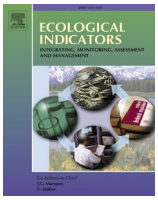
Ecological Indicators 125 (2021) 107536

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind



# An evaluation of the effectiveness of protected areas in Thailand

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ARTICLE INFO

*Keywords:*
Biodiversity hotspots
Ecoregions
Elevation
National parks
Protected areas
Wildlife sanctuaries
Thailand
Gap analysis
IUCN categories

ABSTRACT

Thailand is a biodiversity hotspot and home to over 1000 bird species, 15,000 plant species, and five of the World Wildlife Fund's Global 200 Ecoregions of ecological significance. To preserve their unique ecosystems, the Thai government has established and maintained protected areas (PA) which in 2020, are estimated to cover 19% of Thailand's land area. The success of these areas in preserving biodiversity to date is somewhat ambiguous. Using gap analyses, we evaluated the extent and adequacy of coverage provided by these PAs for the preservation of these unique ecoregions, to threatened amphibian, bird, and mammal species richness hotspots and at a range of altitudes within Thailand.

Regionally, the Indochina dry forests, Northern Khorat Plateau moist deciduous forests and Malaysian Peninsula rainforests are all under-represented. Though opportunities exist for their protection through marine designation, mangrove and wetland ecosystems are also seriously under-represented in the current spatial layout and network connectivity of Thailand's protected area system. Highland areas (>750 m elevation) are well-protected, in contrast to the lower altitude areas where human and agricultural pressures are higher. Hotspots of threatened birds located in the northern and southern regions of Thailand, as well as most of the central threatened mammal hotspot, are inadequately covered (<10%). The current PAs could be expanded with a focus on these key areas, or further PAs created to address these gaps in provision. The Thai PA network is also highly fragmented and, in addition to increasing the area covered, contiguity and connectivity of the network should be considered. With human population expansion in the central lowland area particularly, there will be challenges and trade-offs to be negotiated along with enforcement within existing areas. We hope, though, that the results of this study can aid policymakers in improving Thai conservation effectiveness.

## 1. Introduction

Protected areas (PAs) are designated areas that are established and maintained to maximise biodiversity and ecosystem conservation. The International Union for Conservation of Nature (IUCN) defines these as "a clearly defined geographical space, recognised, dedicated and managed, through legal or other effective means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values" (Ferraro et al., 2013; Chettri et al., 2008a, 2008b). Protected areas are commonly regarded as central to the efforts to conserve species and natural resources the world over (Chape et al., 2008). Accordingly, the 196 parties to the Convention on Biological Diversity (CBD) have adopted Aichi Target 11, committing governments to conserve ≥17% of terrestrial and ≥10% of marine areas through site-based conservation strategies by 2020 (Ford et al., 2020; Balmford et al., 2005). Some argue, however, that the 10% threshold has limited ecological foundations and may not provide adequate biodiversity representation (Svancara et al., 2005). Selecting appropriate biodiversity features for analysis is vital for evaluating PA efficacy and WWF Ecoregions have been previously used in assessing biological representativeness (Schmitt et al., 2009). Ecoregions have been defined as "A relatively large unit of land or water containing a geographically distinct assemblage of species, natural communities, and environmental conditions" (Olson and Dinerstein, 1998). The WWF ecoregion framework provides the most detailed biogeographic global classification system and has become a widely accepted framework for biodiversity analysis. The robust framework that WWF ecoregions provide for conservation planning and protected area establishment at a regional scale meets the four main goals of biodiversity conservation: (1) representation of all distinct natural communities (2) maintenance of ecological and

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https://doi.org/10.1016/j.ecolind.2021.107536
Received 8 March 2020; Received in revised form 1 February 2021; Accepted 15 February 2021
Available online 25 February 2021

evolutionary processes (3) species population maintenance (4) conservation of large blocks of natural habitats (Jepson and Whittaker, 2002). At a global scale it has been used to identify that 73% of 83 countries across Asia, Africa, the Americas and Australia lack adequate protected area coverage (Barr et al., 2011a, 2011b), and to identify the global ecoregions that did not meet the 10% PA coverage target of the CBD (Jenkins and Joppa, 2009a, 2009b). At both regional and national scales, this framework has been used as a basis for assessing whether existing PAs adequately cover transboundary ecoregions (Soutullo and Gudynas, 2006) and for assessing the efficacy of different protected area schemes at a national level (Schutz, 2017). The Thai ecoregions were comprehensively mapped and formally determined in 2002 (Table 1) (Schmitt et al., 2009; Hoekstra et al., 2005; Wikramanayake et al., 2002).

In the 1950s, in the face of rapid forest loss, the Royal Thai government established both a PA network and reforestation schemes declaring that at least 50% of the country's forest cover was to be maintained (Thai Forestry Sector Master Plan, 1993) (Trisurat, 2007; Wikramanayake et al., 2002). This partly protected forests from threats such as commercial logging and supported valuing forests for cultural, recreational, and educational purposes as, not only do PAs mitigate biodiversity loss, they may reduce local poverty by providing multiple socioeconomic benefits (Sims, 2010). These PAs are considered successful in slowing national forest loss (Trisurat, 2007). Furthermore, along with the goal of protecting 50% of Thailand's forests, the government also encouraged sustainable regional tourism, forestry, and agriculture (Trisurat et al., 2015). Later, Thailand's forest cover target was reduced to 40% to accommodate economic growth and agricultural production. The National Forest Policy (1985) declared that 15% of this 40% would be fully preserved forest and 25% of it would be used for production (Appanah, 2016). By 2005, there were 103 national parks, 84 forest reserves, and 55 wildlife sanctuaries established nationwide – all are regulated and controlled by the government. These were managed with the guidance of early conservation legislative acts such as the National Park Act (1961) and the Wild Animal Reservation and Protection Act (1960). The latter provided protection for wild animals in general by establishing wildlife sanctuaries and additional non-hunting areas, some of which are located in key ecoregions. Recently, the National Park Act (2019), and the Wild Animal Reservation and Protection Act (2019) were also passed in Thailand and provide legal support and updated guidance for management and enforcement.

**Table 1**
The percentage area of Thailand occupied by each Ecoregion and the conservation coverage comparison indices (CI) for the IUCN protected area categories "Wildlife Sanctuaries" (Ia) and "National Parks" (II) within these. Ecoregions with a CI lower than 0.2 in both categories indicates serious underrepresentation, those with a CI over 0.2 and less than 1 are underrepresented), those that exceed 1 in either category have good representation.

| | % area of Thailand | CI Wildlife Sanctuaries (Ia) | CI National Park (II) |
|---|---|---|---|
| *Ecoregion Type* | | | |
| Cardamone mountain rainforests | 2.30 | 2.30 | 0.40 |
| Central Indochina dry forest | 41.10 | 0.20 | 0.30 |
| Chao Phraya freshwater swamp | 7.60 | 0.00 | 0.00 |
| Chao Phraya Lowland moist deciduous forest | 3.90 | 0.20 | 0.90 |
| Indochina mangroves | 1.60 | 0.10 | 0.00 |
| Kayah Karen Montane Rainforest | 12.50 | 3.80 | 2.30 |
| Luang Prabang Montane Rainforest | 3.70 | 2.80 | 2.30 |
| Myanmar Coast Mangroves | 0.70 | 0.00 | 0.00 |
| Northern Indochina Subtropical Forests | 0.80 | 0.70 | 2.40 |
| Northern Khorat Plateau moist deciduous forests | 2.20 | 0.20 | 0.50 |
| Northern Thailand-Laos moist deciduous forests | 5.90 | 0.60 | 2.20 |
| Peninsular Malaysian montane rain forests | 0.10 | 4.80 | 2.10 |
| Peninsular Malaysian rain forests | 1.90 | 0.40 | 0.90 |
| Southeastern Indochina dry evergreen forests | 2.90 | 1.90 | 3.40 |
| Tenasserim-South Thailand semi-evergreen rain forests | 12.50 | 1.30 | 1.40 |
| *Global 200 WWF Thai Ecoregions* | | | |
| Cardamone mountain moist forests | 2.30 | 2.30 | 0.40 |
| Indochina dry forests | 44.10 | 0.30 | 0.50 |
| Kayah-Karen/Tenasserim Moist Forests | 24.90 | 2.60 | 1.80 |
| North Indochina Subtropical Moist Forests | 0.80 | 0.70 | 2.40 |
| Peninsular Malaysia Lowland and Montane Forests | 2.10 | 0.70 | 0.90 |

In 2007, satellite imagery revealed that only 33% of the forested area in Thailand was being effectively protected (APFNet, 2015). In response to this, the government of Thailand increased PAs from 25% to 30% of the country in 2016 (Appanah, 2016). However, the world over, the efficacy of protected areas is undermined by locational biases and an inability to provide appropriate coverage to imperilled biodiversity (Joppa et al., 2008). Hence the placement of PAs in Thailand is critical to their effectiveness and may not currently be optimal. PAs can aid in preserving biodiversity, however, their location is most often determined by social needs and may be biased towards low-value lands (Barr et al., 2011a, 2011b; Venter et al., 2014). Their placement is thus often based on the economic potential of a piece of land rather than on ecological information. It thus remains uncertain whether the PAs demarcated to date and those to come in the future are effectively located to conserve the most threatened species and habitats. The majority of the current Thai PAs are in areas of high elevation (66% of Thailand's area >1000 m in elevation is protected in comparison to 6% of the area <250 m). Elevation may be a double-edged sword in that, though areas of high altitude are more inaccessible, harder to harvest commercially and thus easier to protect, they also are home to a particular subset of species and may not offer broad-scale protection. The current 33% of forested area protected in Thailand may not sufficiently cover all of the most ecologically important ecoregions and species if their placement is biased towards 'convenience' factors such as high altitudes (Klorvuttimontara et al., 2011). For an effective and representative coverage, it is essential that PAs cover a sufficient range of elevations to encompass elevation-specific ecotypes (Consortium for Spatial Information, 2019). It is thus crucial that more information on the conservation effectiveness of current PAs is obtained to direct future conservation actions on the ground. The objectives of the 20 Aichi Biodiversity Targets highlight the need to have at least 17% of terrestrial land optimally preserved and effectively managed by 2020 if global ecosystems are to be preserved (Balmford et al., 2005).

Though the protected areas of Thailand cover over 110,000 $km^2$ with almost twice as much located in National Parks (67,725 $km^2$) than in Strict Nature Reserves (37,030 $km^2$), their effectiveness has been variously praised and critiqued. A 2001 review by Bugna and Rambaldi (2001) deemed it satisfactory though others indicated that lowland wet evergreen forests and mangroves along with peat swamps were inadequately preserved by the PA network and that their areas may be too small and isolated to maintain wetland ecosystem health (Santisuk, 1991). >25% of Thailand's endangered birds rely on wetlands and the largest waterbirds use this habitat as a breeding and mating ground (Olson and Dinerstein, 2002). If PAs do not cover this ecoregion, there may be large, detrimental impacts on avian species diversity. There has already been a collapse of many fish populations in river deltas throughout the country associated with wetland loss (Barbier and Sathirathai, 2004). The different categories of PAs have been shown to

vary in their ability to preserve habitats and species. National Parks have had the greatest success in halting forest loss whilst Forest Reserves are the least effective in preserving habitat (Pfeifer et al., 2012). More strictly regulated PAs have also been observed to be located ineffectively relative to endangered ecosystems (Sims, 2010; Brockington, 2002). Although strict PAs have limited human activity, conflict between stakeholders may lead the government to place these in less threatened and lower potential direct economic value habitats (Mascia and Pailler, 2011). The main aims of the research are to analyse whether main IUCN categories of PAs are successful in providing protection status to key ecoregions and their component species and identifying potential elevational biases in PA locations. Much existing research in other regions has focussed on either quantifying the gaps in PA coverage either in terms of ecoregion representation (Squeo et al., 2012; Soutullo and Gudynas, 2006; Chettri et al., 2008a, 2008b) or in terms of covering habitat or hotspots of specific species (González-Maya et al., 2015; Wu et al., 2013; Singh, 2020). Here, instead of taking an either-or approach, we combine three distinct aspects of protected area efficacy: 1) ecoregional representation as a way of supporting the preservation of large natural tracts that maintain both important ecological processes and sustain species population, 2) identifying the existing coverage provided to areas with high concentrations of IUCN listed avian species ('hotspots') and, 3) estimation of elevation bias in PA locations. Together these allow for a more comprehensive analysis of the existing state of Thailand's' PAs which can inform future PA expansion. The use of such global datasets for these analyses underlies that the techniques can be applied to/scaled up to different regions. This study uses gap analyses to explore the proportion of each ecoregion and the threatened taxonomic group covered by PAs. A gap analysis is a systematic approach for identifying the extent to which protected regions effectively represent habitats or species' ranges by quantifying the proportion of coverage provided to the target habitat/species range/ecosystem (Hazen and Anthamatten, 2004). These analyses will provide a quantitative estimation of whether PAs in Thailand are optimally placed to effectively protect key ecosystems and taxa (Jennings, 2000).

## 2. Methods

The study has three sections. First is the estimation of the effectiveness of the current PAs in representing ecoregions in Thailand by calculating the comparison index (CI) for each ecoregion relative to different PA categories. Second is to quantify the effectiveness of PAs in covering taxonomic biodiversity hotspots, in particular, those of the species ranges of threatened amphibians, birds, and mammals. Last is the determination of whether the PAs adequately represent the range of elevations in the country.

Spatial data of current ecoregions and species distributions of threatened birds in Thailand were collected and input to a geographic information system (GIS). These maps have been overlaid with a map of established PAs within the country (Jenkins and Joppa, 2009a, 2009b). The gap analysis allows for a map of ideally placed or expanded PAs to be generated in support of the Royal Forest Department's goal of having 40% of the country lying within protected regions by 2020 (Trisurat, 2007). This map will propose and highlight the gaps that need "filling" and will provide a target for future national conservation efforts (United Nations Environment World Conservation Monitoring Centre, 2019).

## 3. Study area

This study covers The Kingdom of Thailand (513,120 km$^2$) in Southeast Asia within the Indochina and Sundaic biogeographical subregions (Fig. 1, inset). Spatial data for PAs in Thailand were derived from the World Database of Protected Areas (WDPA) and consisted of 208 PAs in polygon format (Boitani et al., 2008). These are classified into the International Union for Conservation of Nature's (IUCN) categories I-VI. These categories represent levels of legislative or regulatory protection, and the nature and intensity of permissible land use, from the strictest to community managed forests (Leroux et al., 2010). Out of these only two comprise the bulk of Thailand's PA realm: IUCN Category 1A (58 of the 208 PAs in Thailand) and IUCN category II (147 of the 208 PAs) (Fig. 1a) and were therefore the focus of this analysis. IUCN category 1A protected areas are referred to as Wildlife sanctuaries in

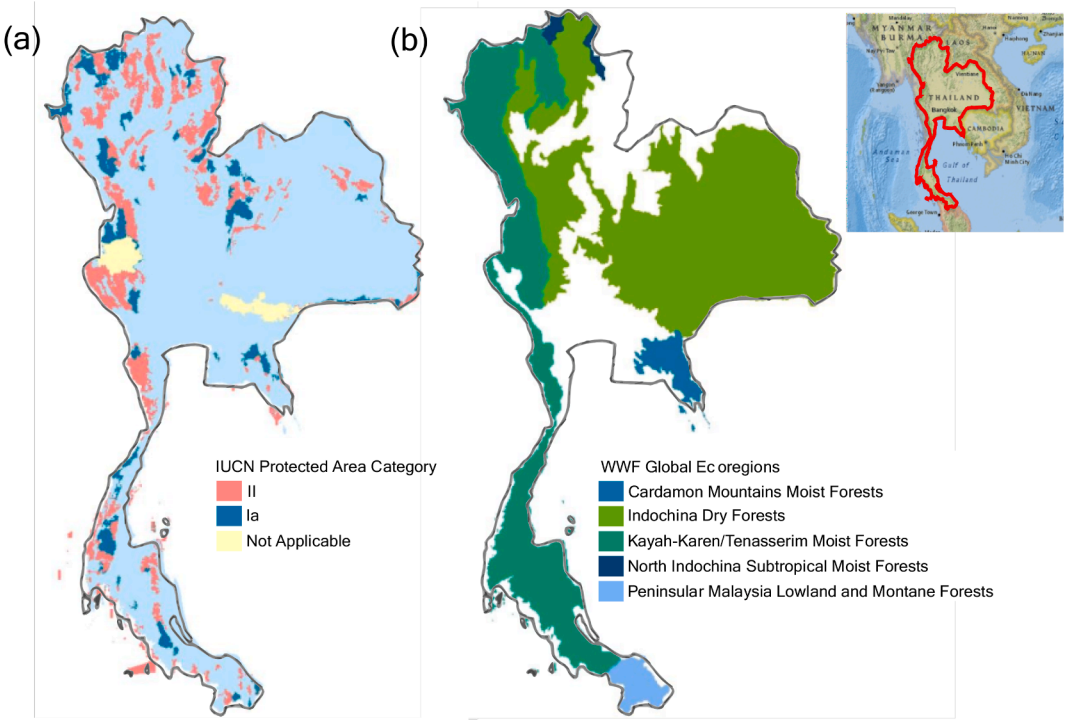


**Fig. 1.** (a) IUCN Protected Areas. (b) World Wildlife Fund Global Ecoregions in Thailand (inset, red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Thailand, IUCN category II are referred to as National Parks (Emphandhu and Chettamart, 2003). In this work, wildlife sanctuaries and national parks conform with their equivalent IUCN nomenclature. All PAs in Thailand are state-owned and managed by the Royal Forest Department, the Department of National Parks, Wildlife and Plant Conservation, and the Department of Marine and Coastal Resources.

### 3.1. Habitat coverage gap analysis

One of the major reasons for continued biodiversity loss is the inability of conservation programs to prevent habitat loss (Jenkins and Joppa, 2009a, 2009b). To evaluate the effectiveness of existing PAs in protecting the high species diversity of the various ecoregions in Thailand, a novel habitat coverage gap analysis was carried out. The gap analysis builds on one previously developed using the World Wildlife Fund (WWF) Global 200 ecoregions (Jenkins and Van Houtan, 2016). These are regions with high levels of endemic species, high species richness, and uniqueness. The WWF ecoregions geographic information system polygons, provide a standard and repeatable manner in which to classify and demarcate forests (Gillespie et al., 2012). There are 15 distinct types of ecoregion within Thailand, of which five are classified as belonging to the WWF Global 200 ecoregions, the most biologically distinct of the world's 825 terrestrial ecoregions (Fig. 1b) (Olson and Dinerstein, 2002).

To assess the degree of coverage and representation of different ecoregions in Thailand, comparison indices (CI) as developed by Hazen and Anthamatten were calculated (Hazen and Anthamatten, 2004). A CI index is calculated by dividing the proportion of protected areas in a particular physiographic region, elevation zone, or ecoregion by that category's share of the country's total land area. A CI value greater than 1 denotes good representation, and a CI value less than 1 represents poor representation (Shrestha et al., 2010).

The representation of each ecoregion within the PA network was calculated by evaluating whether each ecoregion's area share of Thailand was reflected in the extent to which each ecoregion was protected by either National Parks or Wildlife Sanctuaries. Using ArcGIS 10.6.1, a map of the 15 ecological regions within Thailand was superimposed on a map of the PAs. Spatial data of ecological regions within Thailand was collected from the Open Development Organization (2019) and the Global 200 Ecoregions polygons were collected from WWF (Olson and Dinerstein, 2002; Environmental Systems Research Institute, Inc., 2019). The proportion of Thailand taken up by each ecoregion was calculated by dividing the ecoregion area ($km^2$) by the total area of Thailand (513,120 $km^2$). The extent to which each PA category covered different habitat types relative to the percentage that each ecoregion represented Thailand's area was then calculated (Trisurat, 2007; Jennings, 2000). The CI was estimated by dividing each ecoregion's share of Thailand and the amount of that ecoregion falling within PAs.

### 3.2. Taxonomic richness and biodiversity hotspot gap analyses

This study follows a methodology previously described in Powell *et al* to identify and quantify "conservation gaps" where taxonomic richness hotspots are not covered by PAs (Powell et al., 2000). Biodiversity data was obtained from Jenkins and Van Houtan (2016). The dataset provided spatial distributions of mammal, bird, and amphibian species. It also provided information on the IUCN Red List status of species though did not distinguish between varying levels of species vulnerability (e.g. Vulnerable (VU), Endangered (EN) or Critically Endangered (CR)) hence, the analysis focuses on those broadly classified as threatened, that is, VU or worse. To evaluate the effectiveness of the PA system in covering threatened species, the distribution of species hotspots was mapped using a similar methodology to Crain and Tremblay (2014). Firstly, the species richness data was mapped in ArcGIS. Using the Hotspot Analysis Tool (Getis-Ord Gi) from the Spatial Statistics Toolbox, significant hotspots and coldspots of species richness were generated within Thailand (Colwell et al., 2008). Resulting z-scores and p-values for the hotspots aided in identifying species richness clusters that were either high or low relative to the background data matrix. Species richness hotspots (defined as areas with z-scores $\geq 1$; p values $\leq 0.05$) were overlaid with a map of current PAs split into Wildlife Sanctuaries (Ia) and National Parks (II) (Hodgson et al., 2009). The percentage overlap of these two layers was computed. The effectiveness of PAs in covering species ranges was determined according to an adequacy threshold (Venter et al., 2014). The target threshold was met if 10% or more of the hotspot range overlapped with the PAs as Scott et al. (1993) previously determined this level as 'good coverage' of biodiversity hotspots for species conservation.

### 3.3. Elevation gap analysis

The majority of Thailand (64.1%) lies at less than 250 m above sea level and most of the Thai PAs are at higher altitudes. To investigate and quantify the elevational "gap" or bias in coverage by the current PAs, altitude-specific coverage maps were generated which allow correlations of species distributions and performance at varying elevation (Colwell et al., 2008). Elevation data for Thailand (1 km resolution) was provided by the Consultative Group on International Agricultural Research (CGIAR) Consortium for Spatial Information (Consortium for Spatial Information, 2019). Elevation was divided into four ranges (0–250 m, 250–750 m, 750–1500 m, 1500–2700 m) (Khan et al., 1997). The area and proportion of land falling within each was calculated. The map of elevation levels was then superimposed with a map of Thai PAs. The percentage overlap of PAs with the elevation ranges was calculated along with a CI. This study follows a methodology previously described in Powell et al. (2000) to identify and quantify "conservation gaps" where taxonomic richness hotspots are not covered by PAs.

## 4. Results

### 4.1. Habitat coverage gaps

Three Ecoregions were identified as seriously underrepresented by both categories of PA in Thailand (Comparison Index $< 0.2$ in both): the Chao Phraya freshwater swamps (CI = 0.00), Indochina mangroves (CI = 0.10) and the Myanmar coast mangroves (CI = 0.00) (in red in Table 1). National Parks (II) successfully represent>7 ecoregion types with a CI $> 1.00$ whilst 5 remaining ecoregions have CIs that are intermediate (CI $< 0.50$). Similarly, Wildlife Sanctuaries (Ia) effectively represent 6 ecoregion types (CI $> 1.00$) whilst underrepresenting four ecoregions with CIs lower than 0.50. Overall 30% of the habitat types are well represented by the PA network provided by National Parks and Wildlife Sanctuaries. This includes the ecoregions Luang Prabang Montane Rainforest (CI = 2.80, 2.30) and South-eastern Indochina dry evergreen forests (CI = 1.90, 3.40). See Supplementary 1 for more details.

Of the five WWF Global 200 Ecoregions present in Thailand (covering 74.2% of the country) the Indochina dry forests are most underrepresented (Ia = 0.30, II = 0.50). In several other ecoregions, whilst one type of PA fails to effectively represent the biome, the other category represents it well with a CI greater than one (Cardamone mountain rainforests, Northern Indochina Subtropical Forests, Northern Thailand-Laos moist deciduous forests and North Indochina Subtropical Moist Forests). The Kayah Karen and Tenasserim Moist Forests ecoregion, which is the home to the Western Forest Complex, is effectively covered by both the PA types.

The Pru ToDaeng Wildlife Sanctuary, a PA classified as 'Not Reported' by the IUCN does offer some protection to the Indochina mangroves which are currently unprotected by either a National Park or Wildlife Sanctuaries. However, this only accounts for 0.6% of the ecoregion while Indochina mangroves make up 1.6% of Thailand.

Protected areas in the IUCN category "Not Applicable" suggests possible additional minor protection of the ecoregion South-eastern Indochina dry evergreen forest ecoregion which is already well represented by the IUCN PA category II and Ia network (Table 1).

## 5. Taxonomic richness and biodiversity hotspot gaps

### 5.1. Coverage of threatened amphibian hotspots

We identified two currently unprotected hotspots of threatened amphibian species; these were both in the South-east Gulf of Thailand lowland area. No threatened amphibian hotspots were observed in the North or West of the country. Approximately 17% of the identified biodiversity hotspots were covered by PAs suggesting that generally, threatened amphibian species are adequately protected according to our criteria of > 10% hotspot coverage by PAs. Though the two specific gaps were identified, the National Parks in the Gulf of Thailand do provide very good general coverage of the threatened amphibian hotspots (36.8%); This is not the case in Wildlife Sanctuaries where coverage is very low (1.9%). See Supplementary 2 for more details.

### 5.2. Coverage of threatened bird hotspots

There were eight identified hotspots of threatened birds in Thailand, the largest ones being in the Northern and Southern regions of the nation. No hotspots were observed in the Western or Central parts of the country (Fig. 2a). The coverage of threatened bird hotspots demonstrated that National Parks provided adequate protection (15.2%) with a hotspot intersection area of 33,455 $km^2$ whilst Wildlife Sanctuaries were below the coverage target of 10% of the total hotspot area (8.8%) with a hotspot intersection area of only 19,327 $km^2$. See Supplementary 2 for more details.

### 5.3. Coverage of threatened mammal hotspots

The distribution of threatened mammals across Thailand indicated one large central hotspot located across the Western, Central and North-eastern regions of the country. No threatened mammal hotspot was observed in the North or South of Thailand (Fig. 2b). Wildlife Sanctuaries covered 6.24% of this area with an intersection of 20,076 $km^2$. National Parks also fell below the hotspot coverage target, but not by far as these covered 9.9% with an intersection area of 31,950 $km^2$. See Supplementary 2 for more details.

### 5.4. Elevation gaps

Areas at elevations lower than 750 m are underrepresented by the current PA network while those above benefit from being well-covered, in part because these occupy such a small area of the country as a whole (Table 2).

**Table 2**
The percentage area of Thailand occupied by each altitudinal band and the conservation coverage comparison indices for the IUCN protected area categories "Wildlife Sanctuaries" (Ia) and "National Parks" (II) within these. Ecoregions with a CI lower than 0.2 in both categories indicates serious underrepresentation, those with a CI over 0.2 and less than 1 are underrepresented), those that exceed 1 in either category have good representation.

| Elevation Range (m) | % area of Thailand | CI Wildlife Sanctuaries (Ia) | CI National Park (II) |
|---|---|---|---|
| 0–250 | 64.1 | 0.02 | 0.04 |
| 250–750 | 12.5 | 0.29 | 0.32 |
| 750–1500 | 8.8 | 3.17 | 4.36 |
| 1500–2700 | 0.2 | 24.43 | 27.38 |

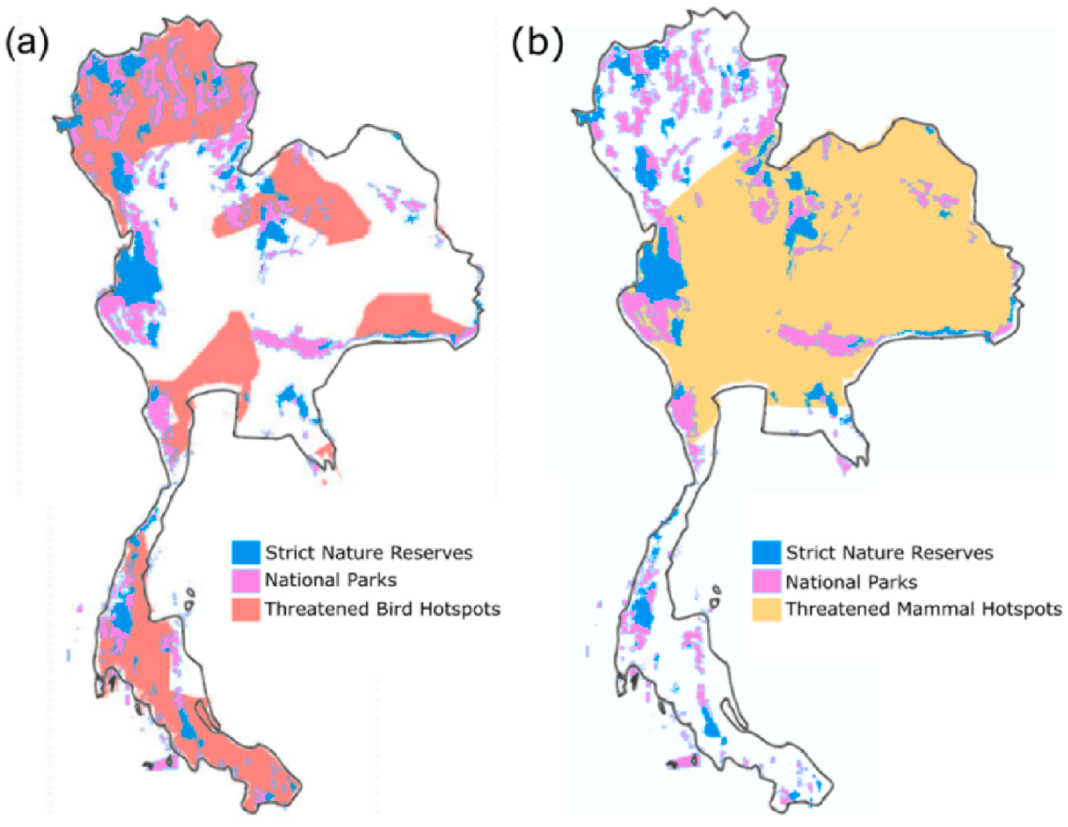


**Fig. 2.** Distribution of protected areas and hotspots of (a) threatened bird species and (b) threatened mammals.

### 5.5. Recommendations for protected area expansion and placement

These analyses indicate that several important conservation gaps exist and strongly indicate three priority areas for future conservation protection. These reflect gaps in important ecoregions and in taxonomic hotspots which are inadequately covered by the spatial layout and network connectivity of Thailand's PA areas. Each area that we recommend for adjustment has a different conservation focus to permit PA expansion relative to varying conservation goals. The areas highlighted in Fig. 2 are the regions in which PAs could expand in the future to meet the Thai government's pledge to protect 40% of the nation.

### 5.6. Which are the underrepresented Ecoregions?

Four ecoregions were underrepresented by the current PA network in Thailand. These regions are the Chao Phraya freshwater swamps, Indochina mangroves, the Myanmar Coast mangroves, and the Central Indochina dry forests. Future conservation allocation should thus focus on these ecosystems to increase the representation of these globally relevant areas (Fig. 3a).

### 5.7. Where are inadequately protected taxonomic hotspots?

We provide recommendations for the expansion and placement of PAs to cover greater areas of threatened Biodiversity hotspots for both birds and mammals. Terrestrial amphibian hotspots are already well-protected with National Parks covering almost 37% of their diversity hotspot area. Fig. 3b indicates two large regions into which PA expansion would give greater coverage of threatened taxonomic hotspots. PA expansion in the central regions of Thailand would deliver protection for greater amounts of threatened mammal hotspots whilst expansion in the South would cover threatened bird species hotspots. The most effective expansion of PAs would potentially be focused on the Central/Western regions of Thailand where threatened bird and mammal species hotspots overlap.

## 6. Discussion

The novel insights that we provide build on the work of Trisurat (2007) which then considered mangrove forests to be the only ecoregion under-protected by the Thai PA network. However, while Trisurat (2007) used the national forest data, we used the WWF global ecoregions framework for identifying habitat coverage gaps. The use of WWF global ecoregions for identifying gaps in Thailand's PA networks is useful for facilitating regional and global scale comparisons. For instance, our research indicates that while Thailand's existing terrestrial PA network provides little coverage of two mangrove ecoregions, the Indochina and Myanmar mangrove ecoregions, at a global scale, mangrove ecoregions enjoy a 20% PA coverage as a result of a high PA coverage in the Neotropics (Jenkins and Joppa, 2009a, 2009b). The Indochina mangrove is one of the tropical ecoregions most likely to be affected by extreme temperature changes and sea-level rise under future climate scenarios (Beaumont et al., 2011; Menon et al., 2010) and expanding PA coverage to prioritise these may help Thailand meet its future climate and biodiversity goals.

Our detailed gap analyses, the taxonomic distributions, and the topographic data, in addition to the WWF Ecoregions framework identifies wetlands, Indochina dry forests, and specific threatened bird and mammal hotspots that should be prioritised for PA coverage. In 1991, preliminary research by Santisuk et al. (1991) indicated that both mangroves and wetlands were underrepresented within the PA network of Thailand and, despite some protection being offered by their 22 Marine National Parks, a substantial protection "gap" persists for these Ecoregions. Since the 1990s, mangroves across Southeast Asia have been lost due to activities such as timber production and aquaculture (Macintosh et al., 2002). The intensive logging of mangrove forests in Thailand as well as the expanded use of the habitat for shrimp farming (Howes et al., 2003) has created increases in economic prosperity but

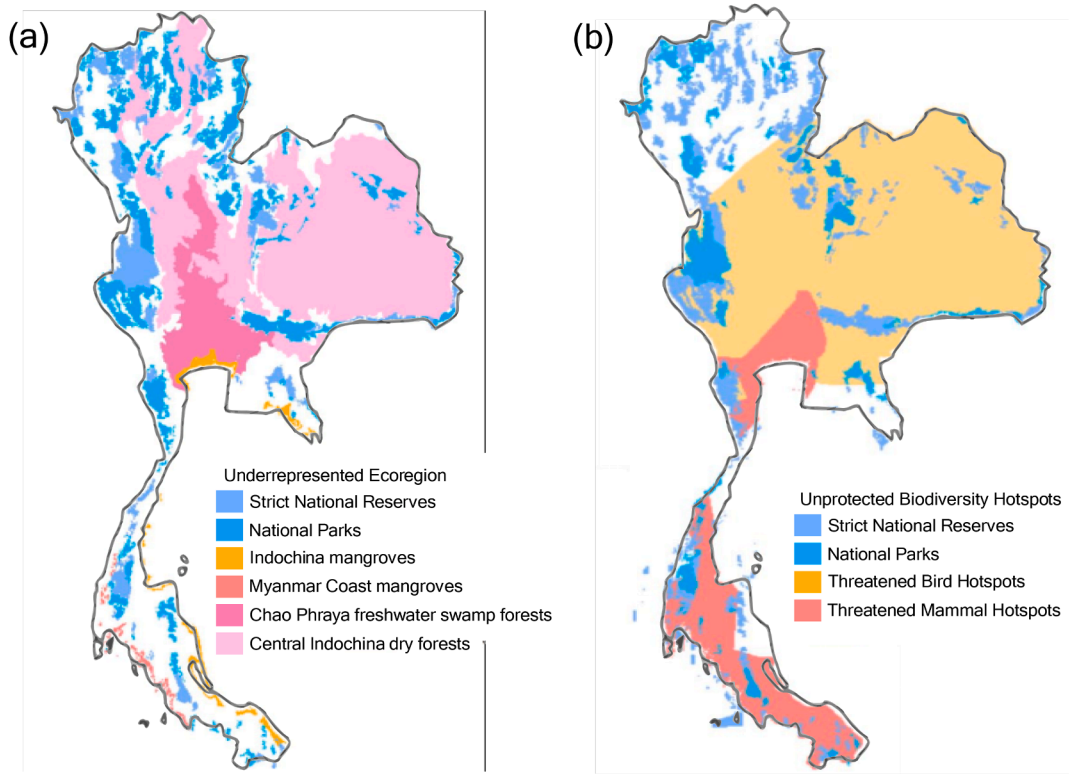


**Fig. 3.** (a) Underrepresented ecoregions and (b) threatened bird (red) and mammal (orange) species hotspots overlain with the current PA network in Thailand. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

has also increased climate risks as this habitat provides a vital buffer against storm surges and numerous other locally important ecosystem services. From 1975 to 2005, 41% of Thailand's mangroves were converted to aquaculture (Giri et al., 2008), making the conservation of remaining the mangroves important. Much of this Ecoregion is proximally governed by local communities that rely on the ecosystem for non-timber related production, for example, feeding livestock (Brenner, 2003) and this provision of both economic and social benefits provides an incentive to protect the habitat in a sustainable manner (Barbier et al., 2011). More state protection is needed to support local conservation potential and more data will inform sustainable mangrove management by local communities (Sodhi et al., 2010). Linking environmental concerns into a socio-economic framework with clear evaluation and reporting activities as a means of supporting coastal conservation has been recommended by (Satumanatpan et al., 2014), along with improving local institutional capacity (Satumanatpan et al., 2017). A specific law, "Promotion of Marine and Coastal Resource Management Act B.E. 2558 (2015), Royal Gazette Volume 132, Part 21, dated 26 March B.E. 2558 (2015)", was passed with the view of designating all remnant mangrove forest in the country to be coastal protected areas. A stronger incorporation of mangroves into marine protected areas (that currently focus on large reefs) and local community-government co-management at scale could improve conservation outcomes for the region's mangrove habitats (Friess et al., 2016). Despite this progress there remains, however, a risk that these vital coastal habitats fall between the focal priorities of both terrestrial and marine management systems.

Another important semi-aquatic habitat, freshwater swamps, currently receive no protection from the Thai PA network. The exposure, for example, of the Chao Phraya freshwater swamps to human activity is critically detrimental as these are home to a wide array of critically endangered fish and amphibians (Ng and Lim, 1992). This ecosystem type also offers many other ecosystem services such as acting as a substantial carbon sink and its preservation would thus be of real value in the context of offsetting Thailand's carbon emissions (Posa et al., 2011). Though multiple important benefits of wetlands are widely acknowledged, in Thailand this Ecoregion is understudied and undervalued; effective conservation would benefit from a greater understanding of the ecosystem functions and linkages (Clews et al., 2018). Closely associated with these swamps are the Chao Phraya Lowland moist deciduous forests which themselves have low levels of representative protection. We propose that providing PA coverage to the Chao Phraya forests and swamps would also help redress the elevation biases we have identified in the existing PA networks. The least protected of the forests, the Indochina Dry Forests in the east of the country, are a globally important WWF Global 200 Ecoregion. These extend from the dry, lower slopes in northern Thailand and the foothills of the Tenasserim Range to the uplands around the Chao Phraya Basin and then across the Khorat Plateau (Wikramanayake et al., 2020). This ecoregion overlaps a region of high human population density and increased fire frequency (Miles et al., 2006). In addition to rising population pressure, economic and agricultural development and particularly the development of rice paddies pose an additional threat to the forests within this ecoregion (Olson and Dinerstein, 2002).

Four of the five WWF Global 200 Ecoregions present in Thailand are largely located at medium to high elevation on commercially low-value land and do offer effective protection to some Thai flora and fauna as these habitats are biodiverse and contain many threatened montane species (Olson and Dinerstein, 2002). These ecoregions are home to over one hundred mammal species including the large Indian civet and one of the last remaining herds of wild elephants (*Elephas maximus*) (Pattanavibool et al., 2004). The current placement of the PA network protects three of these WWF Global 200 Ecoregions well, offering coverage to 20% of the KayahKaren/Tenasserim Forests and 30% of the Cardamone Moist Montane Forests and thus acting to dampen the anthropogenic pressures they are under (Olson and Dinerstein, 2002).

There will always be trade-offs between conservation and human economic development, one of which is preferential placement of protected areas on 'low value' lands such as less-accessible mountainous areas. This pattern is clearly seen in Thailand with a concentration of PAs at high altitude. While protected areas are an important cornerstone of biodiversity conservation, assigning strict protection categories can be difficult in accessible and potentially productive areas, leading to flouting of the protection rules and social conflict over enforcement (Ferraro et al., 2013). Protected area efficacy can thus be impaired by high population densities (Krishnadas et al., 2018), though in areas with existing high levels of human pressure, less strict protections may result in greater avoided losses and better conservation outcomes (Ferraro et al., 2013). A comparison of 40 protected areas and 33 community-managed forests in the tropics revealed that community-managed forests had lower rates of deforestation. Accounting for the socio-economic needs of the local inhabitants can provide a more robust conservation strategy (Porter-Bolland et al., 2012). Community protected areas (CPAs) that were established after consultation with local communities showed high rates of forest cover and biomass recovery in north-western Cambodia (Singh et al., 2018) and provided biodiversity conservation benefits in Southern Mexico (Muench and Martínez-Ramos, 2016). Community-based mangrove management (CBMM) produced higher ecological success for mangrove conservation in Thailand as compared to government run initiatives (Sudtongkong and Webb, 2008). This is evidence that the establishment of community-managed reserves and initiatives developed in conjunction with the local communities can improve conservation outcomes in ecoregions of high human pressure.

### 6.1. Biodiversity hotspots and protected areas

The Thai National Parks and Wildlife Sanctuaries cover approximately 10% of threatened amphibian, bird and mammal hotspots in the country. Thailand is thus ahead of other nations in Southeast Asia where 75% of biodiversity hotspots remain unprotected (Hughes, 2017). The level of protection offered within this area is less reassuring as the Wildlife Sanctuaries are less well located, and offer less coverage of, these hotspots than the National Parks.

Forested areas in Southeast Asia have lost approximately 20–40% of their endemic bird species since the 1990s (Sreekar et al., 2015). This has resulted in the region having the most threatened bird species worldwide with 190 out of 916 bird species being labelled as critically endangered (Pattanavibool and Dearden, 2002). It is crucial that the PA system of Thailand grows to cover the key threatened bird hotspots which lie unprotected in the Southern and Western parts of the country. Mammal decline is a world trend and, since the 1980s, we have lost 13% of tropical mammal species worldwide (Benítez-López et al., 2019). Southeast Asia is home to many endemic and threatened mammal species (Sodhi et al., 2010) and habitat loss and fragmentation are pushing large mammals such as tigers (*Panthera tigris*) to a point where populations are on the verge of becoming ecologically extinct (Duangchatrasiri et al., 2019). In Thailand, the Indochinese leopard (*Panthera pardus delacouri*) has had its range substantially reduced, hindering population survival (Lovari and Mori, 2017). This species along with other subspecies have lost up to 98% of their range forcing individuals to live in isolated and small forested areas (Jacobson et al., 2016).

The most critical biodiversity hotspots for threatened mammals in Thailand lie in, and around, a lowland central area covering districts such as Bangkok, Ayutthaya, Lopburi, and Nakhom Pathom and almost 62% of the nation (Fig. 3b). Protected Area coverage here comes face-to-face with human population and agricultural expansion and the current network covers only 10% of this important threatened mammal hotspot. Increasing PA size and connectivity in this largely peri-urban area has been, and will continue to be one of Thailand's most complex conservation challenges (Wattayakorn, 2006).

National Parks in Thailand provide more protection area within both amphibian and bird biodiversity hotspots than do Wildlife Sanctuaries.

This is likely largely an effect of size with Thai parks covering almost twice the area of the reserves, however, the classification type and effectiveness of governance impacts the quality of protection delivered. This latter factor, the relative effectiveness of governance, may be a valuable addition to future studies evaluating Thai PAs (Eklund and Cabeza-Jaimejuan, 2017). Although PAs in Thailand are government-owned, most are mixed-use and many are simultaneously used for commercial purposes (Ferraro et al., 2013). The IUCN defines Wildlife Sanctuaries (in Thailand, Wildlife Sanctuaries) as "undisturbed by recent human activity" whereas National Parks are in "as natural state as possible" whilst "including subsistence resource use". Where PAs in Thailand have been observed to be multi-use while also classified as Wildlife Sanctuaries then there is either a definition mismatch or a governance failure, either of which may undermine environmental conservation. If PAs within Thailand are being classified as "protected" and yet are not meeting the IUCN criteria this study may have over-estimated the effectiveness of PAs.

Percentage coverage targets are an important step in conserving ecosystems at national scales (Woodley et al., 2019). Targets defined under the United Nation's Strategic Plan for Biodiversity seek to address biodiversity decline by requiring its signatory nations to conserve 17% of their terrestrial areas via protected area coverage (Mappin et al., 2019; Naoe et al., 2015). However, a global scale gap analysis of global ecoregions revealed that only a third of these meet the Aichi Targets (Sayre et al., 2020). Hence, arguably evaluating the coverage protected areas provide to a country's ecoregions is an important first step for national protected area efficacy. However, the remote measurement and mapping techniques presented in this research do enable evaluation of some of the key components of PA effectiveness such as coverage or encroaching land-use change. They cannot assess all aspects of the protection role for which PAs are designed and 'ground truthing', though ideal, often remains out of practical reach. These methods thus have a clear place in the modern lexicon and tool-kit of conservation.

## 7. Conclusions

Thailand treats forest conservation seriously and this study hopes to support the Thai government in delivering an effective conservation program that meets their stated aims. It does so by identifying taxonomic biodiversity hotspots and ecologically unique ecoregions in need of greater coverage from PAs.

We clearly identify that mangrove and wetland ecosystems are seriously underrepresented in the current spatial layout and network connectivity of PA areas and may fall between the priorities of marine and terrestrial conservation aims. Additionally, we identified that the hotspots of threatened birds located in the northern and southern regions of Thailand as well as the majority of the central threatened mammal hotspot are inadequately covered (<10%). We provide a comprehensive overview of where Thailand's PA network could be expanded to include underrepresented ecoregions, essential avian and mammal hotspots and combat elevational biases.

The Thai PA network is highly fragmented and, in addition to increasing the area connected, contiguity and connectivity of the network should be considered. With substantial population expansion in the central area particularly, there will be challenges and trade-offs to be negotiated. We hope, though, that the results of this study can aid policymakers in improving regional PAs.

## Author contributions

Study design and data sourcing: CG; data analysis and drafting: CG. MS provided extensive guidance on data analysis, interpretation, and writing. CMC guided and substantially refined the manuscript.

## CRediT authorship contribution statement

**Minerva Singh:** Conceptualization, Methodology, Software. **Charlotte Griaud:** Conceptualization, Data curation, Formal analysis, Investigation, Project administration, Resources, Visualization. **C. Matilda Collins:** Conceptualization, Data curation, Formal analysis, Investigation, Project administration, Resources, Visualization.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

*Acknowledgements*

We would like to thank Maria Vinogradova for her support during this work as well as Mark Burgman and the Centre for Environmental Policy of Imperial College London for access to ArcGIS, GIS, and R-Studios. This research received no specific grant from any funding agency or commercial or not-for-profit sectors.

*Ethical standards*

No human or animal subjects were interviewed or experimented with; no research ethics assessment or clearance was required.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2021.107536.

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