c, d, e	LC, ED
Spizaetus nipalensis	Mountain Hawk-Eagle	yes	b, c, d	LC
Arborophila crudigularis	Taiwan Partridge	yes	b, c, d, e	NT, ED

Appendix — *continued*

Scientific name	Common English name	Included in Analysis?	Protected Areas	IUCN Status and Endemism
Bambusicola thoracicus	Chinese Bamboo Partridge	no	a, b, c, d, e	LC, ED
Coturnix chinensis	Blue-breasted Quail	yes	e	LC, ED
Lophura swinhoii	Swinhoe's Blue Pheasant	yes	b, c, d	NT, ED
Phasianus colchicus	Common Pheasant	yes	b	LC, ED
Syrmaticus mikado	Mikado Pheasant	yes	b, c, d	NT, ED
Turnix suscitator	Barred Buttonquail	yes	a, e	LC, ED
Turnix sylvatica	Small Buttonquail	no		LC
Amaurornis phoenicurus	White-breasted Water-hen	yes	a, e	LC
Gallicrex cinerea	Watercock	yes	e	LC
Gallinula chloropus	Common Moorhen	yes	e	LC
Porzana fusca	Ruddy-breasted Crake	yes	e	LC, ED
Gallirallus striatus	Slaty-breasted Rail	yes		LC, ED
Hydrophasianus chirurgus	Pheasant-tailed Jacana	yes	e	LC
Rostratula benghalensis	Greater Painted Snipe	yes		LC
Glareola maldivarum	Oriental Pratincole	yes	e	LC
Chalcophaps indica	Emerald Dove	no	c, d, e	LC
Columba pulchricollis	Ashy Wood-Pigeon	yes	b, c, d	LC
Streptopelia chinensis	Spotted Dove	no	a, c, d, e	LC, ED
Streptopelia orientalis	Oriental Turtle-Dove	no	a, b, c, d, e	LC, ED
Streptopelia tranquebarica	Red Collared-Dove	yes	c, e	LC
Treron formosae	Whistling Green-Pigeon	no		NT, ED
Treron sieboldii	White-bellied Green-Pigeon	no	a, b, c, d, e	LC, ED
Centropus bengalensis	Lesser Coucal	yes	a, c, e	LC
Cuculus poliocephalus	Little Cuckoo	yes	b	LC
Cuculus saturatus	Oriental Cuckoo	no	a, b, c, d	LC
Cuculus sparverioides	Large Hawk Cuckoo	yes	b, c, d	LC
Glaucidium brodiei	Collared Owlet	yes	a, b, c, d	LC
Ketupa flavipes	Tawny Fish Owl	no	c	LC
Otus bakkamoena	Collard Scops Owl	no	a, c, d, e	LC
Otus spilocephalus	Mountain Scops Owl	yes	b, c, d, e	LC, ED
Strix aluco	Tawny Owl	yes	b, c, d	LC
Strix leptogrammica	Brown Wood Owl	yes	b, c, d	LC
Caprimulgus affinis	Savanna Nightjar	yes		LC
Apus nipalensis	House Swift	no	a, b, c, d, e	LC
Apus pacificus	Fork-tailed Swift	no	a, b, c, d, e	LC
Hirundapus cochinchinensis	Silver-backed Needletail	no	b, c, d	LC
Alcedo atthis	Common Kingfisher	yes	a, b, c, e	LC
Megalaima oorti	Black-browed Barbet	no	a, b, c, d, e	LC, ED
Dendrocopos canicapillus	Gray-capped Woodpecker	no	a, b, c, d	LC
Dendrocopos leucotos	White-backed Woodpecker	yes	b, c, d	LC, ED
Picus canus	Gray-faced Woodpecker	yes	b, c, d	LC, ED
Pitta nympha	Fairy pitta	no		VU
Alauda gulgula	Oriental Skylark	yes	a, e	LC
Delichon dasypus	Asian House Martin	yes	a, b, c, d, e	LC
Hirundo rustica	Barn Swallow	yes	a, b, d, e	LC
Hirundo striolata	Greater Striated Swallow	yes	a, d, e	LC
Hirundo tahitica	Pacific Swallow	yes	a, b, c, d, e	LC
Riparia paludicola	Plain Martin	yes	c, e	LC
Coracina macei	Large Cuckoo-shrike	yes	b, d	LC
Pericrocotus solaris	Grey-chinned Minivet	no	a, b, c, d	LC
Dicrurus aeneus	Bronzed Drongo	no	b, c, d, e	LC, ED
Dicrurus macrocercus	Black Drongo	yes	a, e	LC, ED
Oriolus chinensis	Black-naped Oriole	yes		LC
Oriolus traillii	Maroon Oriole	yes	d	LC, ED
Corvus macrorhynchos	Large-billed Crow	no	a, b, c, d, e	LC
Dendrocitta formosae	Gray Treepie	no	a, b, c, d, e	LC, ED
Garrulus glandarius	Eurasian Jay	yes	b, c, d	LC, ED
Nucifraga caryocatactes	Spotted Nutcracker	yes	b, c, d	LC, ED
Pica pica	Black-billed Magpie	yes		LC
Urocissa caerulea	Formosan Magpie	yes	a, d, e	LC, ED
Paradoxornis verreauxi	Golden Parrotbill	yes	b, c, d	LC, ED
Paradoxornis webbianus	Vinous-throated Parrotbill	yes	a, b, c, d	LC, ED
Aegithalos concinnus	Black-throated Tit	yes	b, c, d	LC
Parus ater	Coal Tit	yes	a, b, c, d	LC, ED
Parus holsti	Yellow Tit	yes	b, c, d	NT, ED
Parus monticolus	Green-backed Tit	no	a, b, c, d	LC, ED
Parus varius	Varied Tit	yes	a, b, c, d	LC, ED
Sitta europaea	Wood Nuthatch	yes	b, c, d	LC
Actinodura morrisoniana	Taiwan Barwing	yes	b, c, d	LC, ED
Alcippe brunnea	Dusky Fulvetta	no	a, b, c, d, e	LC, ED

Appendix — *continued*

Scientific name	Common English name	Included in Analysis?	Protected Areas	IUCN Status and Endemism
Alcippe cinereiceps	Streak-throated Fulvetta	yes	b, c, d, e	LC, ED
Alcippe morrisonia	Grey-cheeked Fulvetta	no	a, b, c, d, e	LC, ED
Garrulax albogularis	White-throated Laughingthrush	yes	b, d	LC, ED
Garrulax canorus	Hwamei	no	a, d, e	LC, ED
Garrulax morrisonianus	White-whiskered Laughingthrush	yes	b, c, d	LC, ED
Garrulax poecilorhynchus	Rufous Laughingthrush	yes	b, c, d	LC, ED
Heterophasia auricularis	White-eared Sibia	no	a, b, c, d	LC, ED
Liocichla steeri	Steere's Liocichla	yes	a, b, c, d	LC, ED
Pnoepyga albiventer	Pygmy Wren Babbler	yes	b, c, d	LC, ED
Pomatorhinus erythrocnemis	Spot-breasted Scimitar Babbler	no	a, b, c, d, e	LC, ED
Pomatorhinus ruficollis	Streak-breasted Scimitar Babbler	no	a, b, c, d, e	LC, ED
Stachyris ruficeps	Rufous-capped Babbler	no	a, b, c, d, e	LC, ED
Yuhina brunneiceps	Taiwan Yuhina	yes	a, b, c, d	LC, ED
Erpornis zantholeuca	White-bellied Yuhina	no	a, b, c, d	LC
Hypsipetes leucocephalus	Black bulbul	no	a, b, c, d, e	LC, ED
Pycnonotus sinensis	Light-vented Bulbul	no	a, b, c, d	LC, ED
Pycnonotus taivanus	Styan's Bulbul	yes	c, e	VU, ED
Spizixos semitorques	Collared Finchbill	no	b, c, d	LC, ED
Cinclus pallasii	Brown Dipper	no	b, c, d	LC
Troglodytes troglodytes	Winter Wren	yes	b, c, d	LC, ED
Brachypteryx montana	White-browed Shortwing	yes	b, c, d	LC, ED
Enicurus scouleri	Little Forktail	yes	b, c, d	LC, ED
Myophonus insularis	Formosan Whistling Thrush	no	a, b, c, d	LC, ED
Cinclidium leucurum	White-tailed Robin	no	a, b, c, d, e	LC, ED
Rhyacornis fuliginosus	Plumbeous Water-Redstart	no	a, b, c, d	LC, ED
Tarsiger indicus	White-browed Bush-Robin	yes	b, c, d	LC, ED
Tarsiger johnstoniae	Rufous-breasted Bush-Robin	yes	b, c, d	LC, ED
Turdus poliocephalus	Island Thrush	yes	b, d	LC, ED
Abroscopus albogularis	Rufous-faced Warbler	yes	b, c, d	LC
Bradypterus alishanensis	Taiwan Bush-Warbler	yes	b, c, d	LC
Cettia acanthizoides	Yellowish-bellied Bush-Warbler	yes	b, c, d	LC, ED
Cettia fortipes	Brown-flanked Bush-Warbler	yes	a, b, c, d	LC, ED
Cisticola exilis	Golden-headed Cisticola	yes	a	LC, ED
Cisticola juncidis	Zitting Cisticola	yes	a, e	LC
Prinia criniger	Striated Prinia	no	a, b, c, d	LC, ED
Prinia flaviventris	Yellow-bellied Prinia	no	a, d, e	LC
Prinia inornata	Plain Prinia	yes	a, c, d, e	LC, ED
Regulus goodfellowi	Flamecrest	yes	b, c, d	LC, ED
Ficedula hyperythra	Snowy-browned Flycatcher	no	a, b, c, d	LC, ED
Monarcha azurea	Black-naped Monarch	no	a, c, d, e	LC, ED
Muscicapa ferruginea	Ferruginous Flycatcher	yes	a, b, c, d	LC
Niltava vivida	Vivid Niltava	yes	b, c, d	LC, ED
Prunella collaris	Alpine Accentor	yes	b, c, d	LC, ED
Lanius schach	Long-tailed Shrike	yes	c, d	LC, ED
Acridotheres cristatellus	Crested Myna	yes	a, e	LC, ED
Dicaeum concolor	Plain Flowerpecker	no	a, d, e	LC, ED
Dicaeum ignipectus	Fire-breasted Flowerpecker	yes	b, c, d	LC, ED
Zosterops japonicus	Japanese White-eye	no	a, b, c, d, e	LC
Lonchura malacca	Black-headed Munia	yes		LC, ED
Lonchura punctulata	Scaly-breasted Munia	yes	a, e	LC
Lonchura striata	White-rumped Munia	no	a, c, d	LC
Carpodacus vinaceus	Vinaceous Rose-Finch	yes	b, c, d	LC, ED
Pyrrhula erythaca	Grey-headed Bullfinch	yes	b, c, d	LC, ED
Pyrrhula nipalensis	Brown Bullfinch	yes	b, c, d	LC, ED
Passer montanus	Eurasian Tree Sparrow	no	a, b, d, e	LC
Passer rutilans	Russet Sparrow	yes	b, c	LC