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Projected Impacts of Climate Change on the Protected Areas of Myanmar

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Abstract: Protected areas are the backbone of biodiversity conservation but are fixed in space and vulnerable to anthropogenic climate change. Myanmar is exceptionally rich in biodiversity but has a small protected area system. This study aimed to assess the potential vulnerability of this system to climate change. In the absence of good biodiversity data, we used a spatial modeling approach based on a statistically derived bioclimatic stratification (the Global Environmental Stratification, GEnS) to understand the spatial implications of projected climate change for Myanmar's protected area system by 2050 and 2070. Nine bioclimatic zones and 41 strata were recognized in Myanmar, but their representation in the protected area system varied greatly, with the driest zones especially underrepresented. Under climate change, most zones will shift upslope, with some protected areas projected to change entirely to a new bioclimate. Potential impacts on biodiversity include mountaintop extinctions of species endemic to isolated peaks, loss of climate specialists from small protected areas and those with little elevational range, and woody encroachment into savannas and open forests as a result of both climate change and rising atmospheric CO_2. Myanmar needs larger, better connected, and more representative protected areas, but political, social, and economic problems make this difficult.

Keywords: bioclimates; biodiversity; climate change; climate types; conservation planning; Global Environmental Stratification; tropical Asia; tropical forests; Southeast Asia

1. Introduction

1.1. Climate Change and Protected Areas

Tropical East Asia supports 15–25% of global terrestrial biodiversity in around 4% of Earth's total land area [1], but is also one of the most threatened regions of the planet [2]. Major threats include the world's highest deforestation rates [3], widespread habitat degradation [4], hunting [5], wildlife consumption and trade [6], and unsustainable land use [7]. In the near future, climate change is likely to become an additional major driver of habitat degradation and species loss [8]. Warming in the tropics has been large relative to natural climate variability, so most regions are already experiencing thermal climates that were unknown in the 19th century [9]. In contrast, changes in precipitation in tropical East Asia have generally been small relative to natural variability. In other parts of the world, many species are already shifting their distributions towards higher altitudes and latitudes [10], but there have been few observations of this in tropical Asia [1,8].

Protected areas (PAs) are the backbone of global biodiversity conservation, but they are fixed in space and the species they protect can respond to climate change only by acclimation and adaptation in situ, by movements within them, or by dispersing to other areas in the regional PA network [11]. Moreover, the ability to disperse to new areas does not ensure survival, although these range shifts may increase the prospect of persistence for some species and populations. There are barriers to movement such as human activities and species interactions [12], and unsuitable geological substrates [13]. Even where there are no barriers, many species may not be able to track high local velocities of climate change [14,15].

The effectiveness of existing PAs in mitigating the impacts of climate change has been questioned, because of their immobility, spatial bias, and low percentage coverage [16]. Species will be lost from existing PAs if their entire climate envelope shifts outside the boundaries. However, there is empirical evidence that protected areas and networks can help to protect biodiversity in the face of both climate change and habitat loss [10]. These studies also suggest ways in which protected area networks can be modified to reduce their vulnerability. A recent study showed that an optimum configuration of protection for 30% of tropical land area, combined with limiting global warming to <2 °C, reduces tropical extinction risks by more than 50% [17].

1.2. Myanmar

Myanmar is the second largest country in Southeast Asia, with a land area of 676,577 km^2 and human population of 54 million. It extends from 9°28′ to 28°29′ N and 92°10′ to 101°10′ E, bordering India, Bangladesh, the Bay of Bengal, and the Andaman Sea in the west, and China, Laos, and Thailand in the east. Geographically, it is exceptionally diverse, with coastal plains, the central basin and lowlands, the western ranges, the eastern Shan plateau, and mountains in the north, rising to 5881 m at Hkakabo Razi. The climate is dominated by the southwest monsoon, which interacts with the topography to produce a wide range of different climate types. In most areas there are three distinct seasons: a cooler winter season from early November to late February, a hot season from March to mid-May, and a rainy season from mid-May to mid-October. Mean annual rainfall is 500–1000 mm in the central dry zone, higher in the eastern and northern mountains, and highest in the southern and Rakhine coastal regions, where it can exceed 5000 mm. Mean annual temperature declines with altitude, from 26–28 °C in the tropical lowlands to <0 °C on the summits of the highest mountains, and temperature seasonality increases with latitude, with little variation in the south [18].

Myanmar is recognized as one of the most biodiverse countries in the world, as a result of the interaction between geography, topography, and climatic conditions [19]. It forms a major part of the Indo-Burma biodiversity hotspot, which is a global priority for conservation, with high levels of diversity and endemism, but also increasing threats from habitat loss and overexploitation [2]. Myanmar contains a great diversity of ecosystems, but most of the land area would have supported dense forests of some kind, except for areas above the treeline at c. 4000 m in the far north, and the drier parts of the central dry zone, which were covered in open forest and savanna. Dense forests ranged from lowland tropical rainforest in the south to evergreen needle-leaf forests above 3000 m in the far north. Much of this forest has been cleared or badly degraded. Forest still covered 44% of the land area in 2020, but the annual rate of forest loss for 2010–2020 was 1%, which was the second highest percentage loss in Southeast Asia and the 7th highest in the world for net forest area loss [20]. Deforestation rates were even higher in mangrove forest (3.60–3.87% for 1996–2016) [21].

Due to the economic and political isolation of Myanmar over the past 70 years, as well as internal conflicts in some regions, it retains a higher amount of native forest and the largest areas of unfragmented forest ecosystems in the region [22]. However, Myanmar is one of the least developed countries in Asia and, along with the rapid socio-economic development, it is facing accelerating deforestation under a more open and democratic political system [23,24]. The transformation of land use from subsistence to commercial agricultural production has accelerated since the late 1980s: oil palm concessions in southern Myanmar and rubber plantations in south-eastern Myanmar (Tanintharyi Division, Mon State, and Kayin State) have had significant impacts on biodiversity [23,25].

Existing threats to biodiversity in Myanmar can be made more serious by climate change, through both direct impacts, like the loss of suitable habitat for species and reduced resilience in ecosystems, and through indirect impacts on humans and their dependence on the products and services produced by natural ecosystems [26]. Climate change impacts on biodiversity in Myanmar are still understudied, however. Between 1981 and 2010, the mean annual temperature increased by 0.25 °C per decade, within inland regions warming faster than coastal regions, and the mean annual rainfall also increased in most regions [18]. According to the Global Climate Risk Index 2020, Myanmar was the country second most affected by extreme weather events between 1999 and 2018, although 95% of the damage and casualties were caused by a single event, Cyclone Nargis, in 2008 [27]. The number of drought and flood events has increased, as has the intensity and frequency of cyclones. Cyclones Mala (2006), Nargis (2008), and Giri (2010) were the most severe and damaging cyclones Myanmar has experienced. Moreover, during the summer of 2010, 1482 cases of heat-related disorders and 260 heat-related deaths due to extreme high temperature were reported, and in July and August 2015, 1.6 million people were displaced as the result of flooding and landslides [28].

1.3. Myanmar's Protected Area System

Myanmar's first protected areas were established as wildlife sanctuaries around Buddhist monasteries since the 11th Century and some of these were transformed into formal protected areas to protect endangered wildlife species during the colonial period [29]. However, the major expansion in the number of PAs and the total area protected has occurred since 1980. There are currently 45 protected areas, covering 5.85% of the country's area, under the management of the Nature and Wildlife Conservation Division (NWCD) within the Ministry of Natural Resources and Environmental Conservation [30]. Among the 45 current PAs, eight (Hkakaborazi National Park, Htamanthi Wildlife Sanctuary, Indawgyi Lake Wildlife Sanctuary, Alaungdaw Kathapa National Park, Inlay Lake Wildlife Sanctuary, Meinmahla Kyun Wildlife Sanctuary, Lampi Marine National Park, and Natmataung National Park) have been recognized as ASEAN Heritage Parks (AHPs) for their particular biodiversity value or uniqueness within ASEAN countries [30].

The PA system is intended to represent the full complement of the country's biogeographic regions, but in practice, their effectiveness in conserving biodiversity is reduced by additional factors related to size, geographic representation, inadequate funding and management capacity, weak policy, and the regulatory framework [26]. Some PAs are close to national borders, like Khakaborazi National Park, Lenya National Park (with Namtok Huay Yang in Thailand), Tanintharyi Nature Reserve (with Kaengkrachan Forest Complex in Thailand), but still lack transboundary protected area management, which can play a crucial role in preserving biodiversity. Three of the 45 protected areas (Htaung Wi Taung, Thamihla Kyun Wildlife Sanctuary, and Eaisarthaya Cave-Geographic-Features Significant Area Myanmar) were omitted from the analyses in this study because they are very small.

Optimization of the spatial configuration of protected area networks would ideally be based on species distribution data [17], but such data are often missing, very patchy, or inaccessible in Myanmar. In this paper, therefore, we used a spatial modeling approach based on a statistically derived bioclimatic stratification [31,32] to understand the spatial implications of projected climate change for Myanmar's protected area network by 2050 and 2070. Changes in the distribution of bioclimatic zones and strata are used as indicators of potential impacts on species and ecosystems. This approach avoids the "cascade of model uncertainties" associated with the modeling of biological impacts, even in areas where the species distribution data are available [32]. The main objectives were:

1. To summarize the temporal and spatial patterns of climate change projected for Myanmar by 2050 and 2070.
2. To classify and map the climate types currently present in Myanmar and project the changes in the areas and spatial distributions of these climate types by 2050 and 2070.

3. To assess the representativeness of the protected area system in terms of the current climate types present in Myanmar.
4. To assess the impact of projected climate change on the representation of climate types within individual protected areas and in the protected area system as a whole.
5. To identify the likely impacts of climate change on the protection of biodiversity in Myanmar's protected areas.

2. Materials and Methods

2.1. Bioclimatic Stratification

A spatial modeling approach based on a statistically derived bioclimatic stratification was used to predict and understand the spatial implications of projected climate conditions for Myanmar by the year 2050 and 2070. The spatial shifts of bioclimatic zones and strata were evaluated to estimate the potential impacts of climate change across Myanmar. The construction of the Global Environmental Stratification (GEnS), used here, is described in detail by Metzger et al. [33] and its use in the interpretation, understanding, and communication of global climate change projections is discussed by [32]. The GEnS is intended to be a globally consistent classification of land into relatively homogenous units, based on a statistical clustering of climate variables [33]. The GEnS classifies the world's land surface into 125 relatively homogeneous bioclimatic strata, aggregated into 18 zones, based upon a statistical analysis of current climate data (1961–2000). The zones have descriptive names while the strata have unique codes. To produce the original GEnS, Metzger et al. identified a subset of 36 biophysically relevant bioclimatic variables based on a statistical screening of 42 variables available from various climate datasets [33]. Principal Components Analysis revealed that the first three principal components, explaining greater than 99% of the total variation, were determined by only four variables.

➢ Degree days >0 °C [34]
    - Daily sum of annual degrees of temperature above 0 °C, reflecting latitudinal and altitudinal temperature gradients, and plant growth periods [34].
➢ Aridity-Wetness Index (AWI) [35]
    - Ratio of annual precipitation over annual potential evapotranspiration (PET), calculated globally using the Hargreaves (1994) model [36].
➢ Monthly mean temperature seasonality [34]
    - Standard deviation of the monthly mean temperature distribution
➢ Potential evapotranspiration (PET) seasonality [35]
    - Standard deviation of the monthly mean PET distribution.

2.2. Modeling of Projected Future Climate Conditions

Projected future conditions for the years 2050 (average for 2041–2060) and 2070 (average for 2061–2080), also derived from WorldClim 1.4, were selected to represent a short to medium-term time frame relevant to the needs of ecosystem managers, planners, and other policy and decision makers. The environmental stratification of Myanmar, which is based on climate data from 1960 to 2000, was reconstructed for 2050 and 2070, based upon projections for future climate conditions from three CMIP5 Earth System Models (ESMs), HadGEM2-ES, CNRM-CM5 and GFDL-CM3, which have been previously recommended for the region [37,38]. We used two Representative Concentration Pathways (RCPs), RCP2.6 and RCP8.5, representing the low and high greenhouse gas concentration scenarios, respectively [39]. The socio-economic assumptions on which these scenarios were originally based are no longer realistic in 2020, but they still serve to bracket the potential range of radiative forcing by the end of the century. RCP2.6 is consistent with meeting the Paris Agreement's 2 °C global warming target. The ESM runs were downscaled using the Delta method to 1 km^2 resolution, as with the current climate conditions. Note that the stratification is based on the current climate and that future climates are assigned to the most similar current climate zone and stratum.

3. Results

3.1. Projected Climate Change by 2050 and 2070

The mean annual temperature for Myanmar in 1960–2000 was 23.2 °C, mean maximum temperature of the warmest month was 32.9 °C, and mean annual precipitation was 1992.4 mm. The CMIP5 model projections for Myanmar in 2050 and 2070 show an acceleration of recent warming trends. By 2050, mean annual temperature is predicted to increase by 1.1–2.0 °C under RCP2.6 and 1.7–3.0 °C under RCP8.5 (Supplementary Material Table S1). The projected increase in mean annual temperature by 2050 is greatest in the eastern parts of Myanmar, approaching and exceeding 3.0 °C under the RCP8.5 scenario with GFDL-CM3 and HadGEM2-ES (Supplementary Material Figure S1). By 2070, mean annual temperature is predicted to increase by 1.2–2.3 °C under RCP2.6 and 2.6–4.4 °C under RCP8.5 (Supplementary Material Table S1). The increase in mean annual temperature by 2070 is high across almost all of Myanmar, approaching and exceeding 4.0 °C under the RCP8.5 scenario with GFDL-CM3 and HadGEM2-ES (Supplementary Material Figure S2). Mean maximum temperature is predicted to increase by 1.1–1.8 °C under RCP2.6 and 1.4–3.1 °C under RCP8.5 by 2050 and 1.0–1.8 °C under RCP2.6 and 2.4–4.0 °C under RCP8.5 by 2070 (Supplementary Material Table S1) (Supplementary Material Figures S3 and S4).

In contrast to the generally consistent pattern of warming, there is a wider spread among models for projections of mean annual precipitation (Supplementary Material Table S1). By 2050, annual precipitation is predicted to increase by 1.6–5.4% (33–114 mm) under RCP2.6 and change by −1.5–6.2% (−30–133 mm) under RCP8.5 (Supplementary Material Table S1) (Supplementary Material Figure S5). By 2070, it is predicted to increase by 2.4–6.4% (49–137 mm) under RCP2.6 and 5.2–8.5% (109–184 mm) under RCP8.5 (Supplementary Material Figure S6). Note that these changes are small relative to current interannual variation, and to rainfall variability over the last 200 years reconstructed from a tree-ring chronology [40].

3.2. Bioclimatic Stratification of Myanmar under Current Conditions

Nine bioclimatic zones (Table 1) and 41 bioclimatic strata (Table 2) were identified in Myanmar (Figure 1), ranging from the Extremely Cold and Wet zone at the highest elevations in the north, with a single stratum, to the Extremely Hot and Xeric zone at low elevations in the central dry zone, with three strata, of which Q4 is the hottest and driest (Table 1). The mean annual temperatures for these zones are correlated with their average elevation and range from −4.1 °C, for the coldest zone at an average elevation of 5409 m to 26.7 °C, for the hottest zone at an average elevation of 155 m. The maximum temperatures are also correlated with their average elevation and range from 7.0 °C for the coolest zone to 38.1 °C for the hottest zone. However, annual precipitation shows no consistent relationship with elevation. Of the nine zones, the three at the highest elevations (Extremely Cold and Wet, Extremely Cold and Mesic, and Cold and Mesic) each cover <1% of the total land area of Myanmar. The zones with the largest areas are Extremely Hot and Moist, covering 224,377 km^2 (34% of the total area), mostly in the south, and Hot and Mesic, covering 219,324 km^2 (33%), mostly further north.

Table 1. Characteristics of the bioclimatic zones in Myanmar based on climate data from 1960 to 2000.

Bioclimatic Zone	Area (km^2)	Area (%)	Mean Elevation (M A.S.L)	Mean Annual Temperature (°C)	Mean Maximum Temperature (°C)	Mean Annual Precipitation (mm)
Extremely Cold and Wet	3	0	5409	−4.1	7.0	692.3
Extremely Cold and Mesic	816	0	4450	1.2	12.4	749.9
Cold and Mesic	2900	0	3612	5.9	16.3	969.2
Cool Temperate and Moist	4831	1	2842	10.3	19.6	1362.7
Warm Temperate and Mesic	55,576	8	1595	16.6	25.2	2219.7
Hot and Mesic	219,324	33	579	22.7	32.2	2015.7
Hot and Dry	78,900	12	1190	19.8	29.6	1551.2
Extremely Hot and Moist	224,377	34	183	26.0	35.4	2449.8
Extremely Hot and Xeric	77,215	12	155	26.7	38.1	949.7

Table 2. Characteristics of the bioclimatic strata in Myanmar based on climate data from 1960 to 2000.

Zone	Strata	Area (km^2)	Mean Elevation (m)	Mean Annual Temperature (°C)	Mean Maximum Temperature (°C)	Mean Annual Precipitation (mm)
D. Extremely cold and wet	D3	3	5409	−4.1	7.0	692.3
F. Extremely cold and mesic	F4	23	4940	−1.9	9.3	700.6
	F13	793	4436	1.3	12.5	750.6
G. Cold and mesic	G11	1649	3815	4.7	15.3	889.6
	G13	1251	3343	7.5	17.5	1074.2
J. Cool temperate and moist	J1	245	3137	8.7	17.6	1379.4
	J2	21	2695	11.7	19.5	2636.6
	J3	1185	3026	9.2	18.9	1185.9
	J4	3291	2753	10.8	20.0	1422.6
	J5	89	2900	10.2	20.3	1152.4
K. Warm temperate and mesic	K1	1139	2551	12.1	21.4	1380.4
	K2	5943	2236	13.4	22.0	1963.6
	K7	8341	1981	14.9	23.6	1767.9
	K10	5	2028	15.4	24.8	1381.4
	K12	33,429	1347	17.7	26.1	2534.1
	K13	6719	1626	17.0	26.2	1585.6

Table 2. *Cont.*

Zone	Strata	Area (km^2)	Mean Elevation (m)	Mean Annual Temperature (°C)	Mean Maximum Temperature (°C)	Mean Annual Precipitation (mm)
M. Hot and mesic	M1	25,597	783	20.8	29.1	2680.0
	M2	48,533	784	21.7	31.6	1608.4
	M4	23,284	921	22.1	32.6	1315.9
	M5	25,050	294	23.7	31.8	3328.4
	M6	1	892	22.8	33.6	967.0
	M7	23,629	702	23.2	33.6	1351.2
	M8	73,230	320	23.8	33.2	2041.4
N. Hot and dry	N3	24,895	1356	18.7	28.3	1611.0
	N4	27	1725	18.4	28.7	1213.5
	N8	36,707	1060	20.1	29.9	1616.5
	N9	7264	1332	19.9	30.1	1339.9
	N11	10,007	1145	20.9	31.3	1316.4
R. Extremely hot and moist	R1	20,886	533	24.1	34.5	1400.4
	R2	331	783	24.3	35.7	968.3
	R3	17,682	226	25.5	33.8	3076.9
	R4	3400	397	25.1	32.3	1715.3
	R5	44,993	271	25.1	35.7	1233.9
	R6	11,244	270	25.7	34.5	2268.1
	R7	101,364	39	26.7	35.9	3276.1
	R8	5924	70	26.5	33.2	2940.5
	R9	17,097	272	26.1	37.0	1536.6
	R10	1456	67	26.6	33.2	2246.3
Q. Extremely hot and xeric	Q1	45,901	188	26.5	37.8	832.8
	Q3	23,609	110	27.0	38.4	1244.2
	Q4	7705	93	27.4	39.1	744.3

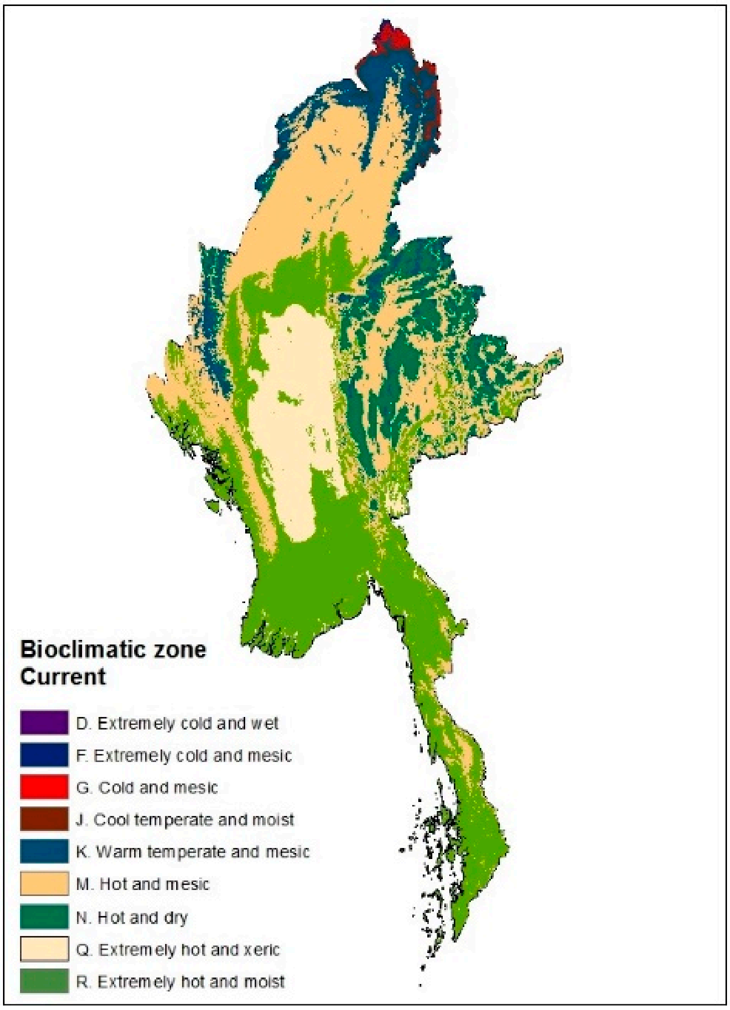

Figure 1. Distribution of the bioclimatic zones of Myanmar based on climate data from 1960–2000.

3.3. Projected Changes in the Spatial Distribution of Bioclimatic Zones and Strata by 2050 and 2070

By the year 2050, substantial spatial displacement of the bioclimatic zones is seen under both RCPs (Supplementary Material Figure S7). Under RCP2.6, there is a large expansion in the extents of the Extremely Hot and Xeric zone (from 77,215 km^2 to 93,411–137,028 km^2) and Extremely Hot and Moist zone (from 224,377 km^2 to 245,484–267,000 km^2), and also in the Hot and Mesic zone (from 219,324 km^2 to 223,454–233,226 km^2), except with HadGEM2-ES, which predicts a small decrease (from 219,324 km^2 to 218,834 km^2), while all other zones decrease with all models (Supplementary Material Table S2). All zones exhibit upward shifts in average elevation of 125–282 m. Under RCP8.5, there are similar expansions in the Extremely Hot and Xeric zone (from 77,215 km^2 to 109,293–154,055 km^2) and the Extremely Hot and Moist zone (from 224,377 km^2 to 245,484–267,000 km^2), but the Hot and Mesic zone expands only in CNRM-CM5 (from 219,324 km^2 to 227,878 km^2), while it decreases in GFDL-CM3 and HadGEM2-ES (219,324 km^2 to 184,533–172,060 km^2). The upward shift for all zones is 181–425 m. There are large decreases in the Hot and Dry zone under both RCP2.6 (from 78,900 km^2 to 23,162–38,695 km^2) and RCP8.5 (to 10,550–25,465 km^2). (Supplementary Material Table S2). Changes in strata are larger than those for zones, reflecting their narrower definitions, but are model-dependent (Supplementary Material Table S4). Four new strata appear by 2050, but most only with GFDL-CM3, and several disappear. Overall, 9–13% of the total area of Myanmar will change zone under RCP2.6 and 11–23% under RCP8.5, while 21–33% under RCP2.6 and 27–39% under RCP8.5 will change stratum (Supplementary Material Table S3).

In general, projected changes by 2070 are in the same direction as 2050, but larger for both zones and strata (Supplementary Material Figure S8). Under RCP2.6, there is a large expansion in the extent of the Extremely Hot and Xeric zone (from 77,215 km^2 to 104,605–146,458 km^2) and the Extremely Hot and Moist zone (from 224,377 km^2 to 242,222–264,775 km^2) while the areal extent of all other zones decreases (Supplementary Material Table S3). All zones show an upward shift in average elevation of 128–309 m. Under RCP8.5, there are similar expansions in the Extremely Hot and Xeric zone (from 77,215 km^2 to 84,563–137,241 km^2) and the Extremely Hot and Moist zone (from 224,377 km^2 to 278,832–426,970 km^2), while all other zones decrease. The upward shift for all zones is 299–614 m. Interestingly, the Hot and Mesic zone will increase under RCP2.6 (from 219,324 km^2 to 222,830–224,671 km^2), but decrease under RCP8.5 (from 219,324 km^2 to 127,610–199,490 km^2) (Supplementary Material Table S4). Changes in strata are similar to but larger than those by 2050 (Supplementary Material Table S5). Overall, 8–14% of the total area of Myanmar will change zone under RCP2.6 and 17–32% under RCP8.5, while 20–35% under RCP2.6 and 34–52% under RCP8.5 will change stratum (Table 3).

Table 3. Land area and percentage of total land area in Myanmar that is projected to change its bioclimatic zone or stratum by 2050 and 2070, with three earth system models and two RCPs.

Model	2050				2070			
	Zone Shift km^2		Zone Shift %		Zone Shift km^2		Zone Shift %	
	RCP 2.6	RCP 8.5	RCP 2.6	RCP 8.5	RCP 2.6	RCP 8.5	RCP 2.6	RCP 8.5
CNRM-CM5	56,453	74,424	9	11	54,881	114,481	8	17
GFDL-CM3	85,050	152,731	13	23	91,766	189,990	14	29
HadGEM3-ES	77,305	137,663	12	21	76,846	209,941	12	32
Model	**2050**				**2070**			
	Strata Shift km^2		Strata Shift %		Strata Shift km^2		Strata Shift %	
	RCP 2.6	RCP 8.5	RCP 2.6	RCP 8.5	RCP 2.6	RCP 8.5	RCP 2.6	RCP 8.5
CNRM-CM5	138,133	182,436	21	27	130,518	225,491	20	34
GFDL-CM3	215,971	256,429	33	39	233,127	319,962	35	48
HadGEM2-ES	174,295	246,351	26	37	177,415	346,135	27	52

3.4. Climates and Climate Change in the Protected Areas

The bioclimatic zones and strata were overlain on a map of the protected areas. All nine zones and 37 out of 41 bioclimatic strata are found in PAs. However, representation of the zones (Table 4) and strata (Supplementary Material Table S6) varied greatly. Of the whole area protected, 47% (19,513 km^2) is in the Hot and Mesic zone, 30% (12,564 km^2) in the Warm Temperate and Moist zone, and 11% (4555 km^2) in the Extremely Hot and Moist zone (Table 4). All other zones contributed <5% each. The five coolest zones had >30% of their total area protected, while the two driest zones had <1%.

Table 4. Representation of bioclimatic zones within protected areas in Myanmar.

Bioclimatic Zone	Total Area (km^2)	Area Protected (km^2)	% of Zone Protected	% of Total Protected Area
Extremely Cold and Wet	3	1	33	0
Extremely Cold and Mesic	816	582	71	1
Cold and Mesic	2900	1958	68	5
Cool Temperate and Moist	4831	1529	32	4
Warm Temperate and Mesic	55,576	12,564	23	30
Hot and Mesic	219,324	19,513	9	47
Hot and Dry	78,900	326	0	1
Extremely Hot and Moist	224,377	4555	2	11
Extremely Hot and Xeric	77,215	646	1	2

Projected changes in climate within the protected areas are similar to those for Myanmar as a whole, with most zones shifting upslope (Supplementary Material Table S7). By 2050, 64–70% of all protected areas are projected to shift at least partly to different bioclimatic zones under RCP2.6 and 67–75% under RCP8.5, while 81–82% are projected to shift at least partly to new strata under RCP2.6 and 80–82% under RCP8.5 (Supplementary Material Table S9). In most cases, the majority of each protected area remains in the same zone, but 0–5% of all protected areas are predicted to shift completely to different zones under RCP2.6 and 2–12% under RCP8.5, and 10–19% are predicted to shift completely to different strata under RCP2.6 and 17–26% under RCP8.5 (Supplementary Material Table S10). The projected changes are similar but larger by 2070 (Supplementary Material Tables S8, S11 and S12). Several new strata are also projected to appear within the Cold and Mesic, Hot and Dry, Extremely Hot and Moist, and Extremely Hot and Xeric zones under both RCPs by 2050 and 2070 (Supplementary Material Tables S13 and S14). In the protected area system as a whole, under both RCPs, there are large declines in the areas of the four coolest zones and large increases in the areas of the two hottest zones by 2050 (Supplementary Material Table S7), but with the amount of change depending on the model. These changes are generally projected to increase further by 2070 (Supplementary Material Table S8). The spread among individual reserves is very broad: 0–100% of each PA shifting to a new zone and/or stratum (Supplementary Material Tables S15–S18). Both the smallest and largest percentage changes are in PAs with a small elevational range and/or total area, where the entire reserve either switches or does not.

4. Discussion

The bioclimatic stratification of Myanmar highlights the climatic diversity in the country, from the Extremely Cold and Mesic zone, above the alpine treeline on the tallest mountains in the north of the country, to the Extremely Hot and Moist zone, until recently largely occupied by tropical lowland rainforest, in the south, and the Extremely Hot and Xeric zone, with remnant patches of savanna and deciduous forests, in the center of the country. Representation of the bioclimatic zones and strata in protected areas is currently very uneven, with >30% of the areas of four coolest zones being protected and <1% of the two driest. To a large extent this reflects human pressures within these zones, with the cool high mountains sparsely populated, while the drier areas have had dense populations for centuries. The hyperdiverse Extremely Hot and Moist zone in the south is also underrepresented in terms of percentage area (2%) and is now under threat from expanding plantations [25]. The percentage of the total land area protected in Myanmar (<6%) is also small, by both regional and global standards, and well below both the 17% area target (Aichi target 11) agreed by the Convention on Biological Diversity for 2020 and the proposed 30% area target for 2030 [41].

The three earth system models used in this study all project an acceleration of recent warming trends across the whole of Myanmar, but with a fairly large spread (<1.5 °C) among models in the amount of warming. This spread is even wider for rainfall, in terms of both the amount and the spatial pattern of increase and decreases. In most projections and over most of Myanmar, rainfall is projected to increase, but the projected increases are small relative to both current interannual variation and variability over the last 200 years [40]. Changes in the bioclimatic stratification are therefore dominated by the increases in temperature, resulting in an upwards shift in average elevation for all zones and strata. The hottest zones increase in area while the cooler zones decline, with the coldest disappearing with two models. Changes in the strata are greater, reflecting their narrower bounds, but mostly model-dependent. Up to a third of Myanmar's land area will change bioclimatic zone by 2070, depending on the model and RCP, while up to half will change stratum. Projected changes within the protected area system are similar to those in the country as a whole, but individual reserves are highly variable, with a complete switch of bioclimatic zone or stratum in some small reserves, as well as some larger ones with a low elevational range.

The consequences of these climatic changes for biodiversity depend on how effective the bioclimatic stratification is as a proxy for species and ecosystems, both now and in the future. Too little biodiversity data is available in Myanmar to validate this assumption for the present day, but there is support from studies in similar ecosystems in southwest China [31] and the transboundary Kailash Sacred Landscape of China, India, and Nepal [42], as well as studies in other parts of the world. Validation of future predictions is not possible, but theory, paleoecological evidence, and some observations of responses to recent climate change suggests that the populations of many well-dispersed species will track changes in climate across the landscape [14,15]. However, poorly dispersed species and those with long life-cycles will not be able to keep up. In particular, most of the individual trees that will dominate Myanmar's forests in 2050 and 2070 are already growing and cannot move, although a majority of 20 tree species studied in Natma Taung National Park had a higher proportion of juveniles at the upper end of their ranges, suggesting that their populations will eventually shift upslope [43]. Failure to track rapid climate change creates ecosystems that are not in equilibrium with the climate of the time, with consequences that are currently unclear, but are likely to be include slower growth and increased vulnerability to pests and diseases [14].

An additional complication comes from the increase in carbon dioxide concentrations, which is not only the largest single driver of climate change, but also has a direct impact on plant physiology and thus on plant growth, competition, and vegetation [44]. This means that bioclimate alone cannot predict future vegetation structure and species composition, which will also depend on the CO_2 concentration. In other words, future analogues of modern climates are not necessarily ecologically equivalent. Rising atmospheric CO_2 does not impact animals directly, but they will be impacted indirectly through changes in vegetation structure and composition. A recent modeling study which simulated the impacts of climate change on vegetation in South Asia (including Myanmar), with and without increasing CO_2, found that simulations with increasing CO_2 resulted in transitions from savanna into forest and deciduous forest into evergreen forest which did not occur in the absence of elevated CO_2 [44]. The vegetation model used (aDGVM2) does not include nutrient limitation, so the impacts of elevated CO_2 may be overestimated, but woody invasion of savannas in other parts of the world has been attributed, in part, to this mechanism [45].

The disappearance from Myanmar of the coldest bioclimatic zone, Extremely Cold and Wet, will have little direct impact on biodiversity, since this represents the summit zone of Mt Khakaborazi, which is barren rock and ice. In contrast, the large declines in the areas of the next three coolest zones, in both the country as a whole and the protected area system, will substantially reduce the area available for species adapted to high-mountain forest and alpine habitats in Myanmar. Upward shifts of several hundreds meters in steep topography, where they represent horizontal movements of a kilometer or two, may be within the dispersal capacities of most plant and animal species, but the area available declines with altitude on most mountains, and reaches zero at the summit. On isolated high mountains, such as Mt Victoria (Natma Taung) (3074 m) in southwest Myanmar, endemic species found only near the summit face potential mountain-top extinction. At the other extreme, species occurring in protected areas with little or no elevational range, because of flat topography (such as Chatthin and Shwesettaw Wildlife Sanctuaries) or small size (such as Chungponkan Wildlife Sanctuary, Lawkanada Sanctuary, and Wetthikan Bird Sanctuary), are threatened by the total loss of the bioclimatic zones or strata to which they are adapted, as the entire protected area undergoes a shift. Species adapted to open forests and savanna, such as the endangered Eld's deer (*Rucervus eldi thamin*) may be particularly vulnerable to woody encroachment and canopy closure, as a result of climate change and/or rising atmospheric CO_2 (see above).

The use of climatic data as a surrogate for biodiversity is not ideal, since bioclimatic zones and strata are not, in themselves, targets for conservation. This approach was necessitated by the patchy availability of biodiversity data in Myanmar. As more such data becomes available, it should be possible to calibrate the bioclimatic stratification in a way that makes it more useful for conservation planning [46]. Where biodiversity data is lacking, the addition of geological information would be an improvement on using just climate as a surrogate. Myanmar's extensive karsts, for example, support numerous narrow-range endemic species whose presence could not be predicted from climate alone.

It would be possible to make recommendations for additional protected areas and the expansion of existing ones based on this study, although recommendations based on climate variables alone should only be a first step. The vulnerability of the existing protected areas depends not only on their exposure to climate change, as assessed here, but also on their resilience (indicated by size, isolation, topographic variability, etc.) and capacity for adaptation [47]. Clearly, both the total area and the representativeness of the protected area system need to be increased, and connectivity across climatic gradients should be enhanced to permit species movements [11]. Extensive restoration of degraded vegetation, both passively (by removing the causes of degradation) and actively (by planting), may be needed, particularly in some lowland and drier areas [48]. Reintroduction of locally extirpated animal species may be practical where hunting can be controlled.

However, the protected area system in Myanmar is not currently limited by technical knowledge, but rather reflects, to a large extent, the legacies of decades of armed internal conflicts, some of which continue at a lower level, despite cease fires and peace agreements. These conflicts have limited the collection of biodiversity data and continue to make it very difficult to create new protected areas agreed by both the central and regional governments. As in many other countries, biodiversity protection in Myanmar is intimately linked with a variety of political, social, and economic issues, and progress in conservation will depend on progress in solving all these. Experience in some of these countries suggests that the best way forward is to take the technical knowledge—in this case, from climate change science—as a starting point and then to focus on policy, planning, and management issues in dialogue with major stakeholders [49].

Finally, we focus in this paper on protected areas, but the same climatic changes will also impact agricultural and urban areas, both directly and through their impacts on the supply of water and other services from natural ecosystems. Biodiversity conservation is easier in remote, unpopulated, areas, but arguably most important near to where most people live. Natural and restored ecosystems can not only provide a reliable source of water, but also reduce the risk from floods, cyclones, and other extreme weather events, regulate local climates, and provide accessible recreational and tourism opportunities, and associated economic benefits for local people [50].

5. Conclusions

Myanmar's current protected area system is small for such a biodiversity-rich country and not representative of the country's great climatic diversity. Projected climate change will result in a general upward shift in climate zones to higher altitudes, as well as model-dependent changes in rainfall, which are mostly small compared with current variability. Threats to biodiversity are expected for mountain-top endemics on isolated peaks, for the biotas of small protected areas and those with a low elevational range, and, in combination with rising CO_2 levels, to species dependent on open habitats vulnerable to woody encroachment. Biodiversity data are needed to refine predictions based on climate alone, but the major factors currently limiting the needed extensions to the protected area system are social and political, not scientific.

Supplementary Materials: The following are available online at http://www.mdpi.com/2225-1154/8/9/99/s1, Table S1: Projected changes in mean annual temperature and precipitation for Myanmar between 1960–2000 and 2050 and 2070, Table S2: Projected change in areal extent and mean elevation of bioclimatic zones and their upward shift by 2050, Table S3: Projected change in areal extent and mean elevation of bioclimatic zones and their upward shift by 2070, Table S4: Projected change in areal extent and mean elevation of bioclimatic strata and their upward shift by 2050, Table S5: Projected change in areal extent and mean elevation of bioclimatic strata and their upward shift by 2070, Table S6: Representation of bioclimatic strata within protected areas, Table S7: Projected change in areal extent and mean elevation of bioclimatic zones in protected areas and their upward shifts by 2050, Table S8: Projected change in areal extent and mean elevation of bioclimatic zones in protected areas and their upward shifts by 2070, Table S9: Percentage of all protected areas shifting to a different zone by 2050, Table S10: Percentage of all protected areas shifting to different strata by 2050, Table S11: Percentage of all protected areas shifting to a different zone by 2070, Table S12: Percentage of all protected areas shifting to different strata by 2070, Table S13; Projected change in areal extent and mean elevation of bioclimatic strata in protected areas and their upward shifts by 2050, Table S14. Projected change in areal extent and mean elevation of bioclimatic strata in protected areas and their upward shifts by 2070, Table S15: Percentage shift of each protected area to different bioclimatic zone for 2050 and 2070, Table S16: Percentage shift of each protected area to different bioclimatic strata for 2050 and 2070, Table S17: Projected change in areal extent of bioclimatic zones in each protected area by 2050, Table S18: Projected change in areal extent of bioclimatic zones in each protected area by 2070, Figure S1: Change in mean annual temperature as projected for the year 2050, Figure S2: Change in mean annual temperature as projected for the year 2070, Figure S3: Change in maximum temperature of the warmest month as projected for the year 2050, Figure S4: Change in maximum temperature of the warmest month as projected for the year 2070, Figure S5: Change in mean annual precipitation as projected for the year 2050, Figure S6: Change in mean annual precipitation as projected for the year 2070, Figure S7: Bioclimatic stratification of Myanmar based on spatially interpolated weather station data and as projected for 2050, Figure S8: Bioclimatic stratification of Myanmar based on spatially interpolated weather station data and as projected for 2070.

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