Identifying Critical Areas for Conservation: Biodiversity and Climate Change in Central America, Mexico, and the Dominican Republic

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Abstract. Given the rapidity and intensity of anthropogenic impacts on natural systems, assessing the effectiveness of current protected areas in preserving biodiversity is especially important in Mesoamerica and the Caribbean, which contain a wide array of species and ecosystems. In light of the growing need to consider climate change in policymaking, combining climate change projections with biodiversity maps allows scientists and decision-makers to understand possible climate change impacts on biodiversity. In this study, we use GIS to identify spatial relationships between regional climate change models and species habitat ranges for Mesoamerica and the Caribbean. Evaluating possible effects of climate change in terms of temperature and precipitation involves three factors: historical averages, historical ranges, and future averages. Because different ecosystems and species exist at different temperature and precipitation ranges, we consider "comfort zones" of each area. We develop a quantitative, spatial measurement of climate change intensity of each area by calculating the difference between historical and future averages and dividing that difference by the area's comfort zone, at a spatial resolution of 1km2. The result is a normalized grid of projected climate change severity. According to the modeling results, should worst case scenario conditions prevail, by the 2020s, the Caribbean coasts of Costa Rica, Honduras, Nicaragua, Panama, and the Dominican Republic, will be significantly impacted by climate change. By the 2080s, all of the ecosystems and species of Central America and the Dominican Republic may be subjected to conditions well outside of their traditional comfort zone, while most of Mexico's ecosystems and species are at lower risk of severe climate change impacts. Integrating species richness data with the climate change severity analyses identifies critical areas that may require specific interventions to facilitate the adaptation of species to climate change. The information generated points not only to the utility of current protected areas, but is also useful in guiding the development of new protected areas and biological corridors, for the reduction of the potential impacts of future climate change.

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INTRODUCTION

Mesoamerica and the Caribbean are two of the world's top twenty-five biodiversity hotspots, teeming with globally significant biological diversity. In Mesoamerica alone, nearly 8% of the world's terrestrial species are found on less than 1% of earth's landmass (Mauri 2002). Yet, deforestation and uncontrolled human development have resulted in the loss of an estimated 70% of original habitat (Conservation International 2004). In response to this situation, the regions' governments have demonstrated their commitment to biodiversity conservation through the Mesoamerican Biological Corridor and Caribbean Biological Corridor, networks of protected areas spanning the isthmus and Caribbean islands. These corridors are home to the globe's only preserves for sensitive species such as the jaguar and whale shark (respectively the largest cat in the Americas, and the world's largest fish), as well as over 250 threatened birds, mammals, and amphibians (InfoNatura 2007).

The richness of species and ecosystems in Mesoamerica and the Caribbean is constantly threatened by human-induced drivers of environmental change. The conversion of natural landscapes such as forests, grasslands and wetlands, into
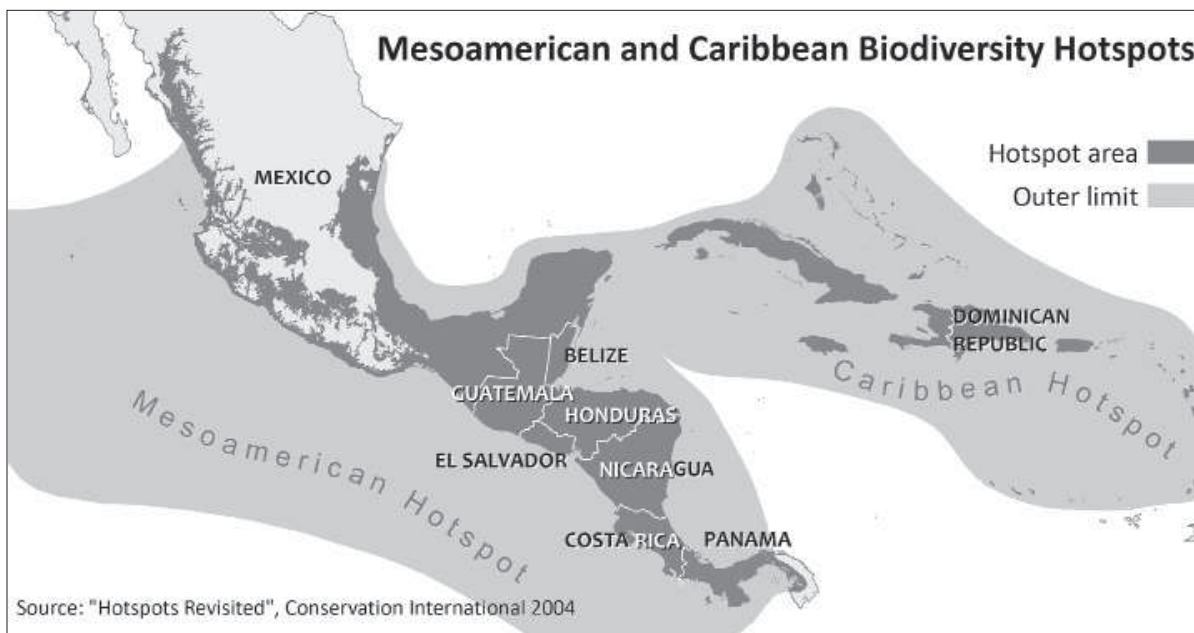

Figure 1. Mesoamerican and Caribbean biodiversity hotspots.

agriculture, pastures, or settlements is the primary culprit of habitat loss and the endangerment of species. Our knowledge of humans' capability to transform landscapes is not by any means novel, however, we are becoming more and more aware of our ability to modify the global and local climate. Like land degradation, the anthropogenic emissions of greenhouse gases such as carbon dioxide, methane, and nitrous oxides, puts the regions' biodiversity at risk. Moreover, climatic catastrophes undoubtedly imperil the stability of the regions' social and economic infrastructures, and global climate change is expected to further exacerbate such susceptibility. Perhaps we are already seeing this effect because now more than ever—at least in recorded history—we are experiencing more frequent and intense hurricanes and tropical storms. (*Editor's Note: At the time of the final revision of this paper the authors were busy churning out maps and rapid analyses of 3 raging tropical storms: Hurricane Gustav, Hanna and Ike).*

Historic climate is a principal factor in shaping landscapes and determining the extent of species' habitats. From the abundant tropical sunlight and water arose diverse arrays of ecosystems and species, filling unique and complex systems of niches. Along with factors such as elevation and geology, these species and ecosystems have adapted to certain temperature and precipitation regimes, or climatic *comfort zones*. Human-induced climate change is threatening to push environmental conditions outside of many ecosystems' and species' comfort zones. This biodiversity comprises many ecosystem services—in the form of plant products that are vital to the regions' livelihoods, ecosystems that filter out pollutants, and rare species that display the world's beauty. Consequently, the United Nations Framework Convention on Climate Change (UNFCCC) and the Convention on Biological Diversity (CBD) jointly recognize these important interactions, stating the need to improve our understanding of these linkages and to "fully integrate biodiversity considerations into climate change mitigation and adaptation plans." Thus, it is especially important to monitor the possible impacts of climate change on biodiversity, as it could guide policy strategies in the expansion and redefinition of protected area networks.

In response to the call for such action, the overall objective of the current study is to integrate geospatial data on biodiversity and climate change in Belize, Costa Rica, the Dominican Republic, El Salvador, Guatemala, Honduras, Mexico, Nicaragua, and Panama, in order to identify critical areas for conservation. The study focuses on biodiversity from the standpoint of both ecosystems and the species which inhabit them, keeping in mind where climatic factors will potentially impact or threaten these species. For the purposes of modeling an entire region, we define ecosystems as the dominant vegetation, or land use if human intervention has occurred. Species richness is a fundamental measure of biodiversity, which counts the number of unique individual species in a place, regardless of the density or abundance of a particular species. Given the availability of spatially-referenced data, we focus on terrestrial amphibians, birds, and mammals, for species richness measures. We compare both ecosystem extents and species richness data to an index of climate change severity, which takes into consideration future projected temperature and precipitation deviations, relative to historic ranges. We assess the overall severity of projected climate change within each ecosystem type and at various altitudinal levels. The final product of this study is the identification of critical habitats: where climate change is projected to most greatly threaten biodiversity-rich places. These processes all utilize geographical information systems (GIS) in aggregating data, the spatial analyses, and the integration of species richness distributions with the climate change severity index.

BACKGROUND

Measuring biodiversity. Biodiversity can be measured at various temporal and spatial resolutions—from months to centuries and from microbes to continents. In order to incorporate both the Mesoamerican and Caribbean regions in the context of climate change, we must first define a reasonable measure for biodiversity. While methodologies for measuring biodiversity differ for each objective and investigator, the Convention on Biological Diversity recognizes biodiversity at three levels: genes, species, and ecosystems. In short, genetic studies are useful for assessing evolutionary abilities or intra-species diversity. Populations of species with higher genetic diversity—or a larger gene pool—are expected to be more resilient against outside disturbances. For studies of regional magnitudes, assessing genetic biodiversity is likely out of the question. Because a high richness of animal species inhabits Mesoamerica and the Caribbean, and because ecosystems determine the habitats of these species, we will focus on these two areas.

Climate change models & scenarios Given the breadth of global climate change scenarios, a few challenges arise when attempting to understand the regional implications of global climate change. First, it is difficult to know which scenarios to choose and how to describe the possible changes. While there are many ways to display and assess climate change scenarios, probably the most common way to display such results are temperature and precipitation anomalies. Because temperature may rise one or two degrees in the tropics but upwards of six degrees in the arctic in the near future, on a global scale, this type of illustration understates the potential impacts of climate change in the lower latitudes (Deutsch 2008). Much more useful than simple anomalies are measurements of severity, which take into account historical climate comfort zones, or a location's customary range of temperature and precipitation.

The second complication of understanding the regional implications of global climate change is a question of scale. These models consider the complex interactions between marine, terrestrial, and atmospheric components, are calibrated with historic climate registers, and can be validated by rigorous sensitivity analyses. However, because of their scale they still cannot capture regional and local phenomena important to ecosystems, species, and human infrastructure.

The necessity of higher resolution climate scenarios for applications to biodiversity has already been demonstrated in numerous investigations, as scientists have underlined climate change's role in driving several species to near extinction. For instance, the Central American Harlequin Frogs and Panamanian Golden Frogs of the region's cloud forests have been victims of a disease caused by certain types of fungus. Recently, climatic changes in these areas have created more favorable conditions for the expansion of this fungus, hence placing these rare frogs under even more pressure (Pounds 2006). Models that demonstrate the intricacies of possible climate changes in particular localities will support studies involving species with similarly small habitat ranges, and such knowledge can better guide our strategies of adaptation to climate change. Methods have been developed to obtain finer results: *regional downscaling* (Hernandez *et al.* 2006; Hijmans *et al.* 2005). Regional climate models provide higher resolution results, which demonstrate local climatic effects. In this sense, they are much more useful for local and regional climate impact assessments, particularly on biodiversity.

METHODOLOGY

The geospatial analyses were conducted in three main stages:

1. **Biodiversity:** classification of ecosystems and derivation of species richness datasets.
2. **Climate change severity:** derivation of a Climate Change Severity Index (CCSI) for various scenarios.
3. **Critical habitats:** Integration of the climate change severity index with ecosystem and species datasets for the identification of critical areas for biodiversity.

Stage one only involves aggregation and simple (but computationally expensive) analysis of various data; whereas in stages two and three, we have developed new methods and measures to identify critical areas in terms of climate change and biodiversity. The type of analyses employed in this study requires that all input datasets exist in a geospatial format.

As such, the lack of georeferenced data on aquatic or marine biodiversity and high resolution climate outputs for the oceans (e.g. sea temperature at multiple depths, pH, salinity) preclude investigation of the impacts of climate change on aquatic and marine biodiversity. This study therefore focuses on analyzing terrestrial biodiversity and relevant climate change scenarios. Since the overall objective is to integrate such a wide array of data, we must also define how to generalize the various factors. Before further describing the methodology, we provide a table of data sources, without which this study would not have been possible.

1. BIODIVERSITY

Ecosystems. The majority of the data used in this analysis come from the Central American Ecosystem Mapping project (Vreugdenhil *et al.* 2002). The project identified a very rich list of 197 ecosystems in Belize, Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua, and Panama. In order to have common ecosystem classes in Mexico and the Dominican Republic as well, we apply a similar classification scheme to the two countries. The ability to distinguish between land covered by natural vegetation and other land cover types is extremely useful in the development of networks of protected areas and biological corridors. We separate broadleaf forest, coniferous forest, mixed forest, savanna, and shrubland, into four distinct divisions based on elevation: lowland, submontane, montane, and altimontane, where the actual altitudinal classes depend upon an ecosystem's location on the Pacific or Atlantic slope (CIAT 2004). We also include mangroves, wetlands, agriculture, and urban land cover types, but do not divide them by altitudinal class. These inputs result in a layer of twenty-five different types of ecosystems, based on vegetation / land cover type and altitude. Figure 1 shows the spatial array of these classes and elevations. We assess the overall severity of projected climate change within each ecosystem type and at various altitudinal levels, in order to identify the vegetation / land use and altitudinal classes likely to experience the most severe climate change.

Table 1:
Data sources and descriptions

Theme	Name	Source	Format
Ecosystems	Ecosystem delineations for Central America	World Bank- and Government of the Netherlands-supported Central American Ecosystem Mapping project, further refined by the Central American Commission for the Environment & Development	Shapefile, resampled to 1km raster
Ecosystems	Land cover data for Mexico	GeoCover LC product developed by the Earth Satellite Corporation	Raster, resampled to 1km
Ecosystems	Land cover data for the Dominican Republic	Caribbean Vegetation Mapping Project funded by the USAID Caribbean Regional Program	Raster, resampled to 1km
Ecosystems	Digital elevation model	International Centre for Tropical Agriculture, CGIAR-CSI SRTM 90m Database	Raster, 90m
Species richness	Species habitat distributions	NatureServe's InfoNatura database	Shapefiles, resampled to 6km raster
Climate – historic	Current conditions: mean monthly temperature and precipitation accumulation	WorldClim interpolations of observed data, representative of 1960-1990	Raster, 1km
Climate – projections	Future conditions: mean monthly temperature and precipitation accumulation	WorldClim downscaling of global climate model outputs	Raster, 1km
Protected areas	IUCN designated protected areas	World Database on Protected Areas Consortium	Shapefile

2

3
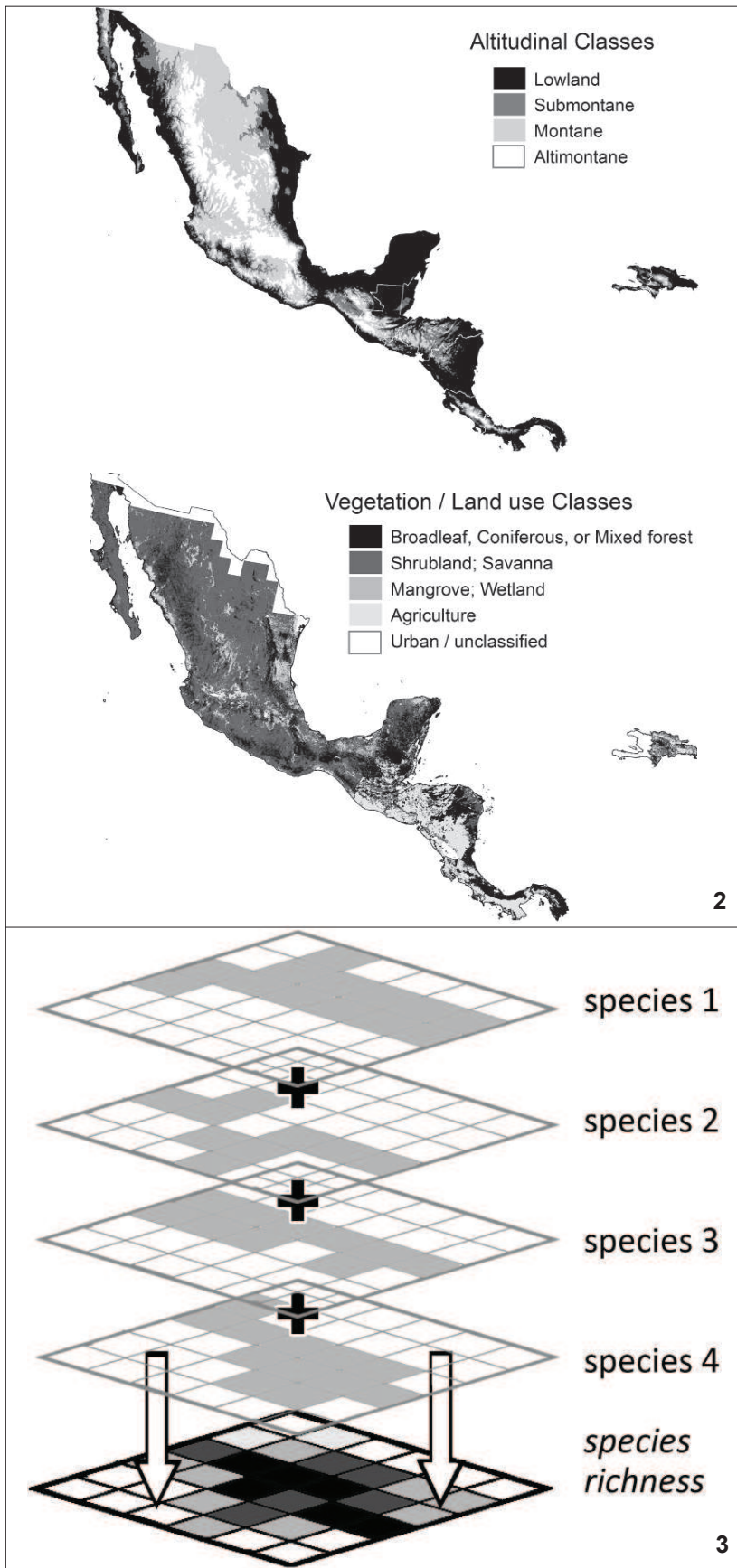
Figures 2-3. 2, The spatial distribution of elevation and vegetation / land use classes. For display purposes, the nine vegetation classes have been grouped together into five categories. Combining these two characteristics result in 25 different ecosystems types that can be found in various countries; 3, Adding individual species habitat ranges to calculate species richness. In the bottom layer, darker gray indicates higher richness because more species inhabit that area.

Species Richness. The number of unique species in a place is known as species richness. In order to obtain this type of biodiversity map, we have overlain thousands of species habitat range maps (distribution data). This compilation of spatial data is the result of aggregating information about all of the documented birds, mammals, and amphibians of Latin America. Two advantages of this system are that it has harmonized disparate types of data into a common format, and it also includes information from multiple reputable sources (InfoNatura 2007).

By overlaying the distribution data for each bird species, each mammal species, and each amphibian species, we obtain richness maps for the entire region. A simplified illustration of this process is shown in Figure 2.

2. CLIMATE CHANGE SEVERITY

In the following section we describe the methods of our regional analyses of climate change data derived from high resolution regional climate scenarios. Here we define a temporal and spatial scale to express projected climate change scenario output, as well describe the climate change severity index.

While there are many ways to display and assess climate change scenarios, a common structure is to observe overall tendencies, rather than to make comparisons simply between "today" and a certain date in the future. In order to consider these overall trends, we use historical baseline data, which is an average of thirty years usually between 1961 and 1990. Climate scenario data is also summarized like baseline data. The most common way to group future projections is by the "2020s," the "2050s," and the "2080s." Like the baseline data, these future time periods include an average of thirty years (CCCSN 2008). For example, the 2020s are an average of all the years from 2011 to 2040. The 2050s include 2041 through 2070, and the 2080s include 2071 through 2100. Earlier we mentioned a measure of climate change severity, which differs from a simple anomaly. Climate change severity takes into account historical climate comfort zones, or the historic ranges of temperature and precipitation ranges to which a place is accustomed. Specifically, we consider mean monthly temperature values and mean monthly precipitation accumulation to determine a climatic range which a place has experienced during the baseline period, what we call the climatic comfort zone.

In the context of this study, we utilize climate change scenario outputs of 1km^2 resolution, which constitute the highest spatial resolution climate change scenario outputs currently available for our region of interest. We consider a range of scenarios and models available from WorldClim, specifically the Canadian Centre for Climate Modelling and Analysis' third generation coupled global climate model (CCCMa), the Commonwealth Scientific and Industrial Research Organization's Mark 3 of the coupled climate model (CSIRO), and the Hadley Centre Coupled model, version 3 (HadCM3), with respect to both worst case (A2) and better case (B2) scenarios (IPCC 2000).

Building off of the framework of an ecosystem vulnerability to climate change index that had been prototyped by Tremblay-Boyer and Anderson (manuscript in preparation), we develop

a Climate Change Severity Index (CCSI). This measures the climate change that a particular location is projected to experience, compared to the natural climate variation (i.e. temperature and precipitation regimes) that a location has experienced historically (i.e. its current 'comfort zone', often called 'climatic space'). In other words, the CCSI is a measure of how far a place is projected to move outside of its current climate comfort zone. In terms of location, the CCSI can be derived at a range of spatial scales, depending on the spatial resolution or detail of the available climate data or desire of level of analysis. Given that the CCSI values are calculated on a cell-by-cell basis, it is also potentially useful to average the measurements within certain boundaries, namely ecosystems.

The derivation for the CCSI is as follows. We build the CCSI from a respective temperature change severity index ($CCSI_t$) and a Precipitation Change Severity Index ($CCSI_p$), where the climatic comfort zones are seen in the denominators of both. Because the overall objective is to integrate temperature and precipitation data, we consider them equally in the overall CCSI.

Temperature Change Severity Index (CCSIt):

$$\frac{\text{Annual mean scenario temperature- Annual mean baseline temperature}}{\text{Baseline temperature range}}$$

Precipitation Change Severity Index (CCSIp):

$$\frac{\text{Annual scenario precipitation accumulation - Annual baseline precipitation accumulation}}{\text{Baseline precipitation accumulation range}}$$

Climate Change Severity Index (CCSI):

Expected CCSI values,given individual CCSIt and CCSIp
Precipitation (CCSIp)
Low CCSIp
High CCSIp
Temperature (CCSIt)
Low CCSIt
Low severity
Depends on combination
High CCSIt
Depends on combination
High severity

$$\frac{CCSI_t + CCSI_p}{2}$$

Derivation of the CCSI yields raw quantitative values which are interpreted as follows:

Table 2.

Values	Severity	Relevance to comfort zone
0 – 0.24	Marginal	Average temperature/precipitation within historical range
0.25 – 0.49	Low	Average temperature/precipitation within historical range
0.50 – 0.74	Medium	Average temperature/precipitation within historical range
0.75 – 0.99	High	Average temperature/precipitation reaching the limits of historical range
1.00 – 1.99	Very high	Movement of average temperature/ precipitation outside historical range
2.00+	Extreme	Movement of average temperature/ precipitation very far outside historical range
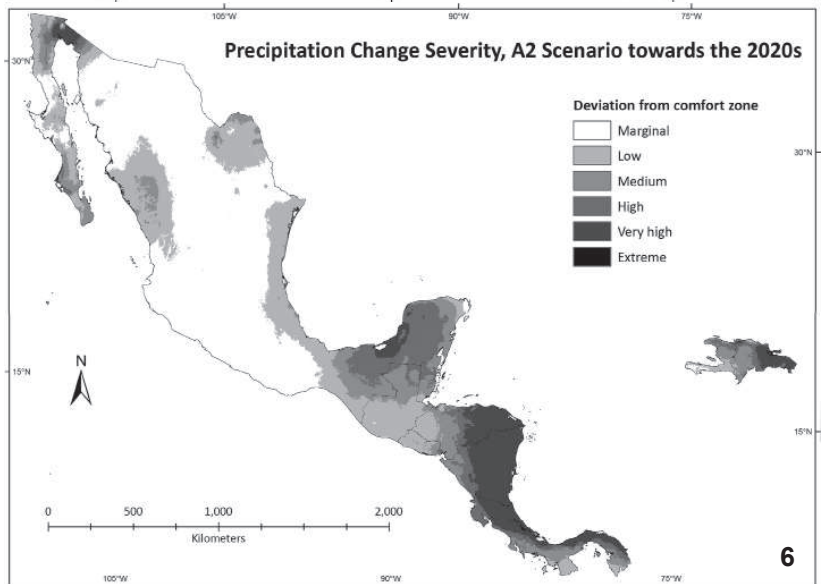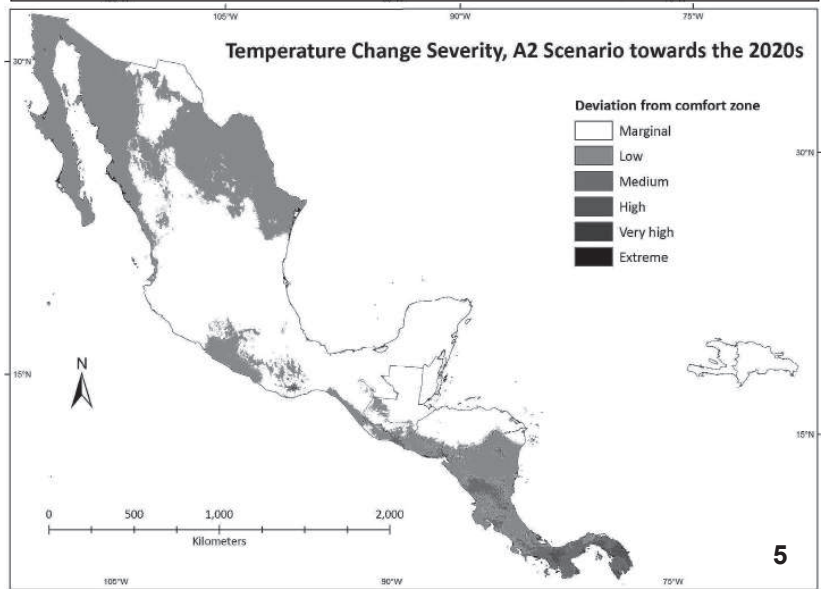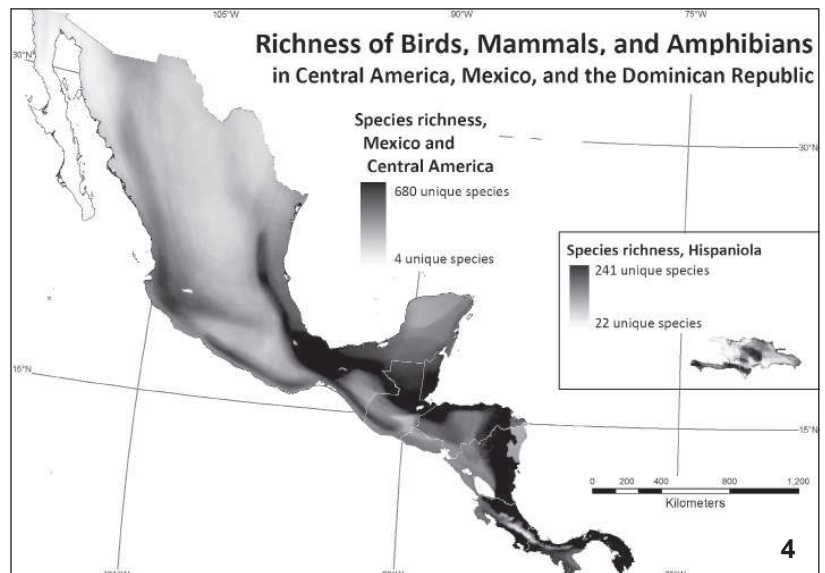
Figures 4-6. 4, Species richness in Central America, Mexico, and the Dominican Republic. Data derived from NatureServe InfoNatura Species Habitat Ranges, 2007; 5,The temperature change severity calculation demonstrates a much higher departure from the comfort zone in the lower latitudes than in the upper; 6, The precipitation change severity calculation shows high departure from the comfort zone mainly on the Caribbean coasts, as well as the lower latitudes.

Figure 7.
Combining the
temperature and
precipitation severity
calculations for the A2
& B2 scenarios in the
2020s and 2050s, these
4 maps demonstrate
the increasing climate
change severity over
time and under a
worse case scenario.
The CSIRO B2 plate
represents one of the
best case scenarios in
the 2020s, while the
HadCM3 A2 plate
illustrates the worst for
the 2050s.

Climate Change Severity Index maps for the A2 & B2 scenarios towards the 2020s and 2080s
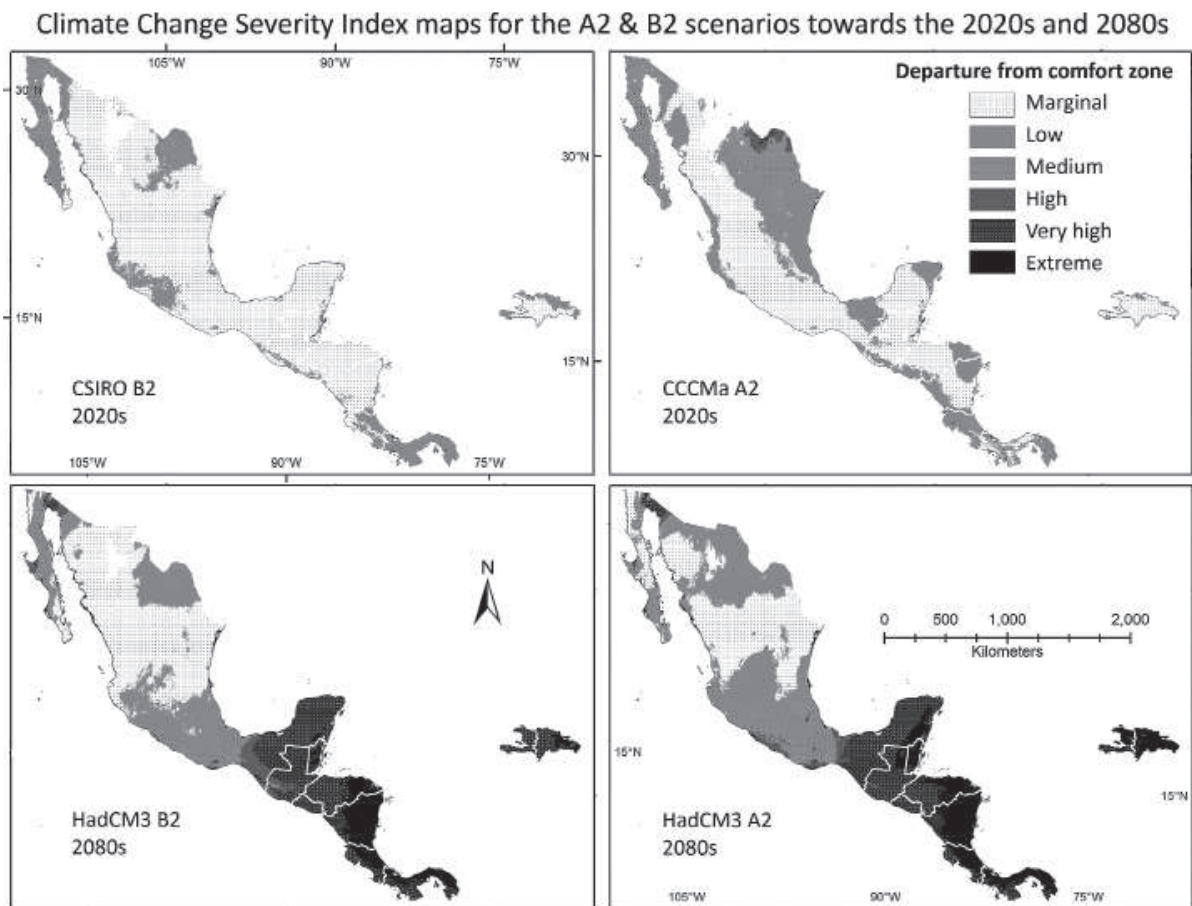
Since there are high resolution climate change scenario outputs from three global climate modeling organizations, for two scenarios, and for three time periods, we calculated the CCSI for all eighteen datasets, for temperature, precipitation, and overall CCSI. We present the results on only a sampling of these analyses, attempting to portray a representative range of scenarios and changes over time, keeping in mind uncertainties in the global climate change models and downscaling techniques.

RESULTS AND DISCUSSION

Here, we explore the implications of the modeling. First, we display the species richness map of Central America, Mexico, and the Dominican Republic, which results from superimposing nearly 3000 individual species distribution datasets. Species richness can also be considered a measurement of how many species' habitats overlap in a certain place. For instance, "680 unique species" can also mean "680 species' habitats intersect at this point." This should be especially important for designing biological corridors.

Although evaluating the disparities between climate change models is not our main objective, we do not disregard the differences. There are inherent uncertainties associated with the downscaled climate scenario data, and we choose to focus on scenarios that have higher levels of agreement. Whereas Table 1 only includes climate data from WorldClim (Hijmans 2005), we have compared these interpolations to other global and

regional climate change scenarios (CCCSN 2008; Hernandez *et al.* 2006; Jones *et al.* 2004) to be assured of general agreement among the regional downscaling outputs. Because the different models diverge so greatly further into the 2080s, we focus only on the 2020s and 2050s, where models show more agreement. The following two maps display the Temperature Change Severity Index (Figure 4) and Precipitation Change Severity Index (Figure 5), using data from the A2 scenario in the 2020s time period. We also show the Climate Change Severity Index for the 2020s and 2050s, both A2 and B2 scenarios, and from different modeling organizations. CSIRO and CCCMa illustrate less severe outputs than the HadCM3 model, but the most noticeable differences are between A2 and B2 scenarios, as well as time frame.

Although not shown in the graphics, most of the scenarios agree in the near-future projections. That is, during the 2020s time frame, nearly all of the models demonstrate very similar increases in temperature, while different models and scenarios deviate from each other further into the future. Precipitation changes vary more greatly among models and scenarios. Hijmans *et al.* (2005) also indicate a higher level of uncertainty in the spatial interpolation of precipitation data than temperature data.

Overall impacts. Temperature change severity increases and moves northward over time. Initially, the most severe temperature changes ($CCSI_t$) are projected to occur at the

lower latitudes. We expect this because there are relatively small comfort zones, or historical ranges, for temperatures closer to the equator; so any temperature anomaly would be greater nearer the equator than in the more temperate latitudes. Precipitation change severity ($CCSI_p$) is highly concentrated on the Caribbean coasts of most countries, as well as extensive areas of the Dominican Republic. In the future, severity is projected to increase to the north and west, so that Caribbean and Pacific precipitation change severity is nearly equal by the 2080s.

In terms of overall trends, according to the spatial analyses, if worst case scenario conditions prevail, the Caribbean coasts of lower Central America will be significantly impacted by climate change in the near-term. Species and ecosystems across specific sites in Central America and the Dominican Republic would indeed face significant climatic stresses by being subjected to precipitation and temperature regimes far outside of the natural variation or comfort zone to which they have been accustomed. Under the B2 scenario towards the 2020s, only the northern part of Costa Rica is projected to move outside of its climatic comfort zone; however, under the A2 scenario there is a substantial expansion of the "high" and "very high" severity classes. This is especially evident in northwestern Mexico, the Dominican Republic, and the Caribbean side of Honduras, Nicaragua, Costa Rica, and Panama, the latter three projected to experience movement outside of the comfort zone. In the 2050s, northwestern Mexico, specifically parts of the states of Baja California and Sonora are projected to experience the most severe climate change, even more so in the A2 scenario. Additionally, the combination of high temperature and precipitation change severity in the southern parts and Caribbean coasts of Central America might greatly affect Panama and Costa Rica ("extreme" severity). The same combination of severe precipitation and temperature changes in the Dominican Republic results in most of the island's categorization in the two highest severity classes. As mentioned earlier, the differences between the B2 and A2 scenarios are more apparent in projections further into the future. While the scenarios mostly agree in the 2020s, the varying implications of different scenarios are very well illustrated in the four panels of Figure 6.

Hence, with the exception mainly of parts of Baja California and the Yucatan Peninsula, Mexico's ecosystems and species would go largely unaffected even under worst case scenario conditions. This is because the majority of Mexico's ecosystems already tolerate a relatively wide margin of climate variation, likely indicating resilience to climate change. On the other hand, irrespective of the climate scenario data, the historic climate data indicates that the vast majority of ecosystems in Central America and the Caribbean are currently exposed to relatively low variation in terms of rainfall patterns and temperature. Overall, the climatic comfort zones of species and ecosystems in Central America and the Caribbean are relatively small.

If worst case scenario conditions prevail by the 2080s, virtually all of the ecosystems and species of Central America and the Dominican Republic will be subjected to conditions well outside of their traditional temperature and precipitation regimes. While this abrupt shift may imply altitudinal migration of some species or the extirpation of less mobile endemic species, further research is needed to better assess the potential resilience of specific species and ecosystems.

In terms of the potential impact on existing protected areas, according to the spatial analysis conducted, the ecosystems and species most likely to be affected by climate change are largely already within protected areas. We therefore expect that if these ecosystems continue to be protected, for a variety of reasons, the chances of these ecosystems' adapting to climate change would be higher compared to those vulnerable ecosystems currently outside existing protected areas networks.

Figures 8-9.
8,Average CCSI per vegetation / land cover type; 9,Average CCSI per altitude class.

Average Climate Change Severity Index per Vegetation / Land cover type, 2020s A2 scenario
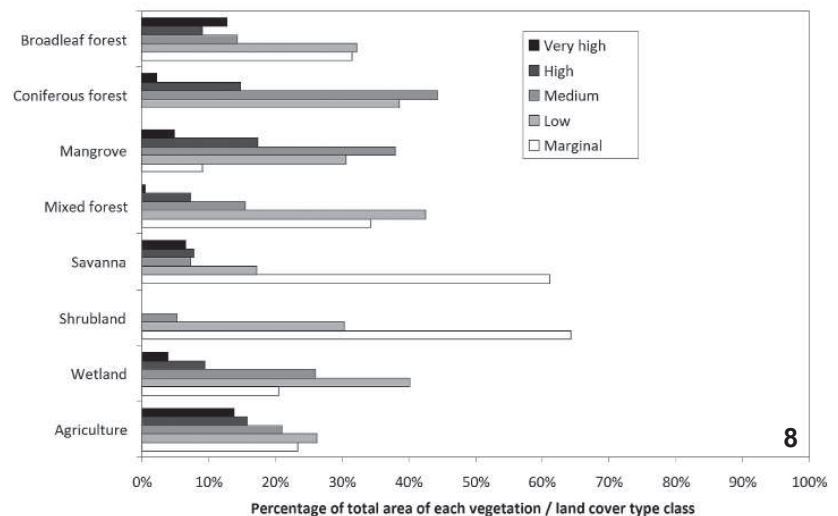
Average Climate Change Severity Index per Altitudinal Level, 2020s A2 scenario
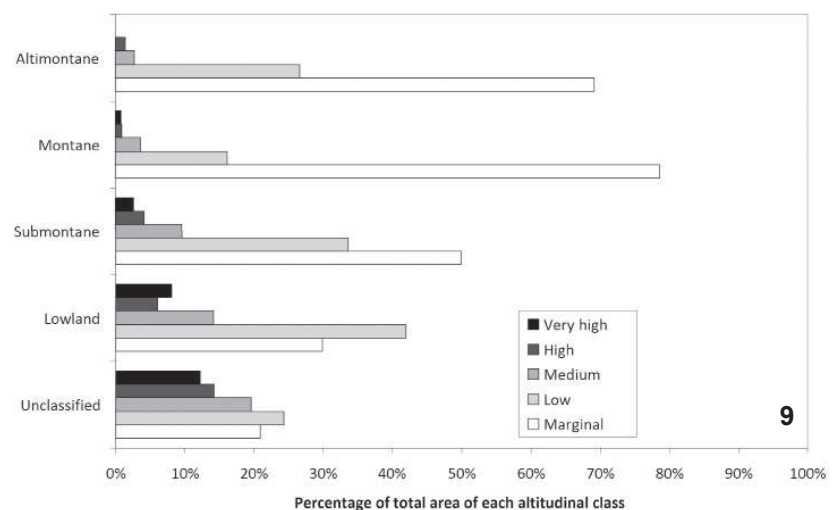
INTEGRATING THE ANALYSES: CRITICAL ECOSYSTEMS AND SPECIES-RICH AREAS

Impact on Ecosystems With regards to the CCSI for the 2020s, averaged for each ecosystem type, we observe the following trends. Comparing the CCSI to ecosystems and species is a step towards showing places where rapid adaptation of vegetation and species must occur if these projections ring true. In this sense, "adaptation" most likely means migration, because species will follow the environmental conditions in which they are most comfortable. Many sensitive species could be displaced when more aggressive species move in to their niches. Invasive plants are an especially important topic to consider when monitoring the changes within and around ecosystems. Impacts of climate change will likely occur too rapidly to allow for evolutionary changes in most species.

Unlike the severity index maps shown before, this type of climate change severity analysis is not designed to locate actual places with severe climate change projections. Rather, it should give an idea of the types of ecosystems and elevations that will feel greater effects of climate change. Significant consideration should be given to those ecosystems that have very small spatial extents and a very high average CCSI. The following graphs inform us of general trends of the potential impact of climate change on ecosystems, in terms of vegetation / land cover and altitude, under the HadCM3 A2 scenario in the 2020s. We discuss other scenarios further.

It should be noted in the results of Figure 7 that in the 2020s under the A2 scenario, there are actually no ecosystems that will experience conditions outside their comfort zone ("very high" or "extreme" severity); however, by the 2050s and 2080s, these degrees of climate change severity are reached. Regardless, the most striking result is that broadleaf forests are projected to experience a significantly high percentage of severe climate change. Savannas and mangroves also have a considerable number of highly susceptible areas. Spatial analysis indicates that shrublands, broadleaf forests, and agriculture are the most dominant land cover types (also evident in Figure 1). It is cause for concern that nearly a quarter of the extensive broadleaf forests have a high, or very high, severity index. The Caribbean coasts of Panama, Costa Rica, and Nicaragua, as well as parts of the Dominican Republic, contain the greatest richness of birds, mammals, and amphibians, extensive broadleaf forests, and "very high" CCSI values. Additionally, some 30% of agricultural areas are also projected to experience highly severe climatic changes.

In terms of altitude, there seems to be a decreasing trend of severity with increasing elevation. This is most likely because ecosystems at higher altitudes are more adapted to greater ranges in temperature; thus, they may be potentially more resilient to changes in climate. Conversely, it is important to keep in mind the other factors that could put montane ecosystems at risk, such as invasive plant and animal species. As montane temperatures increase, it should be expected that lowland species migrate upwards, shifting their contemporary niches further uphill. Further investigation should be applied to the ecosystems without altitude classifications, such as agriculture, wetlands, mangroves, and urban areas. These graphs alone do not express these types of threats to ecosystems, but climate change will unequivocally be a driver of species invasion.

Obviously the calculations of CCSI per ecosystem and altitudinal class would result in higher severity using the A2 scenario than the B2 scenario. The following statements describe the general differences between the B2 and A2 scenarios, regarding both vegetation / land use and elevation. In the B2 scenario, projected climate change severity is "high" or "very high" in only submontane, lowlands and unclassified altitudinal classes. Broadleaf forests and agriculture comprise the majority of the most severe climatic changes, while mixed forests and very small amounts of urban areas lie in the "high" severity category. As seen in the previous maps, these classes of higher severity lie in parts of Costa Rica, Panama, Nicaragua, and northwestern Mexico. There is a visible spread of climate change severity in the A2 scenario, which results in high severity in all elevation classes. Although high CCSI values still dominate the lowlands and unclassified altitude classes, submontane and montane areas have a substantial amount of "high" and "very high" severity zones—evident in Figure 8. As seen in Figure 7, broadleaf forests and agriculture have the highest percentage of climate changes that are projected to move outside of the comfort zone. In the A2 scenario, every class of vegetation or land cover type except shrubland is projected to experience movements outside of the comfort zone as early as 2011 (the 2020s time period). While the higher severity classes in the B2 scenario exist in only a few countries, every country is projected to experience these changes in the A2 scenario, except for Belize, El Salvador, and Guatemala. According to the CCSI maps displayed earlier, by the 2050s, it is possible that movement outside of the comfort zone will occur in at least some parts of every country considered in this study.

We complement this analysis of ecosystem impact with the identification of critical areas. This is the combination of species richness and severity of climate changes. While the values are somewhat arbitrary, those chosen in order to identify critical habitats are as follows:

- Highest 10th percentile of species richness, per country
- CCSI of 0.75 or higher ("medium," "high", and "very high" severities)

The intersections of these criteria determine the "critical areas." Also displayed on the following two maps are the protected areas. One should be able to visually assess the
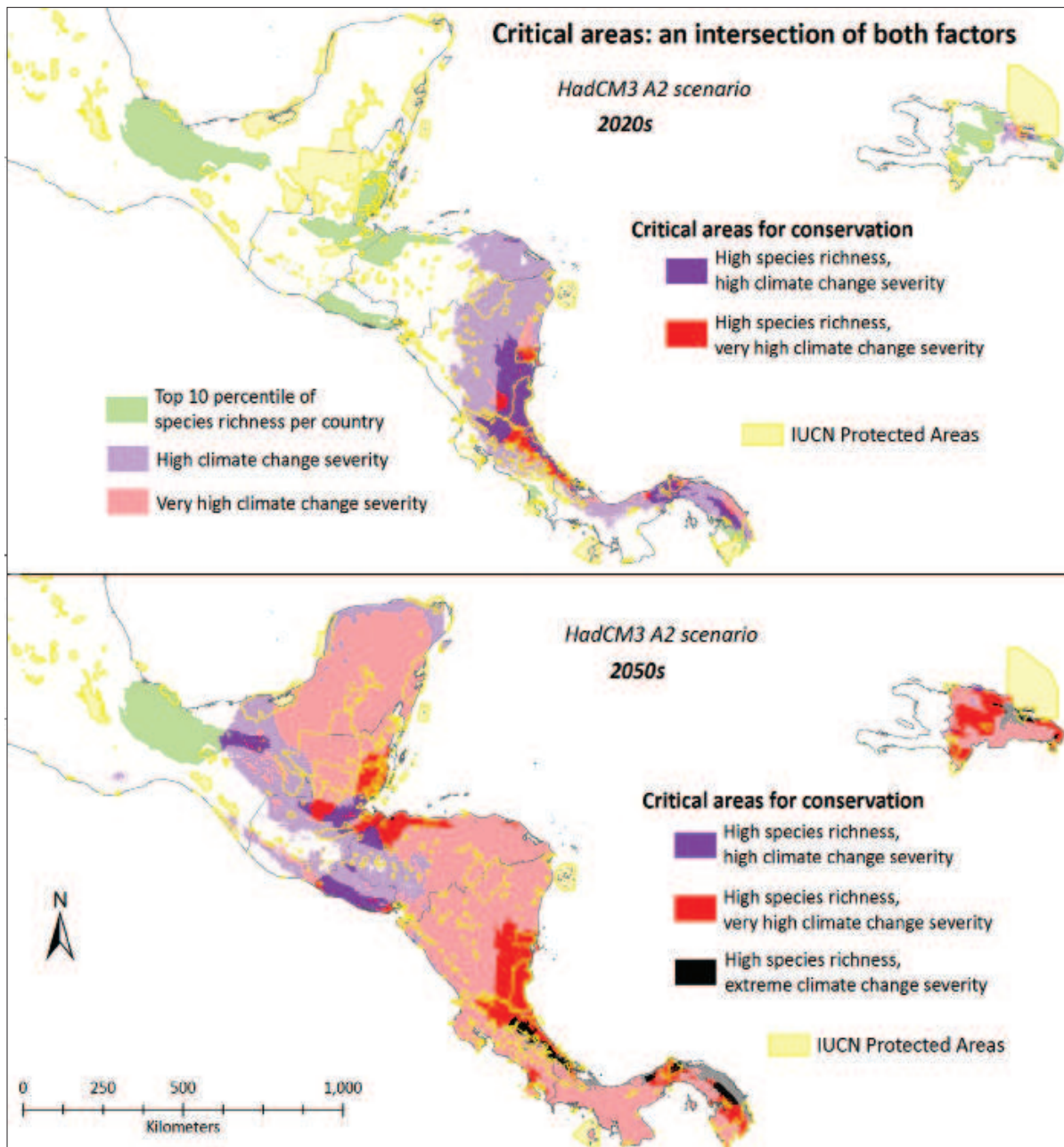
Critical areas: an intersection of both factors

HadCM3 A2 scenario
2020s

Critical areas for conservation

■ High species richness, high climate change severity

■ High species richness, very high climate change severity

Top 10 percentile of species richness per country

High climate change severity

Very high climate change severity

■ IUCN Protected Areas

HadCM3 A2 scenario
2050s

Critical areas for conservation

■ High species richness, high climate change severity

■ High species richness, very high climate change severity

■ High species richness, extreme climate change severity

■ IUCN Protected Areas

N

0   250   500   1,000
Kilometers

Figure 10. Integration of two factors to identify critical areas for conservation. Utilizing the species richness map displayed earlier in this paper, we highlight in green the places in each country that are home to the highest 10th percentile of species. Light purple, pink, and grey, delineate the higher CCSIs. The intersections of the two factors result in critical areas, displayed in bold purple, red, and black.

efficiency of these networks of preserved land. Are they adequately placed to prepare for potential impacts of climate change on biodiversity? (see Figure 9).

In the 2020s HadCM3 A2 scenario, critical areas exist in Costa Rica, Nicaragua, and a small part of Panama. In the case of the 2050s HadCM3 A2 scenario, critical areas spread throughout all nine countries of interest, the most severe in Costa Rica, the Dominican Republic, and Panama. Given that the critical areas in the 2050s (defined by the highest severity in black) will have already experienced severe climate change in the 2020s time period, these places demonstrate the areas of highest concern. The overlain protected areas network gives an insight into the places in which further designation of protected areas should be focused in order to facilitate species' adaptation to climate change.

CONCLUSIONS

From the near-term (2020s) onward, if worst case scenario conditions prevail, the vast majority of the ecosystems of Central America and the Dominican Republic should be affected with varying degrees of climate change severity, with differing effects on their constituent species. Mexico, on the other hand, would be generally much less affected. Since this study considers such a great quantity of data, it presents a critical integration of climate, vegetation, and animal species datasets, providing an overall understanding of how each of these factors is related spatially. While it does not give insight into how individual species may adapt and migrate to climate change, this study is an important step in the integration of often disparate areas of study. The overall analysis has therefore identified critical areas that may require specific interventions to facilitate the

adaptation of species and ecosystems to climate change. It is also worth pointing out that in addition to climate change, ecosystems and species will likely continue to be threatened by deforestation.

In addition to having integrated various types of geospatial data to identify critical areas for conservation, we have also presented a novel framework within which climate change impacts can be analyzed, irrespective of data source, resolution or scenario. This study has focused on presenting which species-rich places and ecosystems will be impacted by climate change according to the worst case (A2) scenario and a better case scenario (B2), giving greater meaning to the implications of different possible futures. Further work is required to also assess the impacts of climate change under the numerous other scenarios.

Temperature change projections between different models are much more in accordance in the 2020s than in the 2050s and 2080s. This is useful information because we should be able to more confidently expect a regional rise of 1˚C as early as 2011 (when compared to the 1961-1990 baseline). Maps of these anomalies can show us that some locations may experience an increase of nearly 2˚C, and others less.

General tendencies in precipitation changes are much more difficult to project than temperature, even in the not-too-distant future. Both the amount and location of changes in precipitation differ from scenario to scenario. Despite the disagreements, there is a general trend in nearly all the models that there could be drier wet seasons. This has significant implications on agriculture, water quality and water availability in our region. Moreover, this drying of the rainy season could have significant impact on forest and agricultural health as a result of forest fires. The scientific consensus is that forest fires in Central America have not played a large role in shaping the region's landscape or in driving vegetation dynamics (Middleton *et al*. 1997). This may be changing. We can learn from previous events such as the 1997-1998 El Niño, in which there was a significant decline in precipitation during the rainy season in Panama. The many impacts included lack of water in the Panama Canal watershed—both for canal operations, drinking water, and fishing—as well as a marked increase in burned area (Donoso *et al*. 2000; López 2004).

Temperature and precipitation anomaly data is invaluable to many biologists who are interested in phenology and the absolute temperature ranges for a species of interest. However, this data does not provide an overall idea of how much climate change will affect different parts of the region as a whole. Moreover, it does not take into consideration any measure of climate variability. The climate change severity index attempts to address these issues. Unlike maps of raw temperature anomalies, the severity index emphasizes the potential impacts of climate change in the tropics. Nearly all of the global climate models demonstrate mild temperature increases at lower latitudes, compared to extreme changes

towards the poles. This is no doubt an important trend for glaciology and studies of the global circulation of temperature and salinity, but it understates the impact that such a small temperature increase could potentially have on tropical ecosystems and species. The tropics exist within much smaller annual temperature ranges than northern latitudes (both in terms of day-night ranges and seasonal variations); therefore, the species and ecosystems have become accustomed to low temperature variability. Because of these facts, what could be considered a "mild" change in the tropics could in fact be devastating (Deutsch 2008).

On the other hand, most countries in Mesoamerica and the Caribbean receive widely different amounts of rainfall during the year. Most places have distinct wet and dry seasons, which the CCSI defines as a very large precipitation comfort zone for the wet tropics. Therefore, the one might expect that the climate change severity index would be very low in terms of precipitation; however, these scenarios project such great changes in precipitation that high CCSI values spread throughout much of the Caribbean coast. Still, precipitation behavior in the tropics is best described intra-annually. hus, an improvement on the CCSI would allow for multi-season comfort zones.

In this study we considered ecosystems, birds, mammals, amphibians, temperature, and precipitation, but other environmental variables are important as well, such as soil moisture content, surface temperature, sea level pressure, and wind direction and velocity (Hernandez *et al*. 2006). Just as there are coupled models in climatology, we should strive to couple high resolution climate scenarios with future land use scenarios. The latter is undoubtedly the major culprit of species endangerment and is the chief threat to biodiversity. Given the current rates of deforestation in Mesoamerica and the Caribbean, it is crucial to include this factor in assessing the potential human impacts on biodiversity. The Millennium Ecosystem Assessment, for example has already established a framework for developing scenarios similar to the SRES for land cover change. Narrative scenarios of future development in Latin America and the Caribbean have been developed by a regional expert group coordinated by the United Nations Environmental Programme (UNEP)'s GEO-LAC group. Explicit land cover change scenarios have already been developed for northern Mesoamerica under the UNEP- / USAID-supported ICRAN-MAR project of 2004-07. Integrating such land use change projections into the CCSI and critical habitats assessment would enhance current impact assessments on biodiversity. Moreover, as this study has focused solely on integrating climate change data with terrestrial biodiversity, useful follow-up for this research would include assessments of climate change's potential impacts on aquatic and marine biodiversity.

Uncertainty is an omnipresent concept in climate change modeling; however, degrees of uncertainty are not the same for all time frames. These analyses of climate change severity and identification of critical areas show a high level of agreement

among various models in the 2020s. These critical areas also coincide with many efforts to further develop the Mesoamerican Biological Corridor and should add to the case for conserving these places (CCAD 2000), especially those on the Caribbean coast of Panama, Costa Rica, and Nicaragua. Moreover, much of the critical area lies just outside of existing protected areas, often spanning across various parks and reserves. This strengthens the argument and demonstrates the utility of expanding and connecting the current system of protected areas in Mesoamerica and the Caribbean, in order to conserve its rich biodiversity.

ACKNOWLEDGMENTS

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