Wildlife-Friendly Farming and Crop Resilience in Southern Costa Rica

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The Group Project is required of all students in the Master of Environmental Science and Management (MESM) Program. The project is a year-long activity in which small groups of students conduct focused, interdisciplinary research on the scientific, management, and policy dimensions of a specific environmental issue. This Group Project Final Report is authored by MESM students and has been reviewed and approved by:

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Dr. Ashley Larsen, Faculty Advisor

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Date

Acknowledgements

We would like to give a special thank you to everyone that has supported us through our master's capstone project. Specifically, we'd like to extend our gratitude to the following:

Land Acknowledgement

We would like to acknowledge that the study area encompasses land historically believed to belong to five indigenous tribes: the Boruca, Guaymi, Teribe, Cabecar, and Bribri (Barrantes et al., 1990). Further, UC Santa Barbara is located on indigenous land. In recognizing the original custodians of this land, we pay respect to the Chumash people.

We stand in support of indigenous land rights.

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Abstract

Agricultural expansion and urban development over the last 100 years has led to substantial fragmentation in the Talamanca-Osa region of southern Costa Rica, threatening the region's outstanding biodiversity. Increasing regional connectivity is vital to ensure local species' long-term viability, particularly for wide-ranging and forest-dependent species like the jaguar *(Panthera onca)*. Wildlife-friendly farming practices, such as integrating shade trees or reducing inputs, can help improve connectivity on managed landscapes, but transitioning practices can be costly to farmers. The region is in need of a holistic approach to improve agricultural sustainability that supports both the environment and the community for the long term. In theory, eco-certifications can enable price premiums and increase market access which can lower the financial barriers to adopting on-farm conservation practices. Further, long-term planning will require an understanding of the projected impacts of climate change. Climate change stands to strongly affect regional farming, driving shifts in crop suitability ranges that may necessitate crop switches or farm expansion. Here, we work with a local nonprofit, Osa Conservation, to inform planning for sustainable agriculture in the Talamanca-Osa region of southern Costa Rica. We employed spatial analyses and reviewed scientific literature to evaluate 1) the key barriers and impacts of wildlife-friendly farming on jaguar connectivity, 2) the environmental and socio-economic impacts of five regionally available eco-certifications, and 3) how suitability for three crops will shift under climate change. Ultimately, our results will contribute to Osa Conservation's work to conserve Costa Rica's outstanding biodiversity while enhancing the community's economic opportunities.

Project Objectives and Significance

Southern Costa Rica hosts two of the most important sites for conservation in Central America: the Osa Peninsula and the Talamanca Mountains. The Osa Peninsula houses an estimated 2.5% of the planet's biodiversity and it has been described as "The most biologically intense place on Earth" by National Geographic (Langenheim, 2019). The small (1,800 km^2), but highly diverse peninsula is home to approximately half of the country's 500,000 species in its rainforests, coastal landscapes, and tropical waters (Sánchez-Azofeifa et al., 2002). The Talamancas contain the largest remaining intact forest in Central America and the largest block of primary forest in Costa Rica. The region between the Osa Peninsula and the Talamanca Mountains ("Talamanca-Osa region") is vital to the connectivity of species within these two highly biodiverse areas. It is specifically critical to jaguars, as local jaguars currently reside in two disconnected habitat patches: one primarily in Corcovado National Park on the Osa Peninsula and one in La Amistad National Park in the Talamanca Mountains (Figure 1).
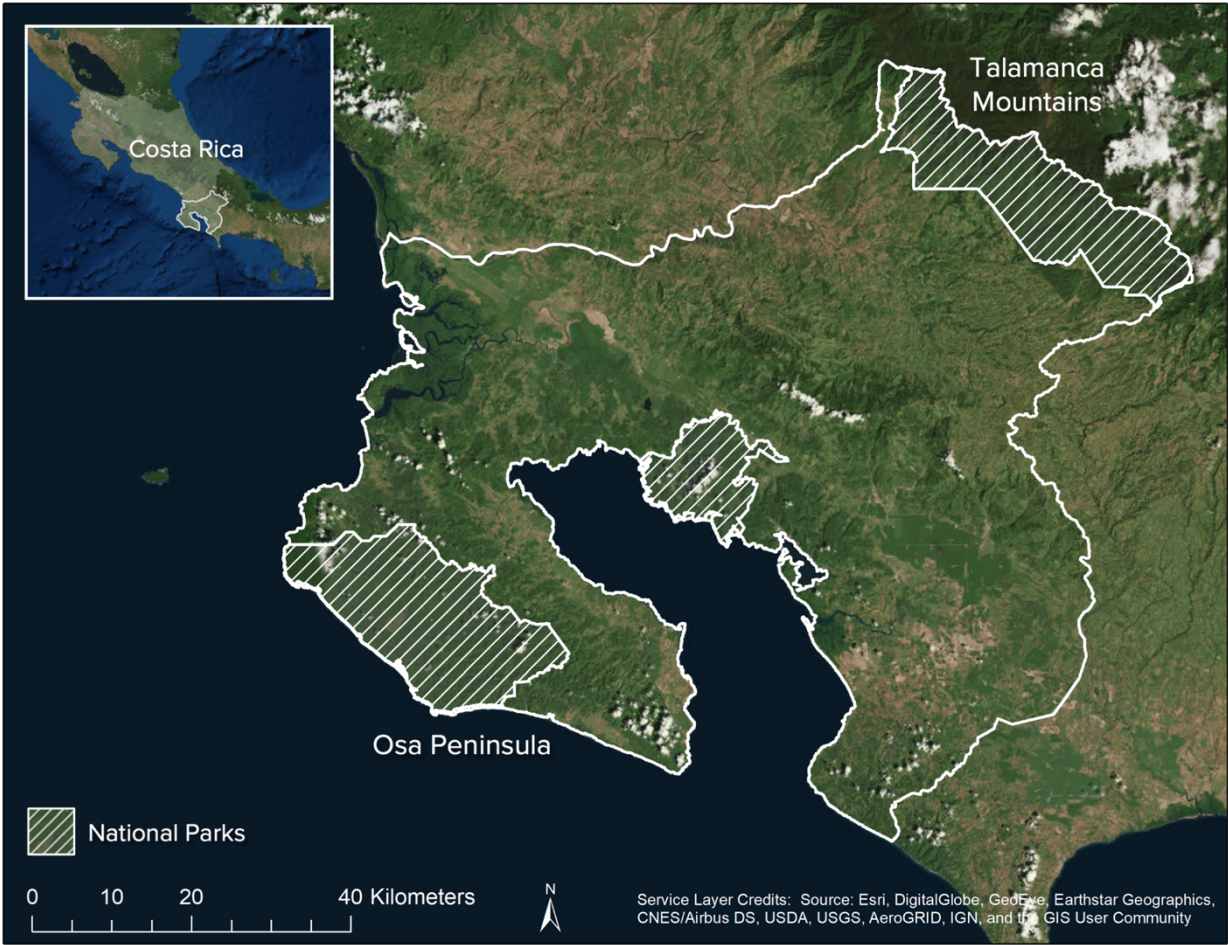
Figure 1. Study area map of the Talamanca-Osa region. Our focal area, the Talamanca-Osa region, in southwest Costa Rica extends from the Osa Peninsula to the Talamanca Mountains. The study area contains three national parks (from west to east): Corcovado National Park, Piedras Blancas National Park, and La Amistad International Peace Park.

The Talamanca-Osa region is a top conservation priority in Costa Rica (Brumberg, 2019). Spatial analysis completed through a recent Osa Conservation and NASA DEVELOP partnership shows ongoing loss of forest, rapid encroachment from large-scale agriculture, and degradation of primary forests (Furey et al., 2019). Certain crops and growing practices, such as large-scale monoculture, impede species' movement between habitats (Shaver et al., 2015). Models predict further reduction in connectivity in this region over the coming decades if "business as usual" practices continue (Zahawi et al., 2015).

Osa Conservation has been working to reduce habitat degradation and its drivers in the Talamanca-Osa region since 2003. Osa Conservation manages multiple forest reserves, conducts on-farm restoration research, and works directly with landowners to develop economically viable strategies which support wildlife-friendly agriculture and climate resilience. Such collaboration offers a path toward preventing habitat degradation and restoring connectivity, both of which are vital to conserving regional biodiversity.

Despite great conservation achievements over the last twenty years, work to restore connectivity in the Talamanca-Osa region is ongoing. This project will examine local wildlife movement and sustainable agriculture, and identify areas where management actions can benefit both. By providing research to farmers about future crop suitability and agricultural certifications, along with identifying key barriers to connectivity for restoration, we will help to strategically promote biodiversity and species movement throughout the region.

We aim to support long-term planning for sustainable farming by completing the following:

1. Identify the primary barriers to jaguar movement and analyze how two wildlife-friendly farming scenarios impact connectivity.

2. Evaluate and communicate the socio-economic and environmental impacts of regionally available eco-certifications.

3. Project climate-driven shifts in crop suitability distributions.

This project will support Osa Conservation's work to conserve the region's biodiversity by fostering ecosystem stewardship, enhancing scientific understanding, providing education, and creating sustainable economic opportunities in the Talamanca-Osa region.

Background

Costa Rica's extraordinary biodiversity is threatened by habitat loss and fragmentation due to agricultural expansion and impending climate change. Habitat fragmentation can isolate animal populations and increase extinction rates (Noss, 1987). Moreover, climate change may substantially alter species' ranges, thus the continual effectiveness of established protected areas is uncertain (Rudnick et al., 2012; Kostyack, 2011). While globally only 15% of land is protected for wildlife, almost 40% of land is dedicated to agriculture (UNEP-WCMC et al., 2018; World Bank, 2016). Integrating conservation in working landscapes is integral to mitigating the biodiversity crisis (Fischer et al, 2006), and an integrated approach beyond a focus on reserve networks is necessary.

To preserve regional species abundance and diversity, wildlife must be able to move between protected areas and across farmland (Estrada-Carmona et al., 2019). Incorporating natural landscape elements into agricultural areas can alleviate some of the impacts of habitat fragmentation. It is imperative that conservation strategies plan inter-patch mobility to combat the negative impacts from habitat fragmentation and climate change. Increased connectivity allows for movement between habitat areas and the ability for species to shift to higher elevations to accommodate warming temperatures associated with climate change (Beier & Noss, 1998; Perfecto & Vandermeer, 2008). There is evidence that a landscape approach of working with small farms, community social networks, and conservationists to implement agroecological systems can facilitate interpatch migration while supporting sustainable livelihoods in rural communities (Perfecto & Vandermeer, 2008).

The agricultural landscapes of different crops vary in their resistance to species movement and potential for integration of wildlife-friendly practices. For example, production of non-traditional agricultural exports like pineapple and banana is increasing in Costa Rica. While these crops typically positively impact the economy, they negatively impact biodiversity in a way that is difficult to mitigate (Shaver et al., 2015). Alternatively, some crops are more amenable to integration of wildlife-friendly practices. For example, cacao and coffee agroforestry systems can host higher species richness when compared to more homogeneous cacao and coffee plantations (De Beenhouwer et al., 2013; Schroth & Harvey, 2007). A focus on conserving native forest and maintaining diverse canopies can help conserve biodiversity in the long-term by increasing habitat and connectivity (Schroth & Harvey, 2007). There is a particularly urgent need for increasing regional connectivity for the jaguar, an economically- and ecologically important species to the region that currently exists in two disconnected populations. As a wide-ranging and forest-dependent species, jaguars act as an umbrella for others, meaning that their conservation is likely to benefit other species as well (Roberge & Angelstam, 2004).

Wildlife-friendly agriculture can decrease resistance to wildlife movement when compared to conventional agriculture (Kostyack et al., 2011). However, these practices are often costly to implement. In principle, eco-certifications can lower this barrier by allowing farmers to generate economic benefits through price premiums and increased market access (Giovannucci & Ponte, 2005). Information is needed on whether adopting eco-certifications can benefit the region environmentally, economically, and socially as the costs and benefits vary substantially depending on the context of each region and each farm.

Increasing urgency to align on-the-ground conservation efforts with the projected impacts of climate change complicates long-term planning for farming in the region. Climate change will alter temperature and precipitation patterns globally, and these impacts will have meaningful consequences for crop suitability. Temperature can have strong impacts on the quality and survival of regional crops such as coffee and cacao (Medina & Laliberte, 2017). As the impacts from climate change intensify, suitable ranges for these crops will likely shift. Shifts in crop suitability may make it challenging for regional farms to support their current practices, which could encourage land use change or more intensive and environmentally- degrading farming practices.

Strategic planning for sustainable farming in southern Costa Rica requires information on how crops will be influenced by climate change, how to incorporate wildlife-friendly farming practices in an economically feasible way, and whether these practices can help to support wildlife connectivity. Our analysis will provide farmers and conservation organizations with the information needed to promote sustainable farming in the region, benefitting both farmers and wildlife.

Chapter 1. Barriers to Jaguar Movement

Abstract

Southern Costa Rica has experienced substantial agriculture expansion and urban development over the last 100 years. Increasing fragmentation has led to two disconnected jaguar populations in the Talamanca-Osa region, greatly reducing the viability of the smaller population. Jaguars are particularly vulnerable to fragmentation because they are forest-dependent and wide-ranging, and therefore require large areas of undisturbed habitat. To reconnect the jaguar populations, managers must understand the barriers to movement in the region and the utility of specific management actions to reduce those barriers. Here, we use multiple connectivity models to predict regional jaguar movement. We identify the highest barriers to movement and examine the efficacy of using wildlife-friendly farming practices to improve connectivity. Our results demonstrate that large roads and extensive swaths of pastureland greatly hinder jaguar movement and that adoption of wildlife-friendly farming practices on its own has little effect on jaguar connectivity. We recommend future actions with the goal of improving connectivity to concentrate on major roads and pastureland in the region.

Introduction

High levels of deforestation and forest fragmentation have reduced the viability of much of Costa Rica's biodiversity (Schlaepfer & Gavin, 2001; Şekercioḡlu et al., 2002). Forest fragmentation is particularly problematic for jaguars (*Panthera onca*), as they require large patches of undisturbed habitat. They are wide-ranging but shy, and decreased habitat quality necessitates a wider range to satisfy habitat requirements (Morato et al., 2016). Further, jaguar persistence is negatively correlated with human-dominated landscapes (De Angelo et al., 2013; Fahrig, 2007). Because jaguars are a long-living species, the effects of habitat loss and fragmentation may not be observed for decades, complicating management (Tilman et al., 1994; De Angelo et al., 2013).

Jaguars are a flagship species in Costa Rica, but populations in the southern part of the country face increased pressure from agricultural expansion and human settlement. Jaguars in the Osa Peninsula are disconnected from those in the Talamanca Mountains and are at increased risk of inbreeding and local extinction as a result (Reed et al., 2002; Zanin et al., 2015; E. Flatt, personal communication, November 24, 2020). Connectivity between the two jaguar populations is fundamental to their survival and persistence, particularly for the smaller population (Salom-Perez et al., 2007). Additionally, as an umbrella species, conservation actions focused on jaguars should cover other, less sensitive species as well (Roberge and Angelstam, 2004).

Increasing jaguar connectivity in the region will require reducing habitat fragmentation between the region's protected areas (Figure 1). In this study, we aimed to achieve three objectives. First, **to map barriers to jaguar movement** between the two disconnected jaguar populations. Second, to **identify land uses on which restoration would be effective** at increasing jaguar connectivity. Third, to **model adoption of two wildlife-friendly farming scenarios** and the impacts to jaguar connectivity. Finally, we recommend management strategies and further research within the region to reconnect jaguar populations in southern Costa Rica and conserve the populations for the long term.

Methods

Study Area

We conducted our analysis in the Talamanca-Osa region of southern Costa Rica. The region is primarily forest and agriculture; land uses include primary forest (31.86%), secondary forest (27.11%), grassland/pasture (16.54%), palm plantation (8.99%), melina/teak (4.24%), wetland (3.03%), mangrove (2.83%), urban/exposed soil (2.46%), coffee (1.71%), water (0.84%), pineapple (0.32%), natural palm (0.07%), and páramos (0.01%; Figure 2). The region hosts two jaguar populations: one population in the Osa Peninsula and one in the Talamanca Mountains. The two populations are currently disconnected.
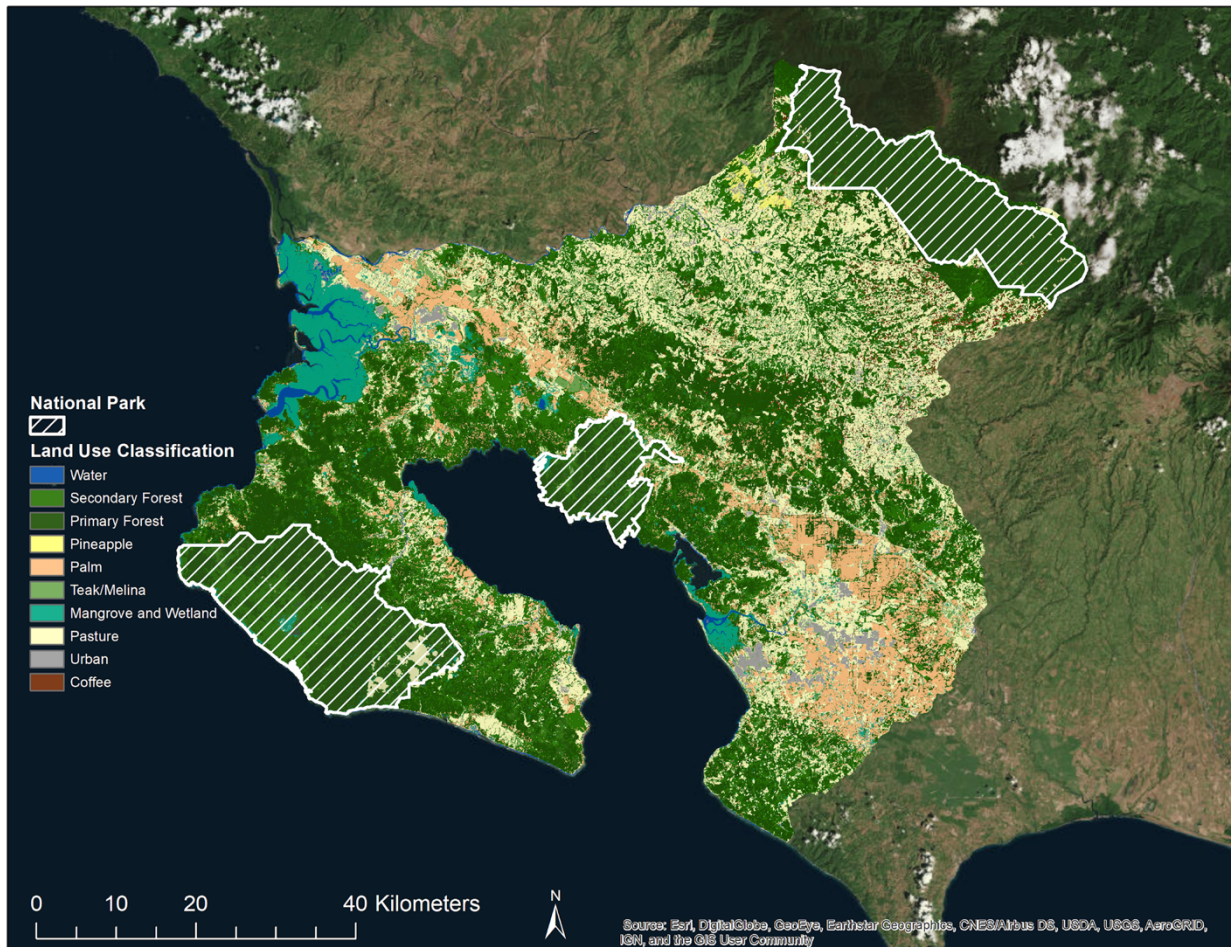
Figure 2. Study area with relevant 2019 land classifications and protected areas. *National parks include La Amistad International Peace Park (northeast), Corcovado National Park (southwest), and Piedras Blancas National Park (central). La Amistad International Peace Park has been clipped to the study area.*

Data

NASA DEVELOP is a NASA Applied Sciences Program which aims to address environmental and public policy issues with research projects informed by NASA Earth observations. In 2019, NASA DEVELOP created land use/land cover (LULC) and resistance to jaguar movement data (Furey et al., 2019; Table 2) that we used for our analyses. LULC data was produced using Landsat 5 Thematic Mapper, Landsat 8 Operational Land Imager, and PlanetScope satellite imagery. Topographic information from Advanced Land Observing Satellite Digital Surface Model was also used to increase accuracy. 2012 RapidEye land use and land cover classification files from Iniciativa Osa y Golfito and a 2012 GeoEye forest cover classification map from Gesellschaft fur Internationale Zusammenarbeit were used to verify classifications.

The resistance to jaguar movement included LULC, elevation, slope, and distance to roads, human settlements, and rivers as inputs. Data sources for these inputs included the LULC, Terra Advanced Spaceborne Thermal Emission and Reflection Radiometer (elevation) 2008 and 2014 Digital Atlas of Costa Rica (boundaries, protected lands, roads, rivers, and population distribution), the Socioeconomic Data and Applications Center (population density), and MapCruzin (human settlements). Resistance values were determined by expert consultation and literature review. Values were assigned to each layer on a scale of zero to ten, with ten as the highest energetic cost or highest level of difficulty for a jaguar to move through that specific cell (see Appendix A for all resistance values). Each raster was assigned a weight of influence within the model and the ArcMap raster calculator tool was used to create an overall resistance surface.

Table 1. *Sources, types, and short descriptions of data used.*

Data Name	Description
Land Use Land Cover (LULC)	Raster with classifications including primary and secondary forest, pineapple, palm plantation, coffee, pasture, teak/melina, urban, mangrove, wetland, and water. Created by NASA DEVELOP and provided by Osa Conservation (Osa Conservation & NASA DEVELOP, 2019).
Jaguar Resistance	Raster with resistance values for LULC (weight = 40%), distance to roads (20%), human settlements (20%), and distance to rivers (10%), slope (5%), and elevation (5%). LULC resistance values included primary forest (resistance value = 0), secondary forest (1), wetland (3), coffee (4), grassland/pasture (5), mangrove (5), palm plantation (6), water (9), exposed soil/urban (10), páramos (10), and pineapple (10). See Appendix A for all resistance values. This raster was created and provided by NASA DEVELOP (NASA DEVELOP, 2019).

Analysis

Mapping Barriers to Jaguar Movement

We used the resistance raster and Barrier Mapper in the Linkage Mapper Toolkit to map the barriers to jaguar movement. Linkage Mapper is a deterministic model that models connectivity based on cost-weighted distance. Barrier Mapper identifies locations within the resistance raster that are highly resistant to movement but, if restored, would change the cost-weighted distance of jaguar movement, called the least-cost path (LCP). The output raster created in Barrier Mapper demonstrates improvement scores, which can be interpreted as the connectivity improvement resulting from restoration. Barrier Mapper measures the cumulative resistance before and after

restoration, and the improvement score is calculated as the difference between the two. Barrier Mapper requires inputs for a minimum and maximum detection radii, which determines the area of potential restoration to simulate. We used a minimum detection radius of 300 meters and a maximum detection radius of 750 meters (with a step value of 225 meters) to approximately mirror average sizes of small and large Costa Rican farms ("Costa Rica: Results of Agricultural Census 2014", 2015; values converted from hectares to meters). We categorized the barriers by improvement score into quartiles (i.e., low, moderate, high, and very high improvement; Dutta et al., 2018) and focused our analysis on what we will call "key barrier areas", or only the top two quartiles.

Identifying Land Uses for Restoration

We focused our analysis identifying barrier area land uses with high restoration for connectivity potential on the region between Piedras Blancas National Park (hereafter, "Piedras Blancas") and La Amistad National Park (hereafter, "La Amistad"). The distinction between east and west of Piedras Blancas was based on preliminary data and insight to local knowledge from Osa Conservation (E. Flatt, personal communication, November 24, 2020) that jaguars are present between Corcovado National Park (hereafter, "Corcovado") and Piedras Blancas, but not present between Piedras Blancas and La Amistad. To understand the land uses within barriers, we converted the key barrier areas raster to a vector and clipped the LULC raster to the key barriers. We then overlaid major roads. Further, we highlighted barriers with very high improvement scores (the top quartile).

Modeling Wildlife-Friendly Farming Scenarios

The restoration scenarios chosen were 1) all coffee modeled as **shade-grown coffee**, and 2) all palm modeled as **palm with an understory**.

Palm and coffee were chosen because they are the agricultural land uses that occupy the largest amount of the study area, excluding pasture. Pasture was excluded from consideration in the analysis due to real and perceived threats to livestock from increased jaguar abundance, and thus a presumed lower likelihood for grower adoption of jaguar-friendly practices. Further, there are several eco-certifications active in the region that may help lower the financial barriers to the transition for coffee growers, which may increase the likelihood for grower adoption. However, no such certifications exist yet for palm with an understory as this research area is relatively new.

We determined modified resistance values for the two scenarios. Relative values are informed by research demonstrating that conservation practices can benefit wildlife in shade-grown coffee (Caudill et al., 2015) and palm (Hood et al., 2019); however, the exact modified values were limited to integer steps based on the methodology of the original resistance raster. For example, in the moderate-impact scenario, shade-grown coffee is one step below conventional coffee. In the high-impact scenario, shade-grown coffee is one step above secondary forest and two steps below conventional coffee. Wildlife-friendly scenarios for palm, too, were one and two steps below conventional palm for moderate and high impact, respectively. While palm does have a near complete canopy, an understory does not bring palm plantations as close to secondary forest as shade-grown coffee does due to high human and machinery disturbance in palm plantations, which are likely disruptive to disturbance-sensitive species like jaguars.

Table 2. Modified resistance values (shaded) simulating moderate and high impact conservation practices for coffee and palm. Original values (unshaded) are the resistance values assigned by NASA DEVELOP in production of the original resistance to jaguar movement raster.

Land Cover Type	Resistance Value
Primary Forest	0
Secondary Forest	1
Shade-Grown Coffee *High Impact*	**2**
Wetland	3
Conventional Coffee	4
Wildlife-Friendly Palm *High Impact*	**4**
Pasture	5
Mangrove	5
Conventional Palm Plantation	6
Water	9
Urban	10

We used Esri ArcGIS Desktop 10.8 and the Linkage Mapper Toolkit (Barrier Mapper, Pinchpoint Mapper, and Linkage Mapper) to model how restoration scenarios impact resistance to jaguar movement. The Linkage Mapper Toolkit has been used extensively to model large mammal movement and design wildlife corridors (Dickson et al., 2013; Joshi et al., 2013; Dutta et al., 2016; Jackson et al., 2016). To simulate adoption of wildlife-friendly practices on palm plantations and coffee farms, we reduced the resistance to jaguar movement of raster pixels intersecting those land uses for each scenario (Figure 3). We created new resistance rasters for each scenario by isolating the land use (coffee or palm) in the LULC raster and reclassifying the pixel values to the difference between the original and modified resistance values, adjusted for the LULC weight (40%). Next, we subtracted the reclassified isolated LULC raster from the resistance raster. We replicated these steps for each scenario for a total of four modified resistance rasters (shade-grown coffee high impact, shade-grown coffee moderate impact, palm with understory high impact, palm with understory moderate impact).
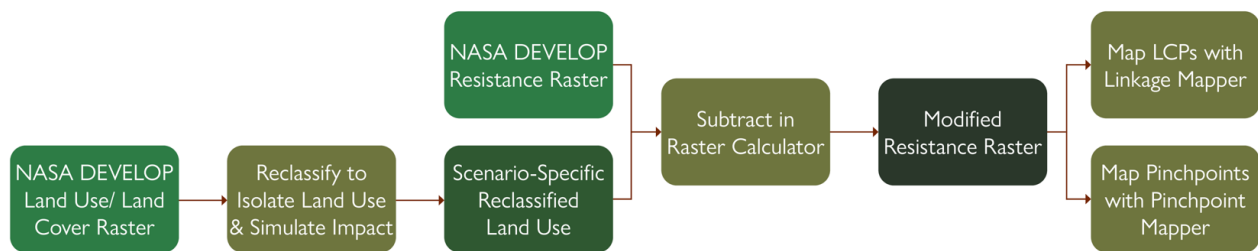

Figure 3. Simplified methods for creating simulating wildlife-friendly farming scenarios using Esri ArcMap and the Linkage Mapper Toolkit. Scenarios included 1) shade-grown coffee high impact, 2) shade-grown coffee moderate impact, 3) palm with understory high impact, and 4) palm with understory moderate impact. See Appendix B. for a more detailed methodology.

We used two different models to analyze the impact of each scenario. The first model created LCPs with Linkage Mapper, which allowed us to understand whether the restoration effort changed the LCP between the national parks from the baseline. The second model mapped pinchpoints to movement using Circuitscape. Circuitscape is a probabilistic model that uses circuit theory to calculate the chances that a random walker would pass through each cell of a raster based on the cell's resistance, creating a corridor of high probability of movement cells (Mcrae et al., 2008). The pinchpoint maps determine whether the restoration effort increases functional connectivity from the baseline. We created LCPs and pinchpoint maps for each scenario using Linkage Mapper and Pinchpoint Mapper with each modified resistance raster as an input (see Appendix B for a more detailed methodology).

Results

Barriers to Jaguar Movement

The predominant land use in the study region is primary forest (31.9%) and in the barrier areas is secondary forest (35.3%). Specifically within the barrier areas, the predominant land use in the west is secondary forest (39.4%) and in the east is pasture (34.0%; Figure 4; Table 3).
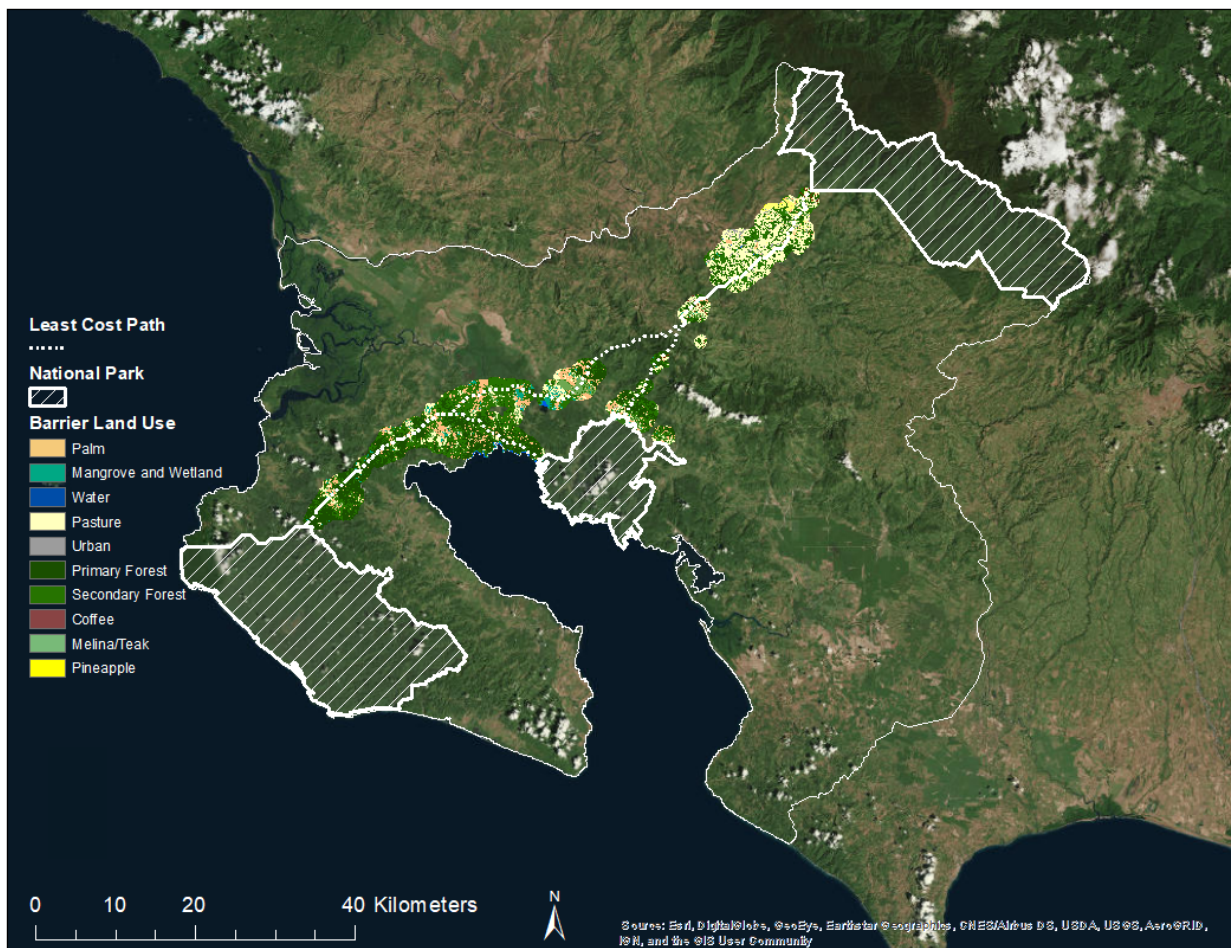

Figure 4. *Study area with land use classifications clipped to key barrier areas with the least cost path for jaguar movement connecting three national parks. National parks include (from west to east) Corcovado, Piedras Blancas, and La Amistad.*

Table 3. *Percentage of focal land use classifications in the study region and barrier areas. Western and eastern barriers are barriers west and east of Piedras Blancas, respectively.*

	Prim. Forest	**Second. Forest**	**Pasture**	**Palm**	**Coffee**
Study Region	31.9%	27.1%	16.5%	9.0%	1.7%
Barrier Areas	26.9%	35.3%	19.8%	8.3%	0.3%
Western	*38.9%*	*39.4%*	*5.9%*	*9.6%*	*0.0%*
Eastern	*14.6%*	*31.1%*	*34.1%*	*7.0%*	*0.7%*

Land Uses for Restoration

Figure 5 focuses on the region between Piedras Blancas and La Amistad where jaguars are not known to be present. The black outlines indicate the barrier areas with the highest improvement scores (the top quartile). The largest high-improvement score area is predominantly pasture and has a major road running through it. The second largest high-improvement score area contains a major road (the Pan-American Highway) where the LCP meets Piedras Blancas. These results suggest that restoration to pasture and roads may have a high to jaguar connectivity.
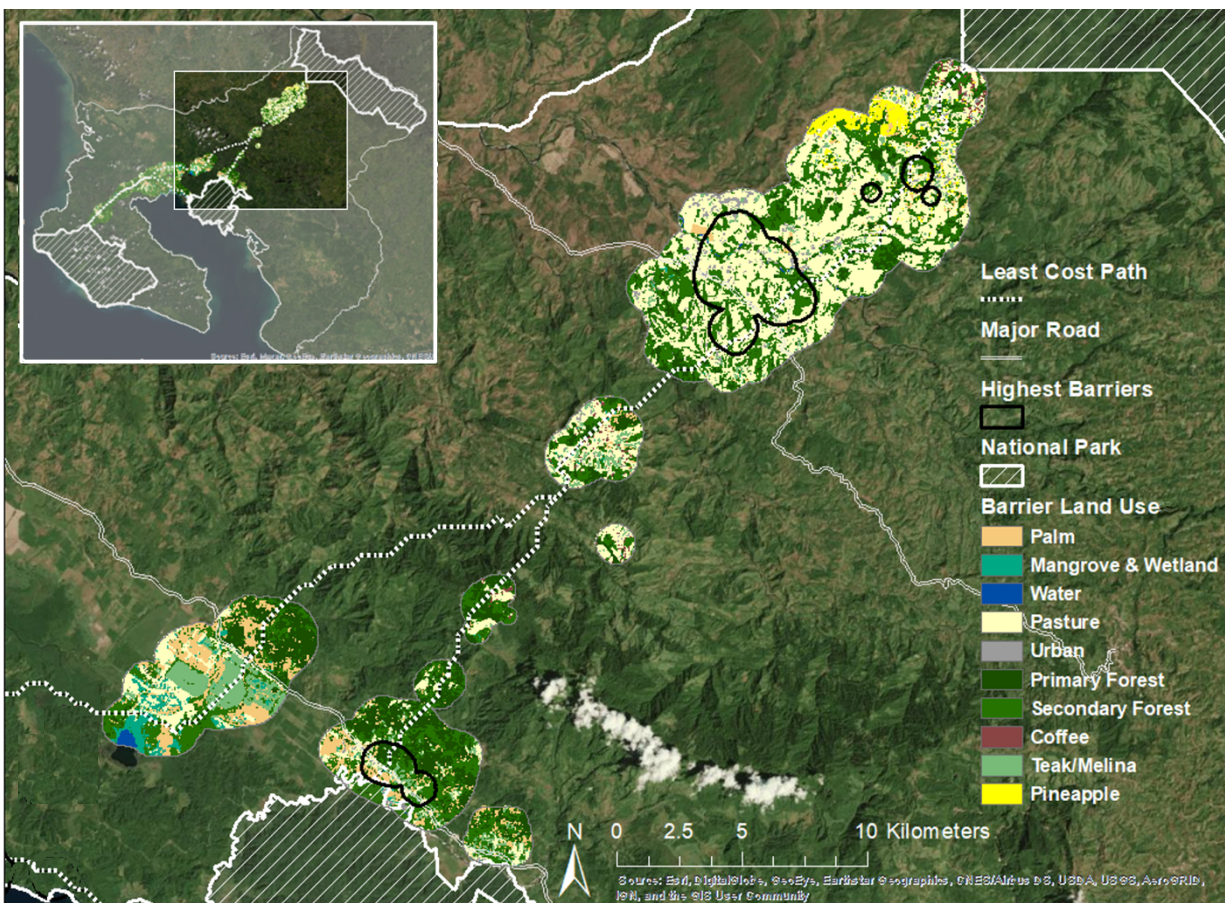

Figure 5. *Major roads and ILULC clipped to the barrier area between Piedras Blancas (west) and La Amistad (east), where jaguars are not known to be present. Black outlines represent the barrier areas with the highest (top quartile) improvement scores.*

Wildlife-Friendly Farming Scenarios

Figure 6 shows the LCP from the original resistance raster and LCPs for the high-impact coffee and palm wildlife-friendly farming scenarios. None of the wildlife-friendly farming scenarios substantially impact jaguar movement in the LCPs or pinchpoint maps (see Appendix D for pinchpoint maps for high-impact scenarios). Moderate-impact scenarios had negligible changes, so only high-impact scenarios are depicted in this report.
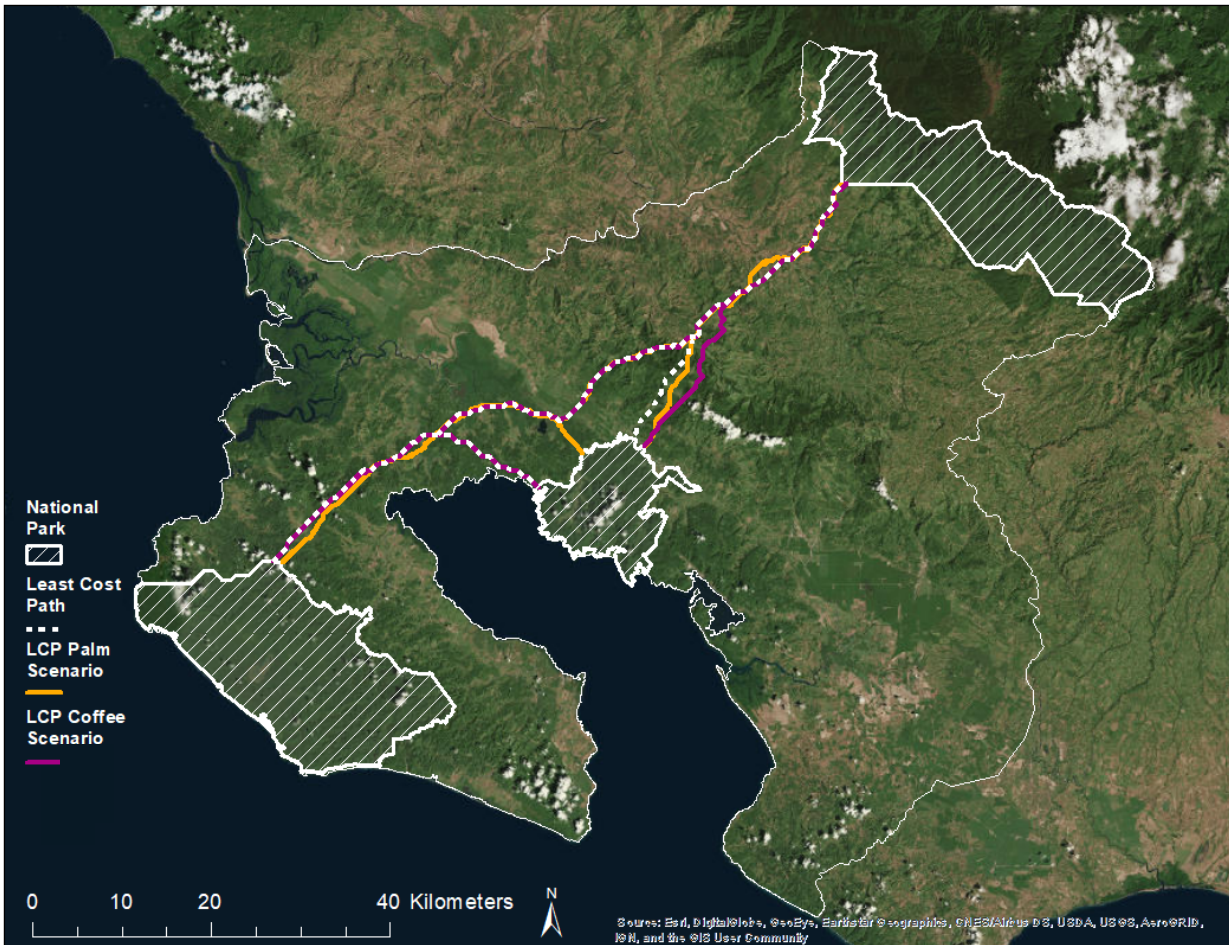
Figure 6. *Original least-cost path (white; LCPs) and LCPs of jaguar movement for high-impact scenarios for shifting conventional coffee to shade-grown coffee (magenta) and conventional palm to palm with an understory (orange). National parks include La Amistad International Peace Park (northeast), Corcovado National Park (southwest), and Piedras Blancas National Park (central). La Amistad International Peace Park has been clipped to the study area.*

Discussion

Our analysis aimed to elucidate the barriers to jaguar movement in the study area, identify key land uses for restoration, and examine the impacts of wildlife-friendly farming practices on jaguar connectivity in the region. We found that the most problematic barriers to jaguar movement are between Piedras Blancas National Park and La Amistad National Park, and they are centered around large swaths of pasture and major roads. Land managers should consider these areas for underpass installation and pasture reforestation. Adoption of wildlife-friendly farming practices on multiple agricultural land uses had little impact on regional jaguar connectivity.

With widespread pasture as a major barrier to jaguar connectivity, it is clear that the vestiges of historic deforestation remain problematic for wildlife. Reforestation on pasture will likely be necessary to restore jaguar connectivity. Reforestation measures can take several forms, and may rely on governmental incentives, such as purchasing land to convert to forest, leasing land from farmers for restoration, or funding organizations to take functionally similar actions (Kamal et al., 2015). The Costa Rican government has one of the most well-established national payments for ecosystems services (PES) schemes in the world, though the scheme focuses primarily on conservation of existing forest rather than building additionality with reforestation (Brownson et al., 2020). Another reforestation mechanism is transitioning from pasture to agroforestry. Regional agricultural uses that allow for agroforestry practices can include teak, coffee, and cacao. We do not recommend agroforestry as a replacement for permanent forest; however, agroforestry is likely more beneficial to wildlife than pasture, and if transition is feasible then it should be considered.

Key barrier areas in the region east of Piedras Blancas intersect two major roads. Roads are a large contributor to forest fragmentation and are highly resistant to wildlife movement (Young, 1994). Installing underpasses along major roads can increase large animal connectivity (Foster and Humphrey, 1995), including jaguars, but comprehensive analysis of priority locations is necessary (González-Gallina et al., 2018). We recommend that future research evaluates the potential effectiveness of underpasses for jaguars in this region, as our results demonstrate installing an underpass at the LCP's eastern entrance to Piedras Blancas could be a crucial first step towards increasing connectivity in the region.

Our wildlife-friendly farming simulations suggested that transition to shade-grown coffee or incorporating understories in palm plantations would have little to no impact on jaguar connectivity. Coffee and palm only cover a small percentage of land use within the barrier areas (0.3% and 8.3%, respectively), and in the study area as a whole (1.7% and 9.0%), leaving little potential for large impacts to connectivity. Our results highlight the issues forest fragmentation in the region pose; the study area is over 50% forest, yet connectivity remains an issue. Further, it is important to note that wildlife-friendly farming practices such as shade-grown coffee and palm with an understory are not necessarily meant to benefit large, wide-ranging species like the jaguar, though they can still benefit other taxa.

Our results from modeling wildlife-friendly farming should not dissuade farmers in the region from pursuing wildlife-friendly practices. While wildlife-friendly farming practices do not appear very impactful on their own, any measures taken that enhance the natural environment may help decrease the ecological impacts of forest fragmentation in the Talamanca-Osa region. Further, restoration of agricultural land can be beneficial to on-farm wildlife and can provide ecosystem services (Karp et al., 2013; Martínez-Salinas et al., 2016; Şekercioğlu, 2012; Power, 2010). Instead, our results suggest that further conservation measures will be needed to reconnect jaguar

populations, and wildlife-friendly farming will not reconnect them independently. Planning for jaguar movement is more robust on a landscape scale, not the patch scale at which wildlife-friendly farming occurs. This means that both the private and public sector will need to collaborate to conserve the Osa Peninsula's jaguar population.

We are aware that improving jaguar connectivity between Piedras Blancas and La Amistad will likely bring jaguars in closer contact with livestock, potentially creating problems for ranchers in the region. Jaguar-livestock conflict in Costa Rica has been well-documented (Amit et al., 2013; The Tico Times, 2014; Montalvo et al., 2016), and retaliatory killings of jaguars for livestock depredation do occur (Amit et al., 2009; Rabinowitz & Zeller, 2010). Conservation measures on pastureland must closely engage ranchers to avoid both jaguar-livestock conflict and subsequent retaliatory killings (Amit et al., 2013; Bogezi et al., 2019). To guide management strategies for reducing the likelihood of conflict, researchers will first need to identify the characteristics of jaguar attacks on livestock . For example, livestock less than one year old face much higher risk of attack (Polisar et al., 2003; de Azevedo, 2007; Soto-Shoender & Guiliano, 2011), and depredation events are strongly correlated with calving peaks (Polisar et al., 2003; Michalski et al., 2006). These findings lend support to the practice of keeping younger livestock in pens or generally safer areas and moving females near birth to safer areas (Amit et al., 2013). Second, researchers should determine the local applicability of multiple financial mechanisms that have been used to reduce predator-livestock conflict, including direct compensation or insurance schemes, revenue-sharing initiatives, and pre-conflict conservation payments. A scheme combining several financial mechanisms, tailored to the context of the study area, will likely be most effective (Dickman et al., 2011). Further, one driver of jaguar-livestock conflict is a reduction in peccary populations, a favored prey of the jaguar (Salom-Perez et al., 2007). Measures to increase peccary populations could have the secondary effect of reducing jaguars reliance on livestock for food.

Our study had several assumptions and limitations. First, our models do not include ground-truthing jaguar observation data. We can not be certain that jaguars exist or will exist along the least-cost path we calculated without observational data; in fact, local understanding is that jaguars do not exist between Piedras Blancas and La Amistad. Similarly, the umbrella species method can miss out on protecting some important regional species. Therefore, this work can be paired with similar analyses for functionally different key regional species to form a multi-species conservation plan (Roberge and Angelstam, 2004). Second, this study did not simulate the potential for increasing jaguar connectivity for any land uses beyond palm and coffee. However, there are multiple other land uses that contribute high resistance to jaguar movement. Pasture and roads were found to be particularly important in our analyses, and other highly resistant land uses include urban areas, pineapple, and rivers. Conservation scenarios addressing these land uses should be considered in a holistic plan for increasing connectivity. Third, we did not directly study the population dynamics of the disconnected jaguar population found in the western part of the study area. Understanding the population demographics of this population would be useful for understanding the timeline for extinction risk (De Angelo et al., 2013). Fourth, our recommendations do not take into account the viability of widespread adoption of wildlife-friendly agricultural practices, reforestation efforts, or underpass installation. After determining priority locations for reforestation and underpasses, researchers will need to work further to understand the most viable pasture for conversion to forest and road sections for construction of underpasses.

Conclusion

Key barriers in areas of the Talamanca-Osa region that lack jaguars include pasture and major roads. Wildlife-friendly farming will not be sufficient to reconnect jaguar populations without additional reforestation efforts. However, these practices can be included in a holistic plan for increasing regional jaguar connectivity that includes wildlife-friendly farming, pasture reforestation, and underpasses beneath major highways. As the jaguar is an umbrella species, these recommendations are also likely to benefit other mammals in the region. Conservation resources should be concentrated in key barriers between Piedras Blancas and La Amistad, where jaguars are not known to occupy.

Jaguars are a flagship species in Costa Rica and their extirpation in the study area will lead to negative ecological and economic consequences. We have explored some barriers to jaguar movement, including forest fragmentation, widespread pasture, and major roads and suggested next steps towards enhancing jaguar connectivity in the Talamanca-Osa region. The Costa Rican government and conservation organizations can use our findings to inform jaguar connectivity efforts and help sustain the species in southern Costa Rica.

Chapter 2. Eco-Certification Requirements and Impacts

Abstract

Costa Rica's extraordinary biodiversity is threatened by habitat loss and fragmentation due to agricultural expansion. Integrating conservation in working landscapes can play a key role in mitigating the impacts. Wildlife-friendly farming practices may decrease resistance to wildlife movement, but these practices are often costly to implement. In principle, eco-certifications can lower the financial barriers by allowing farmers to generate economic benefits through price premiums and increased market access. However, environmental, economic, and social impacts from adopting eco-certifications are likely to vary substantially depending on the context of each individual farm or region. Here, we conduct a review of the scientific literature to evaluate the ecological, economic, and social impacts of eco-certifications available to the Talamanca-Osa region of southern Costa Rica. We found that eco-certifications can provide environmental, economic, and social benefits, but that a net economic benefit is not guaranteed and that there are often substantial trade-offs. Communication of our results will allow farmers to better understand the potential for benefitting from eco-certifications based on their individual context.

Introduction

Globally, agriculture is the leading cause of habitat and biodiversity loss, soil erosion, water stress, and other negative environmental processes (Tayleur et al., 2017). Further, simplification of agricultural landscapes with increasing shifts towards monoculture threatens the landscape heterogeneity necessary for wildlife movement (Höbinger et al., 2012). Crop land and natural habitat are often perceived to be mutually exclusive, necessitating trade-offs between agricultural yields and biodiversity. However, wildlife-friendly agriculture can decrease resistance to wildlife movement when compared to conventional agriculture (Kostyack et al., 2011). For long-term preservation of species abundance and diversity in the region, wildlife must be able to move between these protected areas and across farmland (Estrada-Carmona et al., 2019).

To bring wildlife-friendly agricultural practices to a large scale, they must be economically feasible for farmers. The recent proliferation of voluntary sustainable agriculture initiatives ("eco-certifications") has provided a relatively standardized tool for improving the sustainability of agricultural practices and transparency within international supply chains (Blackman & Rivera 2011; Newton et al. 2013; Potts et al. 2014; Tscharntke et al. 2015). Eco-certifications could be particularly useful in lower income tropical countries that have seen high deforestation for crops typically exported to richer nations (Gibbs et al., 2010, Tayleur et al, 2016). More research is needed to evaluate the impacts of individual certifications, but research has shown that eco-certifications broadly can provide environmental, economic, and social benefits (Kostyack et al., 2011; Loconto & Dankers 2014; Potts et al. 2014; Tscharntke et al., 2015). Multiple studies have evaluated the performance of various eco-certifications in Costa Rica (Lyngbaek et al, 2001; Ronchi, 2002; Blackman & Naranjo, 2010), but variability in how certifications are adopted and evaluated make it necessary to determine the utility of specific certifications on a farm by farm, certification by certification basis.

Similar to much of the tropics, Costa Rica has seen widespread agricultural expansion and its negative consequences over the last century. Much of the country's pristine rainforest has been cut down, heavily fragmenting the landscape and reducing habitat of key species (Rosero-Bixby

& Palloni, 1998; Seaman & Schulze, 2010). To combat this, Costa Rica implemented progressive environmental laws in the late 20th century (Rodricks, 2010), and became the host of one the first eco-certified farms in the world (Rainforest Alliance, 2016). A number of multinational and local eco-certifications are currently active in Costa Rica, certifying crops such as banana, coffee, cacao, and palm oil, among others. While there is not widespread adoption of eco-certifications in the Talamanca-Osa region currently, local farmers have expressed interest in adopting eco-certifications (Rodrigo de Sousa, personal communication, July 29, 2020). This chapter reviews the current literature on the environmental, economic, and community impacts of eco-certifications that are relevant to the Talamanca-Osa region and presents a comparison of their requirements. This will be shared with Osa Conservation to inform the organization's work in the region with local farmers.

Methods

Literature Review

A literature review was conducted to identify studies related to environmental certifications that were available in Costa Rica. Digital databases were searched including Google Scholar and the UC Santa Barbara Library. Search terms included the names of regionally-available eco-certifications ("Rainforest Alliance", "Organic", "Smithsonian Bird-Friendly", "Fair Trade", "Bandera Azul"), as well as more general terms including "environmental certification," and "agricultural certification". Studies that included the impacts of eco-certifications on crops grown in the Talamanca-Osa region were prioritized, particularly coffee, cacao, palm, banana, and pineapple. There was limited data available on the impacts of eco-certifications for many crops, but studies on certified coffee were the most abundant. We did not review studies written in languages other than English.

We reviewed five relevant certification programs. Whether a certification was relevant was based on regional availability and whether it certified regional crops. Many farms in the region are small, so programs that allow cooperative certifications and are more locally known were of particular interest. The programs chosen for analysis were: Rainforest Alliance, Smithsonian Bird-Friendly, Bandera Azul Ecológica ("Bandera Azul"), Organic, and Fair Trade.

After selecting certifications, research was continued by searching for case studies in the scientific literature that evaluated their impacts. We grouped impacts into three broad categories: environmental impacts, economic impacts, and community impacts. These broad impact categories were further narrowed down to more specific impacts of certification. Environmental impacts included agrochemical use and species diversity. Economic impacts included price premiums, improved market access, transition time, and costs of certification for farmers. Community impacts included the impacts of cooperatives, worker health and safety, and education or other projects funded by price premiums. For some categories, careful differentiation between requirements and impacts was necessary. For example, for understanding the impact of agrochemical use, we do not mean whether the certification required reduced use (a "requirement"), but whether the requirement actually led to the farmer changing their use (an "impact").

Scientific papers that addressed impacts of the five selected certifications were tracked using Google Sheets. Since this body of research is limited, information was not available for all of the specific impacts for each certification.

Relevant Eco-Certifications

Many organizations offer environmental and social certification programs for farmers. These certifications typically dictate a set of standards that farms must follow with assurances that better market access and price premiums will come in exchange. In Costa Rica, the highest levels of certification for main commodity crops are in coffee farms where certified farms exceed the number of non-certified ones (Tayleur et al., 2018). The most prevalent certifications amongst coffee farms are Fair Trade and organic certifications (Barham & Weber, 2012). We summarize five regionally available eco-certifications to crops in the Talamanca-Osa region below.

Rainforest Alliance

The most common certification found amongst farms in the Talamanca-Osa region is Rainforest Alliance (Rodrigo de Sousa, personal communication, July 29, 2020). This certification incorporates both environmental sustainability and social welfare into its requirements which center around six primary areas: management, traceability, income and shared responsibility, farming, social, and environment (Rainforest Alliance, 2020a). The standards incentivize continuous improvement by allowing farmers to meet some requirements by setting goals and improving on their own baselines, rather than a traditional pass/fail approach (Rainforest Alliance, 2020b). This added flexibility may make this certification more accessible to farmers in the Talamanca-Osa region, and could benefit small farms for which more stringent certifications could be unfeasible.

After registering in the Rainforest Alliance system, farms have a year-long preparation period before being audited, during which they perform an initial assessment of risks and baselines and implement a management plan to reach the standard's minimum requirements. After this first year, farms are audited by an independent audit organization and become certified if they meet all the necessary requirements (Rainforest Alliance, 2020a). This certification may be particularly useful for farmers in the region because it allows group certifications for small farm cooperatives.

Smithsonian Migratory Bird Center Bird Friendly

If a coffee farm is certified organic, it is eligible to attain a Smithsonian Migratory Bird Center Bird Friendly Coffee certification for certified organic, shade-grown coffee (Smithsonian Migratory Bird Center Bird Friendly Coffee, n.d.). Practices required for certification include minimum percentage of canopy cover, minimum canopy height, native species requirements, vegetation buffers, and more. This certification's stringent environmental requirements make it likely the best for wildlife but potentially the most difficult to adopt. However, while adopting the necessary agroforestry practices can be expensive for a conventional farm to transition to, growers can benefit from the ecosystem services of higher bird abundance in the forms of natural pest control, pollination, and seed dispersal (Şekercioğlu et al., 2019).

Programa Bandera Azul Ecológica

Programa Bandera Azul Ecológica ("Bandera Azul") is a national Costa Rican certification program. Its requirements include reduction of chemical inputs, improved water-use efficiency, and a climate change adaptation plan, among others (Programa Bandera Azul Ecológica, 2016). Many farms in the region are already certified through this program and are interested in

additional certifications that could provide better price premiums and market access. Farmers reported that the Bandera Azul certification helped pave the way to get Rainforest Alliance certified, particularly those who are already using sustainable farming practices (Rodrigo de Sousa, personal communication, July 29, 2020).

Organic

Organic certification ensures elimination of most synthetic agrochemicals and promotes natural methodologies, such as pest control from birds or insects, to increase yields when possible (Kilian et al., 2004). For farmers of any crop to attain an organic certification, they need to fulfill five main requirements ("USDA Organic Production and Handling Standards", 2016):

1. Land must not have any prohibited substances applied to it for at least 3 years before harvest

2. Soil fertility is managed through tillage and cultivation practices, crop rotations, and cover crops when possible, and only supplemented with animal and crop waste materials and allowed synthetic materials

3. Physical, mechanical, and biological controls are used for controlling pests, weeds and diseases when possible, and only supplemented with approved substances

4. Organic seeds must be used when available

5. Genetic engineering, ionizing radiation, and sewage sludge are prohibited

Expected costs from the certification can include yield reductions, expenses from major changes to the production process, increased labor expenses, and certification monitoring. A potential economic benefit of organic certification is reduced production costs if the farmer formerly used chemical inputs. Price premiums are possible as well (Blackman & Naranjo, 2012).

Fair Trade

Fair Trade ensures a reasonable price for a product, requires the producer to have safe and ethical practices for their workers, and requires them to use a portion of their profits to support their local community and environment (Kilian et al., 2004). Fair Trade guarantees both a *minimum price* and a *price premium* for producers. The minimum price is intended to cover the average costs of sustainable production, reducing the risk farmers face from drops in market prices. The price premium is an additional premium to be reinvested by farmers into projects that improve their quality of life and their communities (Dragusanu & Nunn, 2018), such as education projects, healthcare, or farm improvements that can increase income.

Ecological, Economic, and Community Impacts

Ecological Impacts

Eco-certifications that promote sustainability practices can contribute to increased naturalness and connectivity, which can be beneficial for wildlife (Blackman & Naranjo, 2012; Rueda & Lambin, 2013; Rueda et al., 2014) as well as farmers. Increasing a farm's wildlife-friendliness can enhance valuable ecosystem services, demonstrating win-win scenarios for farmers and biodiversity (Power, 2010; Mendenhall et al., 2011).

Wildlife-friendly farming involves lower intensity farming practices that prioritize incorporating native species into farmland as well as other agroforestry principles such as limiting external inputs. This type of farming typically requires more land to produce the same agricultural yield, but these systems can serve as high quality matrices between habitat fragments and may be more sustainable for preserving biodiversity in the long run (Wade et al., 2010). In Costa Rica, important wildlife-friendly farming practices can include natural landscape elements like gallery forests, forest patches, tree lines, hedgerows, and live fences (León & Harvey, 2006; Seaman & Schulze, 2010; Höbinger et al., 2012). With careful and responsible management practices, increasing natural elements in neotropical agricultural regions helps maintain landscape structure and connectivity, and thus are important to consider in conservation efforts (León & Harvey, 2006; Höbinger et al., 2012).

Environmental requirements in eco-certifications such as canopy cover, plant diversity, and reduced agrochemical inputs can lead to environmental benefits. Certified organic coffee production in Costa Rica has demonstrated reduced chemical inputs and increased adoption of more environmentally-friendly practices such as soil conservation and use of shade trees and windbreaks (Blackman & Naranjo, 2012). Similarly, in Colombia, certified coffee farms contributed to an overall increase in regional tree cover (Rueda et al., 2014). However, certifications are not always successful in their conservation goals. For example, in Mexico, efforts toward promoting certification led to the unintended consequence of incentivizing the conversion of natural forest to agroforest, highlighting the importance of careful and responsible certification management and enforcement (Tejeda-Cruz, 2010).

Costa Rica is home to over 800 bird species, more than the entirety of North America (Clark & Stiles, 1989). While the majority avoid agricultural landscapes, they provide habitat to nearly a third of bird species (Şekercioğlu, 2012). Incorporating wildlife-friendly practices is important for the conservation of Costa Rican bird species. For example, increased tree cover on Costa Rican agricultural landscapes has been shown to increase bird diversity (Şekercioğlu et al., 2019), even to a level that resembles diversity in protected areas (Karp et al., 2019). However, the bird species present in agricultural landscapes and protected areas are not necessarily the same. Increasing simplification of agricultural landscapes can result in shifts in bird communities, potentially altering their functional roles in ecosystem services (Şekercioğlu, 2012).

It is important to note that the magnitude of these benefits is dependent on the magnitude of changes to agricultural practices (Boody et al., 2005). There is limited research that constructs a valid counterfactual to compare environmental impacts on certified vs. non-certified farms (Blackman & Rivera, 2010). While it is difficult to determine the environmental effects of eco-certifications themselves, there is evidence that wildlife-friendly farming practices can benefit biodiversity and increase ecosystem services.

Case Study

Do Bird Friendly® Coffee Criteria Benefit Mammals? Assessment of Mammal Diversity in Chiapas, Mexico

While research has shown that shade-grown coffee can increase bird diversity (Şekercioğlu, 2012), Smithsonian Bird Friendly ("Bird Friendly") certified coffee may have the potential to increase mammal diversity as well. Caudill & Rice (2016) assessed mammal diversity within forest and coffee farms with varying degrees of shade trees. The study examined six coffee farms that were Smithsonian Bird Friendly certified, six coffee farms that had at least 40% shade cover but did not meet the additional criteria for Bird Friendly coffee, six sun-grown coffee farms, and five sites in nearby compromised forest remnants that were part of a larger fragmented habitat. Bird Friendly coffee farms had the highest mammal species density and abundance overall, and hosted a significantly higher small mammal species density than the forest, shade, and sun coffee habitats. Large and medium mammal species density was higher in areas with larger and more mature trees, which is often associated with Bird Friendly coffee, but not required. The mean species richness for all mammals was highest for shade coffee, followed by Bird Friendly, but none of the habitat types were significantly different from one another in species richness.

In this study, certified Bird Friendly coffee farms served as high quality matrix that connected a fragmented forest in the region. This is promising evidence that Bird Friendly certified farms can provide habitat for mammals as well as birds in fragmented ecosystems. Increases in shade tree basal area and lower strata vegetation were both found to significantly increase total species density. While lower strata vegetation was significantly greater in Bird Friendly coffee sites compared to conventional shade coffee sites, there was no significant difference in shade tree basal area between the two habitat types. Bird Friendly certification does not include specific requirements for lower strata vegetation, though the authors speculated that other Bird Friendly requirements such as the absence of inorganic substances may encourage it, providing habitat for small mammals (Caudill & Rice, 2016). This result adds on to existing research that eco-certifications can promote environmentally-friendly practices in certified farms beyond what is required (Rueda & Lambin, 2013), expanding the benefits to biodiversity.

Economic Impacts

While certifications have the potential to provide both environmental sustainability and economic benefits for farmers, they must meet certain circumstances to do so effectively. Price premiums alone are not always enough to result in a net benefit for farmers. For certifications to be viable, the price premiums must outweigh the costs of implementing the requirements and the cost of certification itself (Blackman & Naranjo, 2012).

Economic benefits are particularly well documented for Fair Trade certification. Fair Trade certification guarantees a minimum price to cover the average costs of sustainable production, as well as a price premium that is reinvested by farmers into community projects (Dragusanu & Nunn, 2018). Research strongly suggests that these mechanisms are effective in ensuring a higher price for coffee producers in South and Central America (Méndez et al., 2010; Bacon, 2005; Dragusanu & Nunn, 2018). Additionally, Fair Trade certified product sales have grown exponentially over the past twenty years (Dragusanu & Nunn, 2018), suggesting a larger market for farmers to potentially gain access to.

While economic benefits from Fair Trade are possible, they are not guaranteed. For example, Fair Trade's minimum fixed price is set for all of Central America, and the price may not be as beneficial for Costa Rican farmers as it is for farmers in other Central American countries. Because Costa Rica is a more developed country relative to others in the region, production costs are higher. The price guarantees may only enable Costa Rican farmers to cover production costs, whereas the guarantees offer farmers in other countries a price well above those costs (Kilian et al., 2004). Further, production costs to meet the certification's requirements can put coffee farming households in prolonged debt despite the price premiums (Wilson, 2010). Beuchelt & Zeller (2011) demonstrated that organic and organic-fair trade coffee farmers in Nicaragua that have been certified for ten years had a decrease in financial status in comparison to conventional coffee farmers. Finally, a study that compared conventional and organic coffee farms in Costa Rica found that the two groups had similar variable costs and net income when the costs of organic certification were excluded. Yields were lower on average for the organic farms, but the price premiums did make up for this loss in net income. When certification costs were included, however, price premiums would have to increase by 38% for net incomes of the two groups to be equal (Lyngbæk et al., 2001). An additional caveat that exists with all certifications is that the price premiums available for certified products exist in a much smaller market than the regular market, so oftentimes a percentage of certified products must be sold at regular market price because of an already full market for certified products (Bacon, 2010).

Various studies have estimated price premiums to account for 5-20% of farmers' income (Barham & Weber, 2012; Blackman & Naranjo, 2012). Barham & Weber (2012) determined that higher yields were more important than price premiums in increasing net cash returns for coffee farmers. Requirements against synthetic input use may partially explain yield losses. Allowing inorganic inputs may help avoid additional land clearing due to reduced yields (Barham & Weber, 2012).

Despite the deterrents described previously, coffee producers in Latin America do appear to have benefited from eco-certifications. Coffee farmers are less vulnerable to an industry crisis because of their access to price premiums and because they stand out amongst the competition (Kilian et al., 2004). Cooperatives can further alleviate the financial challenges created from competitive low prices of conventional coffee (Wollni & Zeller, 2007).

Ecosystem Services

In addition to direct economic benefits through price premiums and market access, farmers that incorporate wildlife-friendly practices can benefit from an increase in ecosystem services. By incorporating natural landscape elements on a farm, a farmer can benefit from increased pest control, pollination, seed dispersal, and soil quality (Karp et al., 2013; Martínez-Salinas et al., 2016; Şekercioğlu, 2012; Power, 2010). Birds are particularly well documented in terms of ecosystem service provisioning (Şekercioğlu 2012; Karp et al., 2013; Martínez-Salinas et al., 2016). For example, increased forest cover was associated with higher coffee yield in a Costa Rican coffee production system, primarily due to predation of the coffee borer beetle by birds and bats (Karp et al., 2013). Additional broad-scale benefits to humans include increased water quality, wildlife habitat, and carbon storage (Boody et al., 2005; Wade et al., 2010).

By increasing their conservation practices, landowners may be able to increase their land's economic value while also contributing to sustainability (Mendenhall et al., 2011). However, while incorporating more wildlife-friendly practices can benefit biodiversity, it is important to note that solely focusing on ecosystem services will not be sufficient for protecting species at risk (Karp et al., 2015; McCauley, 2006). Additionally, financial benefits gained from ecosystem services are

difficult to quantify and often underappreciated. Thus, cost assistance, particularly for start up costs, can help encourage adoption of conservation practices (Brodt et al., 2007). By aiming to further supplement the financial benefits of wildlife-friendly practices, eco-certifications also hold potential to encourage adoption.

Community Impacts

While the ecological and economic benefits are typically the focus of eco-certifications, direct and indirect impacts to local communities can provide additional benefits. Research from Costa Rica demonstrates positive results (Ronchi, 2002; Dragusanu & Nunn, 2018).

Group certifications, or cooperatives, makes certification more accessible and feasible for smallholders (Brandi et al, 2015), with lower audit costs but the same audit quality and compliance standards (Pinto et al, 2014). Additionally, the benefits of belonging to a larger organization can improve cooperatives' leadership and the impact on their producer members and the communities (Ronchi, 2002). Eco-certifications can also provide benefits to communities including higher incomes (even for those outside of the agricultural sector) and greater education of high school aged children, primarily due to scholarship programs (Dragusanu & Nunn, 2017; Rueda & Lambin, 2013).

However, eco-certification is not a panacea. The additional income is not enough to offset many other aspects of livelihood vulnerability that some farmers in Central America may experience (Bacon, 2005). Additionally, there is concern about standard setting procedures within large certifying bodies. The Rainforest Alliance has members from large companies it certifies on its board, offering high potential for those companies to dictate the standard setting procedures to benefit them (Bacon, 2010).

Distributional Impacts

Certifications have been criticized for being unattainable to smallholder farmers (Tayleur et al., 2018). Only 1.1% of cropland is certified globally (Tayleur et al., 2018), and while certified locations successfully cover regions of high biodiversity, they do not cover agricultural regions with the highest poverty levels (Tayleur et al., 2018). Without a more strategic approach to strengthening, consolidating, and expanding agricultural certification, benefits may not reach the producers that could benefit the most. Schemes could reduce social and economic obstacles to uptake in poorer regions by providing targeted training, support for producer cooperatives, and policies that simplify requirements and reduce certification fees for smallholders.

The failure to reach areas with high poverty levels may be explained by a greater focus on environmental rather than social criteria. In Talamanca, Costa Rica, cacao agroforestry systems are promoted for their conservation value and as a means to provide alternative and supplemental income to people in the Bribri and Cabécar indigenous territories (Dahlquist et al., 2007). Talamanca is the poorest canton in Costa Rica, with unemployment particularly concentrated in the indigenous territories. Despite conservation efforts and the sacred view of cacao, cacao agrosystems are being replaced with other systems such as plantations that have lower conservation value yet the potential for higher income. This demonstrates that conservation and communities' livelihoods are intertwined. To be effective, conservation efforts must more deeply consider household constraints and the socioeconomic and institutional factors driving land use change such as market availability, policy barriers, and income from other crops (Dahlquist et al., 2007). If managed and enforced responsibly, eco-certifications can valuably benefit local communities and the natural environment (Rueda & Lambin, 2013).

Case Study

The Effects of Fair Trade Certification: Evidence from Coffee Producers in Costa Rica

Dragusanu & Nunn (2018) examined the economic impacts of Fair Trade certification on coffee mills in Costa Rica from 1999 to 2014. They found that Fair Trade certification can benefit skilled coffee growers, reduce regional inequality, and protect producers from price fluctuations. However, these gains were a reflection of economic losses to intermediaries, and unskilled coffee growers did not benefit.

Fair Trade certification increased incomes of skilled coffee growers, who are primarily farm owners and make up about a third of the workers in the coffee sector. However, while farm owners benefited, about 10% of this effect was due to a transfer of wealth from intermediaries, who are responsible for coffee transportation, storage, and sales. The decrease in wealth share for intermediaries was a result of their role being replaced by cooperatives. Though there was a negative economic impact to intermediaries, intermediaries are typically wealthier than farm owners, so this reduced inequality in the regions that had Fair Trade certifications. Unskilled farm workers, who make up about 61% of workers in the coffee sector, did not benefit economically from Fair Trade certification. However, this study focused primarily on income, and did not examine effects related to working conditions or workers' rights, which are requirements included in the Fair Trade standard (Fairtrade International, 2019).

Another key takeaway from this study was that the Fair Trade minimum price protected producers from coffee price fluctuations, resulting in greater revenues for both producers and coffee mills when the minimum price was greater than the global price of coffee. This was especially the case for exported coffee. Further, since many certified cooperatives have their own certified mills, the producers have the potential to earn a portion of the mills' profits. However, only about 12% of Fair Trade certified coffee was sold at Fair Trade prices. Therefore, while there is a potential premium from Fair Trade, producers are rarely able to benefit from the full premium amount.

While Fair Trade certification does not necessarily benefit all workers in the coffee sector, it can provide net economic benefits to skilled coffee farmers. The price floor is also effective in mitigating risk when the world price is lower than the Fair Trade minimum price, which has made up a significant portion of the past three decades. Other certifications can model their requirements after Fair Trade to decrease financial risk to growers.

Communication of Results

Comparative Table of Requirements

After reviewing the impacts of each selected certification, it was evident that impacts vary greatly and will depend on the current state of the farm transitioning. For example, the net benefits may depend on a particular farm's size, location, crops, soil, or experienced weather patterns, as well as how many requirements the farmer already satisfies. Communication tools are needed that allow farmers to compare different certifications and decide if eco-certification will be beneficial to them. As the first step in providing this information, the following table was created to compare the requirements of the selected certifications.

	Pesticide Use	Fertilizer Use	Soil Management	Non-GMO	Organic Certification	Buffer Zones	Plant Diversity	Canopy Cover	Water Use	Energy Use	Climate Change Adaptation	Pesticide Use Safety	Fair Pay	Worker Rights & Conditions
			Environmental Requirements									Worker Requirements		
RA	✓	✓	✓	✓		✓	✓		✓	✓		✓	✓	✓
BF	✓	✓	✓	✓	✓	✓	✓	✓						
BA	✓	✓	✓						✓	✓	✓	✓		
O	✓	✓	✓	✓	✓									
FT	✓			✓								✓	✓	✓

Figure 7. Table comparing the requirements for five selected eco-certifications: Rainforest Alliance, Smithsonian Bird Friendly, Bandera Azul, USDA Organic, and Fair Trade. The certifications are shown along the left-hand side as rows and the requirement categories are shown along the top as columns. Checkmarks indicate if a certification includes any requirements related to the category.

The available standards for Rainforest Alliance (Rainforest Alliance, 2020a), Smithsonian Bird-Friendly (Smithsonian Migratory Bird Center Bird Friendly Coffee, n.d.), Bandera Azul (Programa Bandera Azul Ecológica, 2016), USDA Organic ("USDA Organic Production and Handling Standards", 2016), and Fair Trade (Fairtrade International, 2019) were reviewed and requirements with similar purposes were grouped into categories. The goal of the requirement categories was to capture the variety of requirements across all five selected certifications so that they could then be compared side-by-side. For example, USDA Organic and Rainforest Alliance both have lists of approved and prohibited pesticides, while Bandera Azul has a requirement to prioritize integrated pest management strategies over the use of chemical pesticides. These requirements were broadly grouped together into a category titled "Pesticide Use." We indicated in the table when the certification had any requirements related to the requirement category. This binary system (indicating that either requirements existed or did not exist) was used rather than a scale to communicate the information as clearly as possible.

The requirements fell within two categories: those related to the environment and those related to workers. Environmental requirements included those that were related to farming practices, such as plant diversity requirements and water management requirements, and worker requirements included those related to working conditions, such as the right to a fair wage. While certifications may have also mandated additional requirements such as those related to animal agriculture, business administration and management, and certification label use, these were not included to maintain our focus on environmental, economic, and community impacts and requirements for relevant crops in the region. Further, certifications and requirements related to deforestation were not included because deforestation is illegal in Costa Rica.

Eco-Certification Brochure

The next step is to incorporate the comparative table into a brochure (see Appendix D) that Osa Conservation will use to communicate the results with local farmers. This brochure will also incorporate other relevant information, including a brief description of each certification highlighting its unique impacts and next steps describing how farmers would move forward with getting certified.

Recommendations for Future Research

While many studies exist that describe the environmental, economic and community impacts of eco-certifications, the evidence varies substantially. Further, net impacts need to be assessed on a case-by-case basis. More information is needed to understand how to ensure environmental, community, and especially economic benefits. We have identified the following gaps in the literature that we recommend future research address:

- **How the farm- and regional-specific context influences the net impacts from eco-certification adoption**. For example, the farm's current environmental practices will relate to transition costs (Blackman & Naranjo, 2010), but other factors such as crop type, farm size, and regional climate may also play a large role. Greater understanding of these relationships will help us better understand transition costs and net economic benefits, which can help decrease risk for a farmer interested in adopting eco-certifications.
- **How to measure environmental, economic, and social benefits and costs**. Understanding the net impacts of eco-certifications requires comparing the environmental, economic, and social costs and benefits, and a method for direct comparison is not clear. Methods for consistently comparing impacts across categories and for communicating them would be useful. Further, a limitation of measuring environmental and community impacts from eco-certification adoption is that farms that already meet eco-certification requirements tend to select into certification (Dragusanu & Nunn, 2017; Blackman & Naranjo, 2010). If a farm is already meeting certification requirements, there are fewer barriers to becoming certified and gaining the additional benefits. While the economic benefits of certification reward the farmers' good management practices, there may not be positive environmental impacts as a result of the certification if the farm does not change its practices (Blackman & Naranjo, 2010).
- **Types of programs or policies that lower transition costs and maximize environmental and community benefits**. Conservation organizations and governments could help decrease financial risk and encourage adoption with programs or policies, for example by offering incentives or subsidies. Further, in the long run, government regulations may also spur innovation regarding agronomic efficiency of wildlife-friendly agriculture.
- **What requirements have the largest returns on investment**. Certifying organizations may be able to increase adoption and environmental, economic, and social benefits if they can determine which requirements offer the largest return on investment. This will require a deeper understanding of the tradeoffs between environmental and community benefits with economic costs, and how to balance these in a way that makes the requirements feasible for farmers.
- **Research on the impacts of eco-certifications for a greater variety of crops**. While our literature review was conducted for several regional crops (coffee, cacao, palm, banana, and pineapple), most of the research we found was related to coffee production. The focus on coffee may be because coffee quality increases with some conservation practices

(Hernandez-Aguilera et al., 2019) or because coffee makes up a large portion of the eco-certification market (for example, coffee accounts for 48% of fair trade certified farmers; Dragusanu & Nunn, 2017). As net impacts of eco-certification adoption is likely to be dependent on factors including crop type, future research on a wider variety of crops would be useful.

- **How to incorporate best practices for monitoring and evaluation in eco-certifications or incentive programs**. To maximize benefits, farmers should monitor and evaluate the impacts from adoption and revise their practices accordingly. Clear steps for adaptive management with adoption of eco-certifications would be helpful.

We recommend researchers design studies in a way that farmers and planners can isolate the impacts from the eco-certifications. Specifically, we recommend ensuring there is a valid counterfactual to compare the effects of certification (Blackman & Rivera, 2010; Blackman & Naranjo, 2010). Many studies measure impacts by comparing certified farms to non-certified farms, but a more accurate counterfactual may be an estimate of what outcomes would have been on certified farms had they not been certified. Research designed with this in mind could select farms to certify from a group of interested participants and conduct monitoring and evaluation to more accurately measure the impacts (Blackman & Rivera, 2010).

Conclusion

Eco-certifications have the potential to reduce the net financial costs of wildlife-friendly farming. While eco-certifications in many cases can provide environmental, economic, and social benefits, these impacts are very difficult to measure, are not guaranteed, and occur at different times.

Further, there are trade offs among environmental, economic, and social impacts. For example, certifications with more stringent environmental requirements, such as Smithsonian Bird Friendly, can have positive impacts on wildlife and create quality matrices in a fragmented landscape (Caudill & Rice, 2016). However, meeting these requirements can be difficult to attain and net economic benefits are not always guaranteed for farmers. Certifications that have a guaranteed minimum price, such as Fair Trade, can mitigate risk from price fluctuations faced by producers and provide better market access when prices are low (Dragusanu & Nunn, 2017), though there is limited research on the impacts of Fair Trade certification on environmental conditions since it is primarily intended to economically benefit farmers.

Trade-offs among environmental, economic, and social benefits make it challenging to improve biodiversity while also improving social and economic impacts to farmers. However, the impacts often depend on the context of the individual farm, and there is potential for scenarios that benefit both the environment and the community. Further research is needed to define practices and requirements that can maximize benefits to biodiversity while enhancing the local economy and community.

Chapter 3. Crop Suitability Under Climate Change

Abstract

Rising temperatures and changing precipitation patterns associated with climate change stand to strongly affect farming and food systems worldwide. As climate change intensifies, suitable ranges for the quality and survival of crops important to the Talamanca-Osa region in Costa Rica may shift and necessitate crop switches, farm expansion, or farm relocation. Here, we analyze future crop suitability for three crops in the Talamanca-Osa region: coffee, cacao, and pineapple. Biological data on crop presence and environmental data on bioclimatic factors provide the basis for predicting present and future suitable crop habitat in the Talamanca-Osa region. We conducted a suitability analysis for these crops using spatial data on 19 predicted environmental factors and Maxent species distribution modeling software. We found that under climate change, suitability for coffee may shift to higher elevations (mountainous regions) and suitability for cacao and pineapple may expand in lowland regions. Our results can benefit both farmers and conservation organizations; farmers can use our predictions to make informed long-term planning decisions, and organizations can use the projected shifts coupled with information on important areas for connectivity to identify potential conservation and restoration sites.

Introduction

Increasingly variable precipitation patterns and temperatures due to climate change could disrupt farming and food systems across the globe (Medina & Laliberte, 2017). The effects of climate change will differ by region, and Central America is predicted to see disproportionately high impacts on its ecological and agricultural systems. Suitable ranges and yields for most crops in the region are expected to decrease significantly (Hannah et al., 2013). Historical climate records show that temperatures in most of Central America have increased and precipitation has been highly variable over the past hundred years. These trends indicate a risk of decreased water availability and drier soils as warming temperatures increase evapotranspiration (Hidalgo et al. 2017). Regional-level models of future climate change impacts in Central America suggest that warming will continue across the region, and a warmer, drier climate is likely to be realized within a century (Hannah et al., 2013). Increased variability in temperature and precipitation are expected to shift the areas suitable for growing some of Central America's major crops (Hannah et al., 2013). Climate-driven shifts are also expected to affect wildlife (Kostyack et al., 2011). Direct impacts of climate change on wildlife include shifted or reduced suitable habitat, and indirect impacts include habitat loss from agricultural development expansion to accommodate a changing climate (Kostyack et al., 2011; Zebiak et al., 2015).

Shifts in crop suitability may necessitate farmland expansion or crop switching. Smallholder farms that rely on agriculture for their livelihoods and food security are particularly vulnerable (Hannah et al., 2013). Smallholder farmers make up 75% of the world's farms and provide 80% of the developing world's food (Donatti et al., 2018). As climate change progresses and crop suitability ranges shift, a major challenge will be meeting food requirements and sustaining livelihoods.

Crop response is highly variable based on location and species, so local-scale climate modeling is important for managing climate variability and risk for smallholder farms (Vermeulen et al., 2012). To support farmers and conservation organizations in long-term planning, we projected shifts in suitability ranges for three regionally significant crops: cacao, coffee, and pineapple.

Cacao

Cacao requires a tropical humid environment for its beans to produce chocolate and is predominantly produced by smallholder farms and (Lahive et al., 2018; CABI, 2001). The longer rainfalls, flooding, and droughts that are predicted due to climate change could have detrimental effects on cacao crops as rainfall is the main environmental driver of its yields (Lahive et al., 2018). Cacao is particularly vulnerable during tree growth, when a juvenile cacao plant is sensitive to the soil moisture content and stress (Lahive et al., 2018). The physiology of cacao limits its ability to adapt to water shortages because the shallow roots are unable to extract deep water. Extreme rainfall can also lead to excessive dampness in the soil, increasing the incidence of disease (Lahive et al., 2018). Climate change effects are predicted to globally reduce 13-17% of cacao crop suitability range by 2050, particularly in lowland regions (de Sousa et al., 2019).

Coffee

Coffee, specifically Arabica coffee, is the main commodity crop of Costa Rica, annually generating more than $200 million in export revenue (Blackman & Naranjo, 2012). Arabica coffee is a staple crop in the Talamanca-Osa region and is primarily grown by smallholder farms. Based on climate models predicting different climate scenarios for the years 2050 and 2080, Arabica coffee is at a high risk for extinction globally due to climate change and its high sensitivity to environmental factors (Davis et al., 2012). Arabica coffee's crop suitability range will continue to decrease as it shifts to higher elevation, forested areas (Ovalle-Rivera et al., 2015).

Coffee is a crop for which quality has a strong influence on profitability. The optimal average temperature range throughout the year for quality coffee is between 18 and 21°C, and quality can decrease when temperatures exceed 23°C. An increase or decrease beyond the favorable average temperature range will cause stress to the crop, leading to growth abnormalities and crop yield reduction (Davis et al., 2012). Because the global temperature has increased almost 1°C in the past 100 years, coffee farmers have already experienced severe damages to crop yields due to its limited growth tolerance range (Davis et al., 2012). Changes in environmental conditions threaten not only coffee growth but coffee quality, which is of economic importance in Costa Rica. The country is known to produce some of the highest quality Arabica coffee globally (Bamber et al. 2014).

Pineapple

Pineapple production is likely to be the most lucrative crop in Costa Rica (Shaver et al., 2015). Development of land for these plantations contributes to habitat loss and fragmentation which harmfully impacts biodiversity. Monoculture pineapple plantations present a significant movement barrier to many species. Additionally, poor working conditions can expose employees to harmful pesticides (Shaver et al., 2015).

Pineapple crops are mainly grown in resource intensive monoculture plantations using high quantities of pesticides (Echeverría-Sáenz et al., 2012). Pineapple is a non-traditional agricultural export (NTAE) in Costa Rica grown in lower elevations to produce less acidic fruit with an ideal temperature range between 18 and 35°C (Shaver et al., 2015; Morton, 1987). Temperatures outside of the specified range can impede maturation and crop yield and decrease quality. Additionally, excessive rainfall beyond the range of 650 to 3,800mm can lead to crop failure (Williams et al., 2017; Morton, 1987).

Methods

We projected shifts in crop suitability for cacao, coffee, and pineapple in the Talamanca-Osa region of Costa Rica for the years 2050 (average of years 2041-2060) and 2070 (average of years 2061-2080) under four different climate models and under two climate change scenarios.

Data

Spatial data on environmental factors that are important for cacao, coffee, and pineapple suitability, such as temperature and precipitation, were collected for present and future time periods in order to conduct a suitability analysis. Predicted future environmental data inform the projected impacts of climate change (Table 4).

Table 4. *Metadata Table. Biological data of crop presence and environmental data of bioclimatic factors provide the basis for identifying suitable growing areas in the Talamanca-Osa region.*

Source	Type	Parameters	Use	Citation
Global Biodiversity Information Facility (GBIF)	Tabular	Cacao Presence	Cacao species occurrence records	GBIF.org (13 January 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.vfccv3
GBIF	Tabular	Pineapple Presence	Pineapple species occurrence records	GBIF.org (18 January 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.yxhmjq
International Center for Tropical Agriculture - CIAT	Point	Coffee Presence	Coffee species occurrence records	Ovalle-Rivera, O., Läderach, P., Bunn, C., Obersteiner, M., & Schroth, G. (2015). Projected shifts in Coffea arabica suitability among major global producing regions due to climate change. PloS one, 10(4), e0124155.
Osa Conservation	Point	Cacao Presence	Cacao farm locations	Hilary Brumberg, Osa Conservation, personal communication, January 23, 2021
Osa Conservation	Point	Cacao Presence	Cacao farm locations	Rodrigo de Sousa, Osa Conservation, personal communication, January 14, 2021
Osa Conservation	Point	Coffee Presence	Coffee farm locations	Rodrigo de Sousa, Osa Conservation, personal communication, October 19, 2020
Osa Conservation	Point	Pineapple Presence	Pineapple farm locations	Rodrigo de Sousa, Osa Conservation, personal communication, January 14, 2021
WorldClim - Global Climate Data	Raster, 30 sec	Elevation and bioclimatic variables such as minimum and maximum temperature and monthly total precipitation	Current and future projected bioclimatic data used in MaxEnt to predict the relationship between environmental factors and coffee crop suitability.	CMIP5: Hijmans, R.J., S.E. Cameron, J.L. Parra, P.G. Jones and A. Jarvis, 2005. Very high resolution interpolated climate surfaces for global land areas. International Journal of Climatology 25: 1965-1978. CMIP6: Fick, S.E. and R.J. Hijmans, 2017. WorldClim 2: new 1km spatial resolution climate surfaces for global land areas. International Journal of Climatology 37 (12): 4302-4315.

Environmental Data Layers

Table 5 demonstrates the average current environmental conditions present at the cacao, coffee, and pineapple occurrence points used for our future suitability projections.

WorldClim - Global Climate Data:

The WorldClim data, containing 19 bioclimatic variables, was originally created from weather stations averaging climate data on a monthly basis on a 1 km^2 resolution grid (Hijmans et al., 2005). The WorldClim historical/near present and future climate data for 2050 (average of years 2041-2060) and 2070 (average of years 2061-2080), as well as a global elevation layer, were downloaded as .tif files from the WorldClim website's Global Climate and Weather dataset as gridded weather and climate data in the WGS 1984 coordinate system. Both datasets were downloaded at a 30 second spatial resolution for four global climate models (CNRM-CM5, MIROC-ESM-CHEM, MIROC5, MPI-ESM-LR) under two representative concentration pathways (RCP 4.5 and RCP 8.5). The four global climate models were chosen based on a similar report conducting climate projections in Costa Rica (AlMutairi et al., 2019). The two RCPs were chosen for the analysis because pathways RCP 4.5 and 8.5 represent middle-of-the-road and severe climate scenarios respectively (Hausfather, 2020). The parameters of the data include variables such as monthly average minimum and maximum temperatures (°C), monthly total precipitation (mm), monthly temperatures, precipitation of wettest and driest quarters, temperature annual range, maximum temperature of the warmest month, minimum temperature of the coldest month, and isothermality (Ovalle-Rivera et al., 2015). Processing included clipping rasters to Central and South America to narrow the scale closer to the study area and converting .tif files to ASCII format to be usable for the MaxEnt software. Clipped rasters were combined with crop presence data in MaxEnt to model current and future crop suitability ranges. Current and predicted environmental factors collected from the WorldClim website inform the projected impact of climate change on areas within the study region that can support crops.

Elevation Data:

While the influence of elevation is partially captured within the temperature and precipitation layers in the bioclimatic factors, elevation was still considered because of its impact on additional factors. For example, elevation influences solar radiation and oxygen availability, which can be important for crop growth and quality (Louzada Pereira et al., 2018; Martins et al., 2020). All of the environmental layers used are common in MaxEnt analyses (Bradie & Leung, 2017).

Table 5. *The average current environmental conditions present at the cacao, coffee, and pineapple occurrence points used for our future suitability projections.*

Variable	Environmental Layers	Unit	Mean for Cacao (*Theobroma cacao*)	Mean for Coffee (*Coffea arabica*)	Mean for Pineapple (*Ananas comosus*)
1	Annual Mean Temperature	℃	25.62	20.84	24.78
2	Mean Diurnal Temperature Range	℃	9.38	10.65	10.58
3	Isothermality	N/A	78.49	73.38	71.44
4	Temperature Seasonality	N/A	75.52	118.17	138.11
5	Max Temperature of Warmest Month	℃	31.60	27.96	32.31
6	Min Temperature of Coldest Month	℃	19.54	13.23	16.97
7	Temperature Annual Range	℃	12.06	14.73	15.33
8	Mean Temperature of Wettest Quarter	℃	25.74	21.46	25.30
9	Mean Temperature of Driest Quarter	℃	25.43	19.89	23.69
10	Mean Temperature of Warmest Quarter	℃	26.41	22.10	26.26
11	Mean Temperature of Coldest Quarter	℃	24.60	19.24	22.94
12	Annual Precipitation	mm	2,562.93	1,846.74	2,006.27
13	Precipitation of Wettest Month	mm	339.95	319.15	295.94
14	Precipitation of Driest Month	mm	93.74	29.55	57.72
15	Precipitation Seasonality	N/A	43.20	70.21	52.44
16	Precipitation of Wettest Quarter	mm	940.34	828.55	815.26
17	Precipitation of Driest Quarter	mm	325.51	113.03	208.94
18	Precipitation of Warmest Quarter	mm	579.31	510.91	432.96
19	Precipitation of Coldest Quarter	mm	598.09	232.12	466.73
N/A	Elevation	m	203.00	1,066.00	271.00

Biological Data Layers

Observation datasets were used as the species presence input in MaxEnt. Maxent models species suitability based on the relationship between these presence points and the environmental layer inputs. This baseline suitability model is then projected to future scenarios for each global climate model and relative concentration pathway used in this analysis.

Presence Points Quality Control:

Following the methodology of Ovalle-Rivera et al. (2015), observation points available on the Global Biodiversity Information Facility (GBIF) were filtered to exclude any data from elevations outside the suitable production ranges provided by literature review of each crop. This was done to ensure results were accounting for quality crops only.

Based on computational limitations, we narrowed down the global set of available crop presence points to Central and South America based upon similar growing conditions and crop production (Magrin et al., 2014). Suitability was first modeled for all of Central and South America and then clipped to the actual study area because modeling suitability for only our study area may be too small for accurate future suitability results based upon the limitations of WorldClim bioclimatic accounting for smaller global regions (Peterson & Nakazawa, 2008).

The presence-only observations used in our MaxEnt analysis were used based on the assumption that presence points are random and/or representative samples. To help ensure the quality of the observations used in this analysis, we followed the methodology of a similar suitability projection study for Arabica coffee by Ovalle-Rivera et al. (2015). We followed similar steps to the study by filtering the presence points by elevation obtained from GBIF for cacao and pineapple. This was done to only include samples within suitable elevation ranges indicated in the literature for each species. The average values of all remaining points were calculated for each bioclimatic factor and compared to known ranges present in the literature for each crop to ensure that results were reasonable (Table 5).

Crop Presence Points:

Cacao: Cacao crop observation points were downloaded from the Global Biodiversity Information Facility (GBIF) dataset and combined with cacao farm ground truth data collected by the Osa Conservation. The initial 879 GBIF observation points were first restricted to Central and South America and then filtered to only include points between 0 - 600 m above sea level which is considered the suitable elevation range for growing cacao (Sitohang & Siahaan, 2018). These remaining 737 points were combined with the presence points provided by Osa Conservation and used as the presence layer in MaxEnt.

Coffee: The first set of coffee presence points were downloaded from the study conducted by Ovalle-Rivera et al. (2015). For their study, they collected 62,000 coffee growing presence points for Arabica coffee from the International Center for Tropical Agriculture (CIAT). Points were collected from the 20 top coffee growing countries and supplementary locations based on the researchers' literature review. The presence points were then filtered to meet thresholds for elevation, temperature, and annual precipitation, and resolution. This left the dataset with 17,625 observation points that met coffee suitability thresholds derived from literature review (Ovalle-Rivera et al., 2015). Observation points from the study were downloaded and clipped to Central and South America and then combined with coffee farm ground truth data collected by Osa Conservation to make 2,212 total presence points used in the analysis.

<u>Pineapple</u>: Pineapple crop presence points were downloaded from the GBIF dataset. The 12,330 total pineapple presence points available were first restricted to Central and South America. Presence points were then filtered for elevations between 0 - 900 m above sea level based upon the considered suitable elevation range in our study area and the tendency for fruits to become acidic above that range (Dorey et al., 2018; Rodrigo de Sousa, personal communication, January 27, 2021; Morton, 1987). The remaining 633 observation points were used in the analysis along with pineapple farm ground truth points collected by Osa Conservation.

Approach

We first collected spatial distributional data for cacao, coffee, and pineapple crops. We then modeled present suitability and projected future suitability under four different climate models and two different climate scenarios (Figure 8). Analyses were conducted using the MaxEnt software, which is used for modeling species distributions from presence-only species data. Maxent predicts suitability based on the modeled relationship between species presence in an area and the environmental characteristics in that location.

For each crop analysis, projections of suitable habitat ranges were based on the present environmental layers (historical climate data from 1970-2000 categorized as "current") and projected suitability for the years 2050 (average of 2041-2060) and 2070 (average of 2061-2080) by using the 19 bioclimatic variables provided by WorldClim. In line with common methodology, we used all 19 bioclimatic variables in our analysis (Varela et al., 2015). The 19 bioclimatic factors listed on WorldClim were originally selected from a set of 35 bioclimatic variables from the BIOCLIM software to decrease correlation between variables (Porfirio et al., 2014). CMIP Phase 6 (CMIP6) was used for current environmental conditions and CMIP Phase 5 (CMIP5) was used for future climate change projections because 30-second resolution is not yet available for future CMIP6. To account for differences in the variety of global climate models (GCMs), we used four separate GCMs and averaged the results. The four GCMs, CNRM-CM5, MIROC-ESM-CHEM, MIROC5, MPI-ESM-LR, were chosen based on the methodology of a similar study in Costa Rica and availability in the WorldClim database (AlMutairi et al., 2019). Projections were made under two of the Intergovernmental Panel on Climate Change (IPCC) representative concentration pathways (RCPs), RCP 4.5 and 8.5, to account for uncertainty and the impacts of different climate change scenarios on the crop suitability distributions. The RCP 4.5 scenario represents a future in which warming is limited to 3°C by 2100 and is considered a fairly middle-of-the road projection (Hausfather, 2020). The RCP 8.5 scenario differs in that it is considered a high baseline scenario and is often regarded as a potential worst-case scenario (Hausfather, 2020).

For each MaxEnt analysis, we kept most of our parameters to default settings to set up a replicable methodology. This was based on the difficulties of fine-tuning parameters to individual species (Phillips & Dudík, 2008). Only four "Basic" parameters were changed:

- "Random test percentage" was changed to 20, which means 20% of our presence points will be held back to validate our model's accuracy to replicate the methodology of a similar study done by Ovalle-Rivera et al. (2015).
- "Random seed" was selected so different samples were chosen each time in the model sampling (Beane et al., 2013).
- "Bootstrap" was selected for the replicate run type to have our presence points sampled with replacement (Beane et al., 2013).
- To further validate the models, the amount of "Replicates" of a model run was changed to 10 to use the averaged final result at the end of a model run.
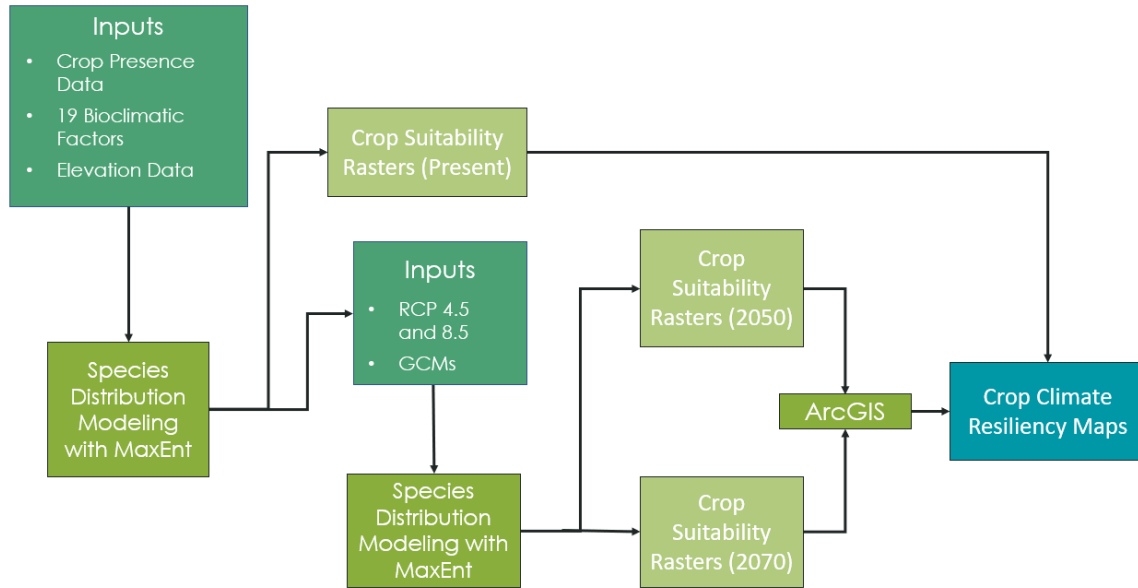
Figure 8. Methodology Logic Model. *This visual of the workflow depicts data inputs (dark green), to be modeled through MaxEnt and ArcGIS (green), outputs from developed analyses (light green) which will be further analyzed to produce final data outcomes (teal).*

After running the four selected GCMs under the two different RCP scenarios (4.5 and 8.5) for the three chosen crops, the results were clipped down to the Talamanca-Osa region. Binary maps were then created using ESRI ArcGIS to highlight suitable vs. non suitable locations for growing each of the crops. These binary maps were used to compare changes in suitability from the current time period to future time periods in order to most effectively communicate the functional impacts of climate change on suitability. We set the suitability thresholds for each crop by using the average 10th percentile training presence threshold produced from each Maxent model run. The 10th percentile training presence omits 10 percent of areas anticipated to hold the least values of suitability, which helps to account for outliers (Radosavljevic & Anderson, 2014; Donegan & Avendaño, 2010). This methodology for threshold selection was based on a similar study done by Khanum et al. (2013) and Brito et al. (2009) using presence only data. We then averaged the four GCM threshold values for each RCP and projection year (See Appendix H Tables H1-H6).

The binary suitability maps were then combined for each crop to illustrate the results of the three different time-period suitabilities for each climate scenario. A crop overlap analysis was also done by combining binary crop suitability rasters for each time period to identify where suitable ranges for the three crops intersect with each other over the three time periods and climate scenarios.

The final products are crop-specific binary suitability maps comparing current and projected habitat suitability for current conditions and 2050 and 2070 time periods under two different climate change scenarios. Crop overlap maps were also created to highlight how crop ranges intersect and change over the projected time periods. Maps were all created in ESRI ArcMap.

Results

Cacao

Results of the current and future cacao suitability analysis suggest that cacao suitability will expand in the lowland regions of our study area under the RCP 4.5 scenario with a gain of 13,178.18 hectares by 2070 (Figure 9; Table 12). However, according to the RCP 8.5 scenario projection, cacao suitability will decrease by 8,471.69 hectares by the year 2070.
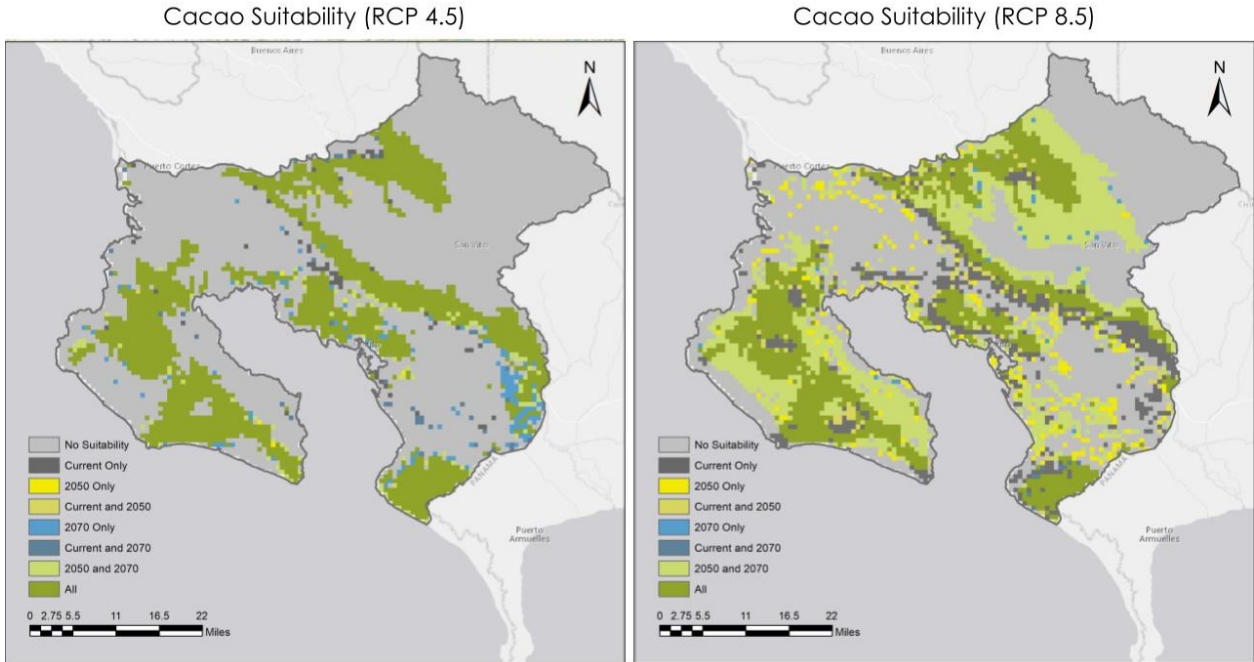
Figure 9. *Cacao suitability maps displaying spatial shifts and expansion in the Talamanca-Osa region for future decades under two different climate scenarios.*

There is a stark contrast in cacao suitability in net area change between the two RCP scenarios. Results showed a net gain of suitable hectares for cacao production for both time periods under RCP 4.5, with the largest gain of 13,178 ha in the 2070 time period (Table 12). However, a loss in suitable hectares was shown for both time periods under RCP 8.5 where climate change impacts are more severe.

Table 12. *Total suitable area for cacao (in hectares) lost or gained between current and future time periods under each RCP in the Talamanca-Osa region.*

Time Period	RCP	Suitable Area Loss (ha)	Suitable Area Gain (ha)	Total Net Change (ha)
Current to 2050	4.5	8,300.54 (1.55%)	8,728.40 (1.63%)	+427.86 (0.08%)
Current to 2070	4.5	5,219.93 (0.98%)	18,398.11 (3.44%)	+13,178.18 (2.47%)
Current to 2050	8.5	9,070.69 (1.69%)	5,733.36 (1.07%)	-3,337.33 (0.63%)
Current to 2070	8.5	11,124.44 (2.083%)	2,652.75 (0.50%)	-8,471.69 (1.59%)

Coffee

Results of the current and future coffee suitability analysis suggest that coffee suitability will increase overall due to expansion into higher elevations in the Talamanca Mountains, located in the northeastern portion of the study area (Figure 10).
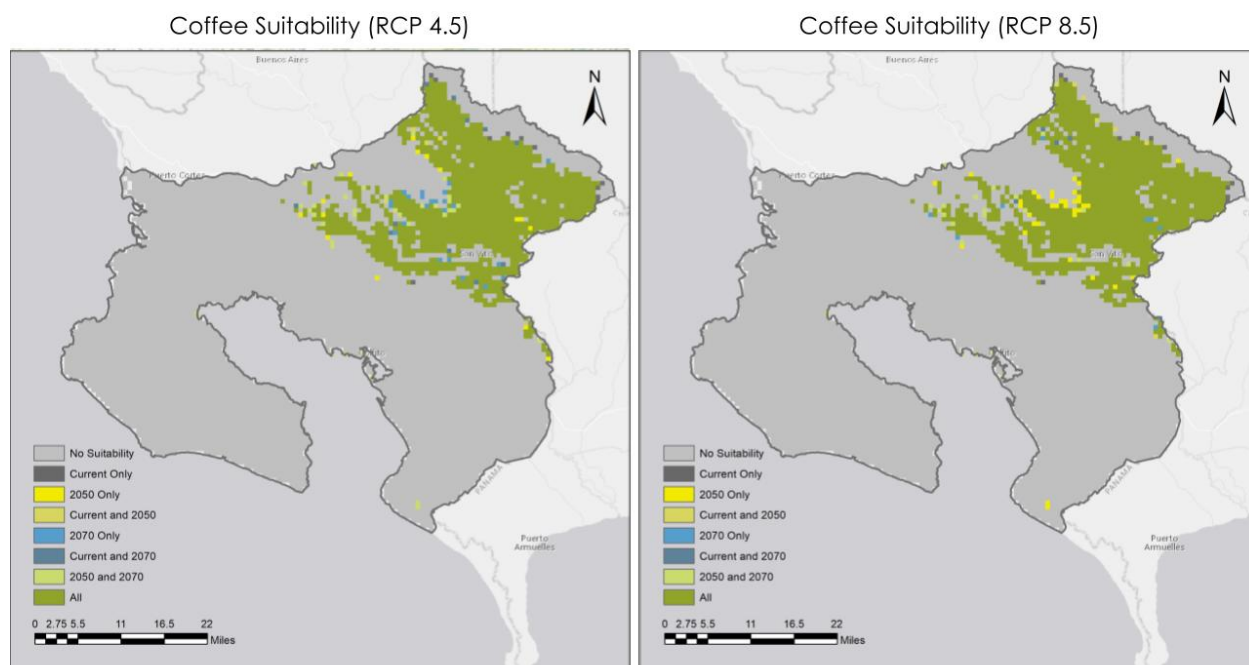
Figure 10. *Coffee suitability maps displaying spatial shifts and expansion in the Talamanca-Osa region for future decades under two different climate scenarios.*

The RCP 4.5 scenario showed a larger increase in suitable area for coffee production, with 3,251.76 hectares gained in higher elevations, in contrast to the 684.58 hectares gained under the RCP 8.5 scenario (Table 13). All scenarios saw a net gain in suitable coffee growing areas. The largest area gain was between the current and 2070 time periods under the RCP 8.5 scenario, where climate change is the most extreme of the scenarios analyzed, while the smallest gain was seen between the current and 2050 time periods under the RCP 4.5 climate scenario (Table 13).

Table 13. *Total suitable area for coffee (in hectares) lost or gained between current and future time periods under each RCP in the Talamanca-Osa region.*

Time Period	RCP	Suitable Area Loss (ha)	Suitable Area Gain (ha)	Total Net Change (ha)
Current to 2050	4.5	1882.60 (0.35%)	3850.77 (0.72%)	+1968.17 (0.37%)
Current to 2070	4.5	1283.59 (0.24%)	4535.35 (0.85%)	+3251.76 (0.61%)
Current to 2050	8.5	1882.60 (0.35%)	5391.07 (1.01%)	+3508.48 (0.66%)
Current to 2070	8.5	1540.31 (0.29%)	2224.89 (0.42%)	+684.58 (0.13%)

Pineapple

Results of the current and future pineapple suitability analysis imply that pineapple suitability will increase overall, especially in lowland regions (Figure 11). The current to 2070 time period under the RCP 4.5 scenario saw the largest net increase with 58,702.79 additional hectares of suitable pineapple growing area (Table 14). The areas that most contributed to the increase are the region east of Piedras Blancas National Park, the area around the Terraba Sierpe National Wetlands, and the expansion further up into the mountains on the Osa Peninsula.
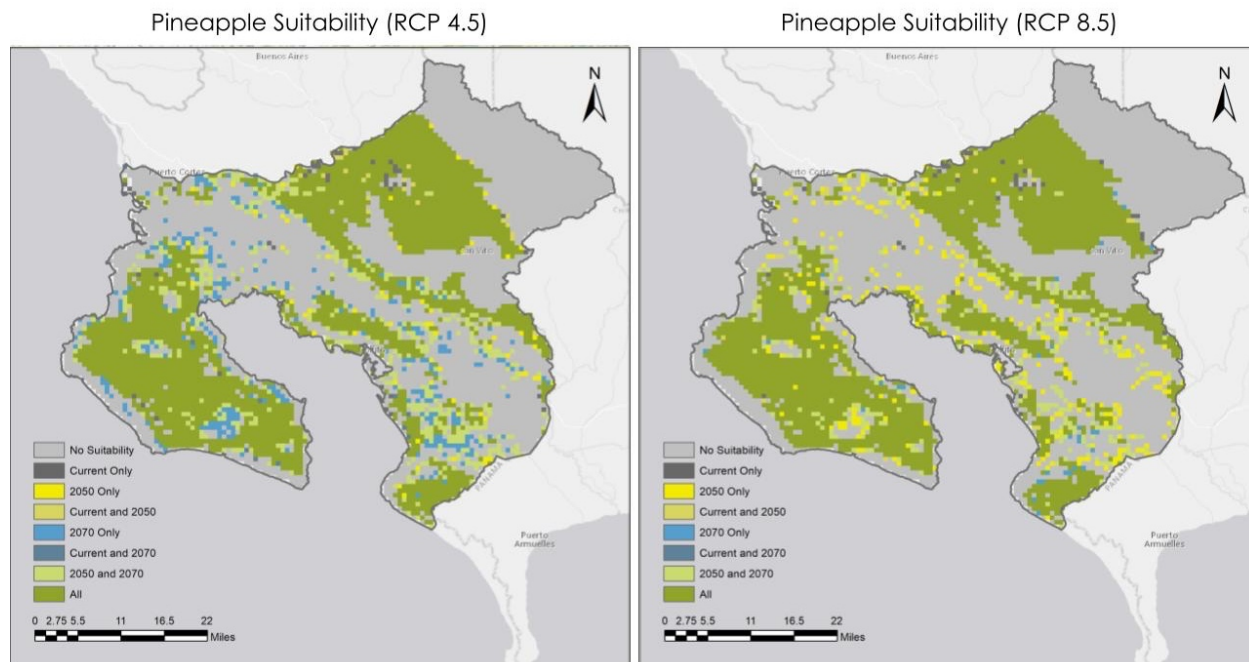
Figure 11. Pineapple suitability maps displaying spatial shifts and expansion in the Talamanca-Osa region for future decades under two different climate scenarios.

All scenarios saw a large net gain in suitable pineapple growing areas. The net change from current to 2050 time periods were similar under both climate scenarios, with the RCP 8.5 scenario seeing just over 3,000 ha greater area gain than the RCP 4.5 scenario. The greatest net gain in suitability was between the current and 2070 time periods under the RCP 4.5 scenario. While the current to 2070 time period under the RCP 8.5 scenario, where climate change is the most extreme of the scenarios analyzed, saw a net gain in suitable pineapple growing area, it was the smallest gain at an increase of 20,965 ha (Table 14).

Table 14. Total suitable area for pineapple (hectares) lost or gained between current and future time periods under each RCP in the Talamanca-Osa region.

Time Period	RCP	Suitable Area Loss (ha)	Suitable Area Gain (ha)	Total Net Change (ha)
Current to 2050	4.5	4,620.92 (0.87%)	46,465.91 (8.70%)	+41,844.99 (7.83%)
Current to 2070	4.5	6,417.94 (1.20%)	65,120.73 (12.19%)	+58,702.79 (10.99%)
Current to 2050	8.5	3,251.76 (0.61%)	47,492.79 (8.89%)	+44,241.03 (8.28%)
Current to 2070	8.5	6,332,37 (1.19%)	27,297.65 (5.11%)	+20,965.28 (3.93%)

Crop Overlap Analysis

Crop suitability overlaps were mapped to identify where and when crop ranges intersect and how future climate conditions impact and shift these intersections (Figure 12).
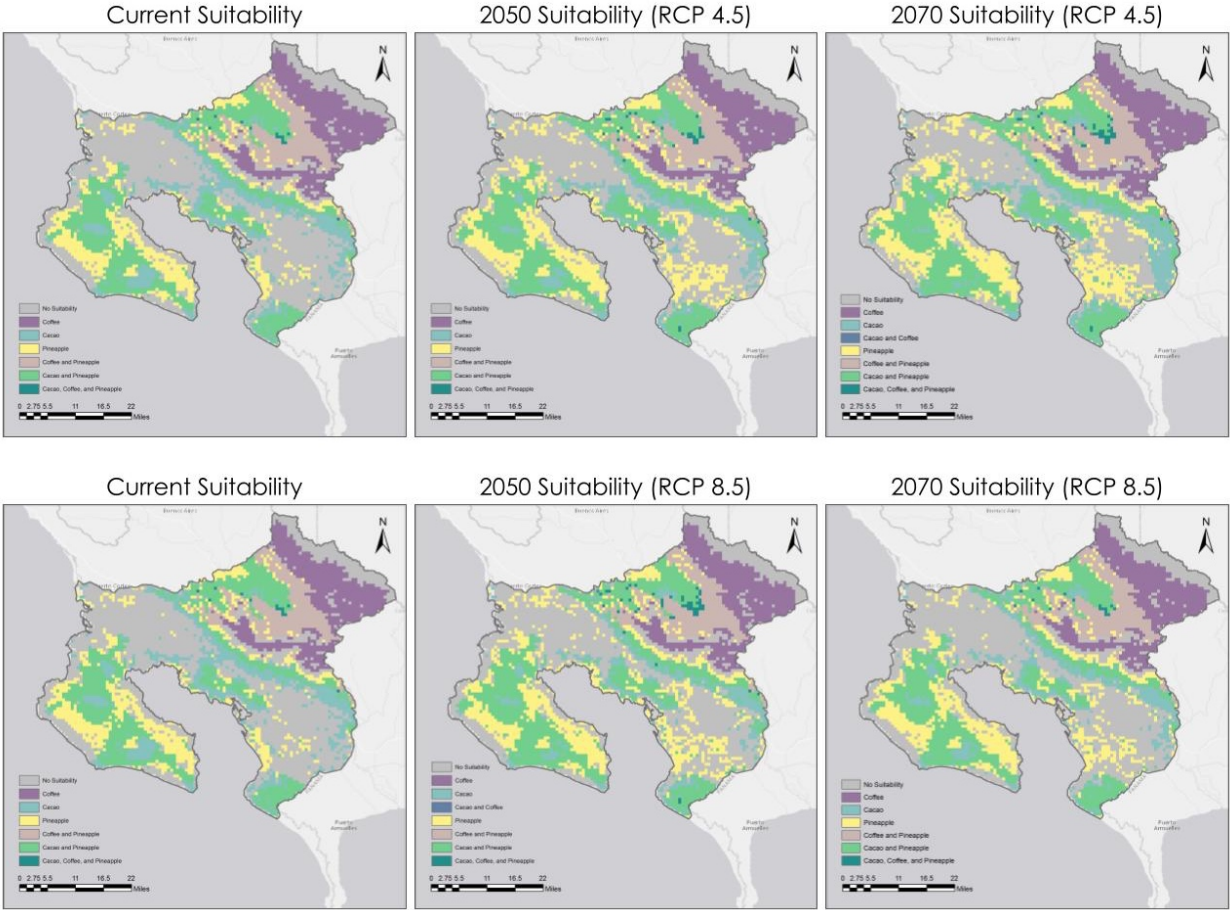
Figure 12. Crop suitability ranges in the Talamanca-Osa region for cacao, coffee, and pineapple were combined to highlight where suitability would overlap between crops and time periods for RCP scenarios 4.5 and 8.5.

Under the RCP 4.5 climate change scenario, the proportion of the total area that supports any of the three crops or combination of crops increased (Figure 13). Total suitable area for only pineapple and the overlap between pineapple and cacao increased the most, while the total area suitable for only cacao decreased from the current to 2070 time periods. The total area suitable for only coffee and for coffee and pineapple remained fairly stable each time period. The area where suitability for all crops overlap and the area where suitability for coffee and cacao overlap were both low overall, but saw slight increases over the time periods under the RCP 4.5 climate scenario.

Under the RCP 8.5 scenario, the proportion of area suitable for any crop increased (Figure 13). The total hectares suitable for pineapple production and the area in which pineapple and cacao overlap increased during the 2050 time period but then decreased in the 2070 time period to slightly above the current level. Suitable hectares for cacao decreased overall, first steeply during

the 2050 time period, and then increasing slightly in the 2070 time period, but not returning to the level of the current time period.

The smallest overlap in crop ranges over all time periods was between coffee and cacao. These two crops only overlapped for 256.72 hectares (0.05% of the study area) in 2070 under RCP 4.5 and for 85.57 hectares (0.02% of the study area) in 2050 under RCP 8.5. The remaining scenarios had no overlap between coffee and cacao (see Appendix H for Tables H9 to H13).
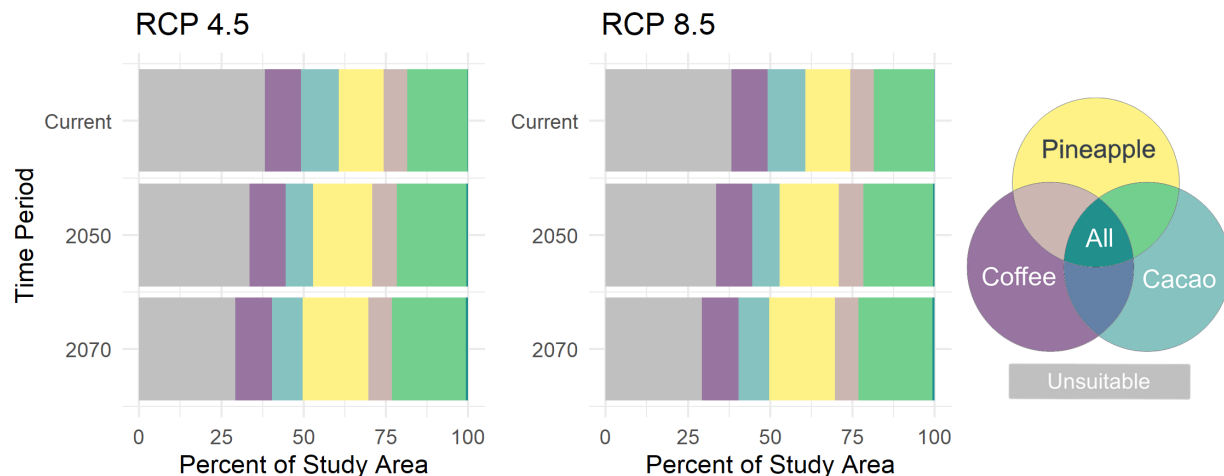
Figure 13. *Proportion of study area suitable for each crop and crop combination for current, 2050, and 2070 time periods under RCP 4.5 and 8.5 scenarios in the Talamanca-Osa region.*

Discussion

Based on our suitability results, pineapple and cacao suitability ranges will overlap the most in our study area (Figure 12). As suitability expands for both pineapple and cacao, pineapple may be more economically appealing for farmers to switch as pineapple is likely to be the most lucrative crop available (Shaver et al., 2015). However, growing pineapple is associated with adverse social and environmental impacts (Shaver et al., 2015). Pineapple is mainly grown in large monoculture plantations and tends to be associated with poor working conditions, including exhausting physical labor demands, exposure to unhealthy levels of pesticides, low income, and lack of work security (Shaver et al., 2015). Creating a large pineapple plantation is an expensive endeavor and has high barriers to entry. These barriers are particularly challenging for smallholders; large pineapple plantations are preferred in the pineapple market sector (Piñero and Díaz Ríos, 2007).

In addition to the negative social impacts, pineapple production is also harmful to the environment. Compared to perennial crops, such as coffee and cacao, pineapple plantations have little to no tree cover, providing poor substitutes for wildlife habitat and strongly impeding connectivity between forest fragments (Shaver et al., 2015; Batello et al., 2014).

Unlike for pineapple production, agroforestry in cacao and coffee can bridge the gap between conservation and the monetary demands for smallholder farmers (Parrish et al., 2003). The majority of cacao crops in Costa Rica are grown by smallholder farms where they can sustain wildlife connectivity and biodiversity through shaded agroforestry practices (Wood and Lass, 1985; Young, 1996). Agroforestry practices include growing crops in the understory of native trees, which imitate the characteristics of a forest and harbor higher levels of biodiversity (Parrish

et al., 2003; Young, 1996; Vandermeer and Perfecto, 1995). Importantly, the potential to benefit species is greater when the farm is closer to forest fragments (Parrish et al., 2003).

By implementing agroforestry practices for cacao and coffee production, farmers can financially benefit from increased bird abundance through ecotourism (Parrish et al., 2003). Ecotourism is one of Costa Rica's leading industries in profitability and can allow for a linkage between conservation and employment in local communities (Parrish et al., 2003; Koens et al., 2009). Shade trees can also provide ecosystem services such as improved soil management, pollination, seed dispersal, and natural pest control (Young, 1997; Wood and Lass, 1985; Şekercioğlu et al., 2019). Shade trees can also benefit farmers economically if they can be used for timber or for production of other crops (Rice and Greenberg, 2000; Parrish et al., 2003).

While agroforestry can hold high levels of biodiversity, it is not recommended to deforest primary or secondary forested areas where suitability for agroforestry crops exist. Forested areas (two or more hectares with multiple species) are protected from deforestation through Costa Rica's 1996 Forest Law 7575 and cannot be considered for areas of crop suitability (see Appendix G for Figures G14 and G15; Rodrick, 2010; Forestry Law, 1999).

There are some limitations to our analysis. We used current and future datasets from the WorldClim database with the assumption of an accurate representation of the 19 bioclimatic variables available in our study region. However, there are limitations to the datasets in that they have not been thoroughly tested in accuracy for smaller global areas (Peterson & Nakazawa, 2008). We used four different global climate models (GCMs) out of the 19 available from the WorldClim database based on the assumption that they provide accurate future climate change simulations, an assumption supported by the Intergovernmental Panel on Climate Change (IPCC). Nonetheless, most GCMs cannot sufficiently integrate all biological and chemical systems needed holistically to determine accurate climate predictions (Lupo et al., 2013). To limit bias and account for this inherent variability and uncertainty in global climate models, we selected four GMCs based on a similar study done by AlMutairi et al. (2019) in northern Costa Rica and averaged the results.

Conclusion

Climate change will increasingly alter temperature and precipitation patterns around the world and these changes will have meaningful consequences for suitable habitat ranges for many species. The shifting climate can result in habitat loss for many wildlife species, both due to shrinking suitable areas for local species and due to encroachment of farmland as crop distributions shift. If crop transitions are necessary, farmers should consider agroforestry practices if possible. For example, cacao will be suitable for all climate change scenarios where there is a cluster of existing pineapple farms (see Appendix H for Figures H16-18). Additionally, cacao and coffee suitability will overlap grassland and pasture for all climate change scenarios creating the opportunity for grassland and pasture owners to implement cacao and/or coffee agroforestry for supplementary benefits such as added income and providing protection from the elements for livestock (Jose & Dollinger, 2019).

Changes in crop suitability can be especially disruptive to small farms since they often have fewer resources with which to adapt to the changing climate (Morton, 2007). Long-term planning is necessary to reduce vulnerability to climate change and maintain local livelihoods.

Concluding Remarks

Costa Rica's extraordinary biodiversity is threatened by habitat loss and fragmentation due to agricultural expansion and impending climate change. We studied three aspects of this issue to help inform sustainable farming in the Talamanca-Osa region: 1) land uses that pose the largest barriers to connectivity, 2) the environmental and socio-economic impacts from eco-certifications, and 3) shifts in crop suitability under climate change.

Compared to conventional practices, wildlife-friendly agriculture can decrease resistance to wildlife movement (Kostyack et al., 2011). For long-term preservation of species abundance and diversity in the region, wildlife must be able to move between protected areas and across farmland (Estrada-Carmona et al., 2019). We analyzed the key barriers to movement of jaguars, an economically- and ecologically-important species in the region. These barriers included widespread pasture and major roads, two primary drivers of forest fragmentation. We also suggested next steps towards enhancing jaguar connectivity in the Talamanca-Osa Region, including a holistic plan that includes pasture reforestation, underpasses beneath major roads, and wildlife-friendly farming. Governmental and conservation organizations can use our findings to inform jaguar connectivity efforts and help sustain the species in southern Costa Rica.

Another way to improve connectivity and on-farm biodiversity is through wildlife-friendly farming. Wildlife-friendly agricultural practices must be economically feasible for farmers to increase adoption at scale. In theory, eco-certifications can make conservation practices more economically feasible through price premiums and increased market access. We reviewed scientific literature related to the ecological, economic, and social impacts of regionally available eco-certifications. We found that eco-certifications broadly can provide environmental, economic, and social benefits (Kostyack et al., 2011; Loconto & Dankers 2014; Potts et al. 2014; Tscharntke et al., 2015), but that there are also often substantial trade-offs between biodiversity and community impacts and economic impacts to the farmers. Further, net economic benefits are not guaranteed, and there is no clear way to ensure beneficial results. While the impacts from eco-certifications are uncertain and difficult to measure, the growers and organizations are more often than not working to better their impact on the environment and community.

In long-term planning, regional farmers and governmental and conservation organizations also need to anticipate impacts from climate change. Climate change will increasingly alter temperature and precipitation patterns globally, and these impacts will have meaningful consequences for crop suitability. We studied cacao, coffee, and pineapple, and found that climate change will influence their regional suitability. These shifts have the potential to be economically disruptive to regional farmers; to mitigate these effects, they will need to consider climate change impacts in their planning. When crop switches are necessary, we recommend, when feasible, shifting to crops that allow agroforestry practices for environmental and climate resilience benefits.

Strategic long-term planning for sustainable farming in southern Costa Rica requires information on how to support wildlife with on-farm practices, how to incorporate wildlife-friendly farming practices in an economically feasible way, and how crops will be influenced by climate change. Our analysis will provide farmers and organizations with the information needed to promote sustainable farming in the region, benefitting both farmers and wildlife.

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Appendices

Appendix A. Jaguar Connectivity Resistance Raster Values

The resistance raster used for our analysis was created by NASA DEVELOP using inputs including LULC, elevation, slope, and distance to roads, human settlements, and rivers. Resistance values were assigned to each layer on a scale of zero to ten, with ten as the highest energetic cost to a jaguar to move through that specific cell. Each raster was assigned a weight of influence within the model and to create an overall resistance surface.

Table A1. Weights of influence assigned to each raster layer used in the raster calculator for production of the resistance raster.

Layer	Weight (%)
Slope	5
Elevation	5
Distance to Rivers	10
Cities	20
Roads	20
Land Use Land Cover	40

Table A2. Resistance values assigned for land cover type used for resistance raster input.

Land Cover Type	Resistance Value
Primary Forest	0
Secondary Forest	1
Wetland	3
Coffee	4
Grassland/Pasture	5
Mangrove	5
Palm Plantation	6
Water	9
Exposed Soil/Urban	10
Páramos	10
Pineapple	10

Table A3. Resistance values assigned for elevation used for resistance raster input.

Elevation (m)	Resistance Value
0-500	0
500-1000	0
1000-2000	2
2000-3000	6
>3000	10

Table A4. *Resistance values assigned for slope used for resistance raster input.*

Slope (°)	Resistance Value
0-15	0
15-30	2
30-45	5
45-60	7
>60	10

Table A5. *Resistance values assigned for distance to river used for resistance raster input.*

Distance to River (km)	Resistance Value
0-0.5	0
0.5-1	1
1-2	2
2-4	3
4-8	4
8-16	5
16-32	5

Table A6. *Resistance values assigned for bivariate key values (based on settlements and roads) used for resistance raster input.*

Bivariate Key Values (based on settlements and roads)	Resistance Value
0	0
1	2
2	4
3	6
4	8
5	10
6	10

Appendix B. Jaguar Connectivity Supplementary Methods

Appendix C. Jaguar Connectivity Pinchpoint Maps
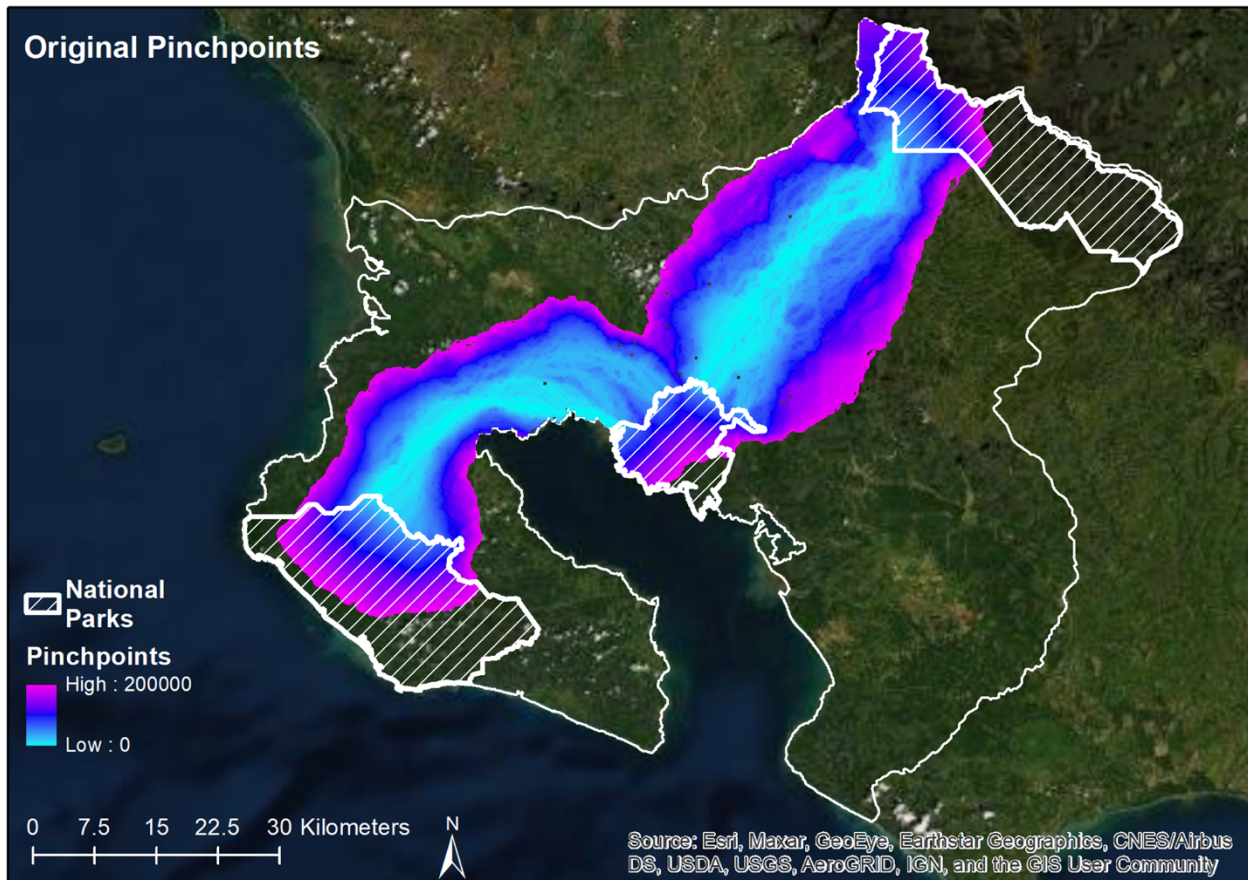
Figure C1. *Pinchpoint map without any modifications to resistance values (baseline), truncated to 200K. National parks include La Amistad International Peace Park (northeast), Corcovado National Park (southwest), and Piedras Blancas National Park (central). La Amistad has been clipped to the study area.*
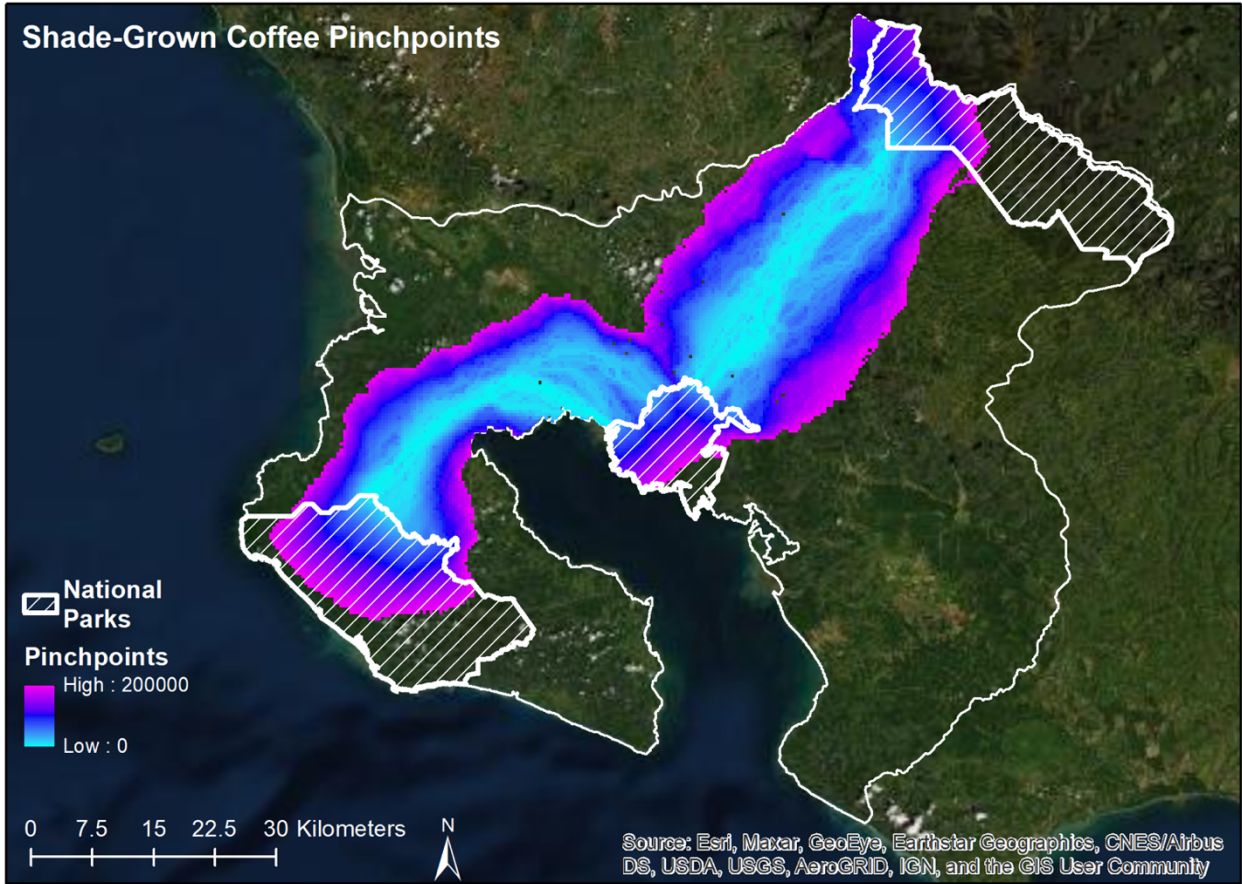
Figure C2. *Pinchpoint map for shade-grown coffee high impact scenario, truncated to 200K. National parks include La Amistad International Peace Park (northeast), Corcovado National Park (southwest), and Piedras Blancas National Park (central). La Amistad has been clipped to the study area.*
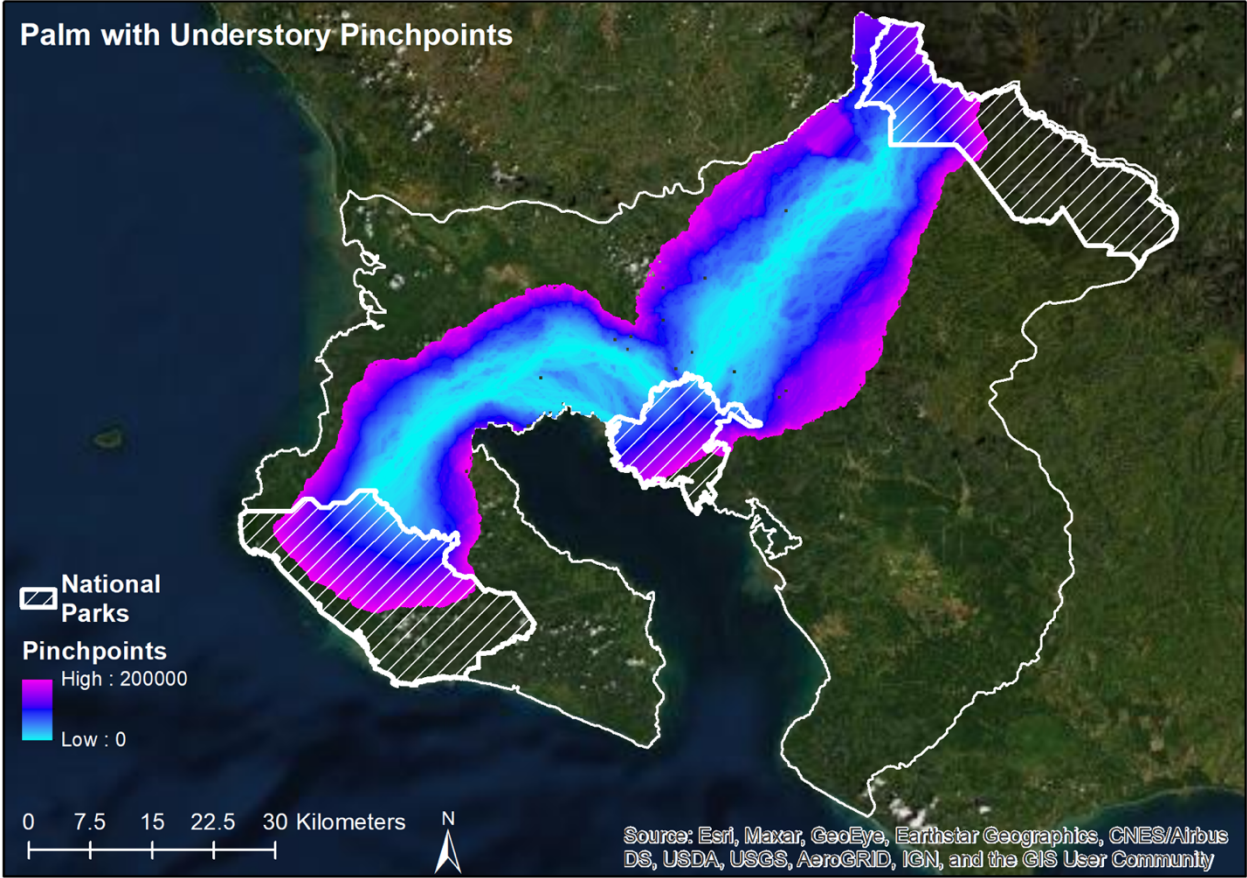
Figure C3. *Pinchpoint map for palm with understory high impact scenario, truncated to 200K. National parks include La Amistad International Peace Park (northeast), Corcovado National Park (southwest), and Piedras Blancas National Park (central). La Amistad has been clipped to the study area.*

Appendix D. Eco-Certification Brochure

The eco-certifications brochure is on the following two pages.

REQUIREMENTS

	RA	BF	BA	O	FT
Environmental Requirements					
Pesticide Use	✓	✓	✓	✓	✓
Fertilizer Use	✓	✓	✓	✓	
Soil Management	✓	✓	✓	✓	
Non-GMO	✓	✓		✓	✓
Organic Certification		✓		✓	
Buffer Zones	✓	✓			
Plant Diversity	✓	✓			
Canopy Cover		✓			
Water Use	✓		✓		
Energy Use	✓		✓		
Climate Change Mitigation			✓		
Worker Requirements					
Pesticide Use Safety	✓		✓		✓
Fair Pay	✓				✓
Worker Rights & Conditions	✓				✓

CONTACT INFORMATION

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WILDLIFE-FRIENDLY FARMING
CERTIFICATIONS

Overview of Five Eco-Certifications Available to the Talamanca-Osa Region of Costa Rica

osa CONSERVATION
CONSERVING COSTA RICA'S NATURAL TREASURE

UC **SANTA BARBARA**
Bren School of Environmental Science & Management

RAINFOREST ALLIANCE

Rainforest Alliance promotes sustainable agriculture, conservation, and social welfare. The standards incentivize continuous improvement by allowing farmers to improve on their own baselines.

Potential Benefits:
- Provides training and technical assistance to help farmers improve efficiency
- Allows group certification

Highest Barriers to Transitioning:
- Requirements for environmental and labor conditions, including limited agrochemical use and fair working conditions

Applicable to most regional crops.

FAIR TRADE

Fair Trade seeks to improve the lives of farmers while benefiting the environment. This certification guarantees both a minimum price and a price premium for farmers.

Potential Benefits:
- Farm owners gain increased revenue
- Minimum price reduces farmers' risk during global price fluctuations
- Allows group certification

Highest Barriers to Transitioning:
- Requirements for both environmental and labor conditions, including rigorous safety and workers' rights standards

Applicable to most regional crops.

BANDERA AZUL

Programa Bandera Azul Ecológica is a Costa Rican program that awards farms for environmental practices. Farms can earn 1-5 stars depending on their environmental efforts and additional certifications.

Potential Benefits:
- Requirements are flexible and can be met in a variety of ways

Highest Barriers to Transitioning:
- Farms earn national recognition, but certification is unlikely to be known outside of Costa Rica
- Variety of environmental requirements to promote sustainable practices

Applicable to most regional crops.

USDA ORGANIC

USDA organic crops are grown under criteria regarding soil quality, pest and weed control, and use of additives. Organic growers use natural methods whenever possible.

Potential Benefits:
- Can increase ecosystem services from insects like pest control and pollination
- Costa Rican government offers financial and tax incentives

Highest Barriers to Transitioning:
- Cannot use certain agrochemicals for three years before harvest

Applicable to most regional crops.

SMITHSONIAN BIRD-FRIENDLY

Bird Friendly coffee is organic, shade-grown, coffee certified using criteria from the Smithsonian Migratory Bird Center that is scientifically proven to provide bird habitat.

Potential Benefits:
- Provides excellent bird habitat and associated ecosystem services
- Higher price premiums than organic alone

Highest Barriers to Transitioning:
- Requirements for canopy height, foliage cover, and number of plant species
- Must also be certified USDA Organic

Only applicable to coffee.

PROCESS & NEXT STEPS

What to Expect:
- **Audits**: Contact the organization and they will help with becoming certified, including an initial audit. Ongoing audits are required every 1-3 years.
- **Potential Costs**: Costs vary, but may include audits, transition costs to meet requirements, and cost of certification.

Considerations for Decreasing Costs:
- **Cooperatives**: Applying as a group of farms can make certification more accessible and feasible for small farms.
- **Government Incentives**: The Payment for Ecosystem Services Program and the National Forestry Financing Fund offer incentives for conservation practices.

Appendix E. Processing Climate and Presence Data for use in MaxEnt

Processing Climate Data

Climate data were downloaded as .tif files from the WorldClim website at 30 second resolution using the WGS 1984 coordinate system. These data were processed in ArcGIS for use in MaxEnt using the following steps:
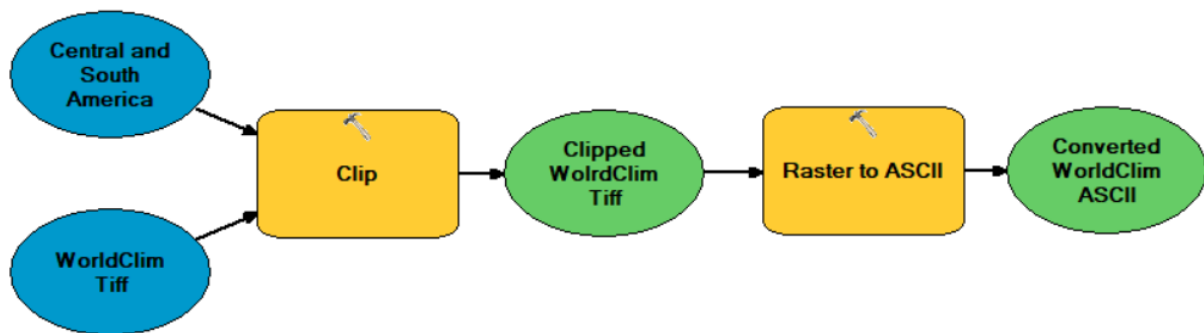
Figure E1. *WorldClim climate data processing model.*

- All tiff files downloaded from WorldClim were clipped using Clip (Data Management) to the same extent of a Central and South America shapefile provided by ArcGIS, to have the same cell size and raster extent.
- All clipped tiff files were converted to ASCII files using Raster to ASCII (Conversion) for use in Maxent.

Processing Crop Presence Data

Coffee

The first set of coffee presence points obtained from the Ovalle-Rivera et al. study. Their points were obtained from CIAT. Starting with 62,000 points, they filtered the data to meet the following criteria:

- Located within one of the top 20 coffee growing countries: Brazil, Colombia, Ecuador, Mexico, Costa Rica, El Salvador, Nicaragua, Guatemala, Honduras, Ethiopia, Kenya, Rwanda, Burundi, Tanzania, Uganda, Zimbabwe, India, Yemen, Indonesia, and Vietnam
- Located at an elevation within the specific suitable ranges for each country
- Annual rainfall of above 750
- At a resolution of 2.5 arc minutes

The resulting datasets after filtering consisted of 17,625 points with mean annual temperatures ranging from 14-26°C and mean annual precipitation of 750 - 4930 mm.

Cacao

Cacao presence points were obtained from the Global Biodiversity Information Facility (GBIF) dataset and filtered following the same process as by the Ovalle-Rivera et al. study.

- Caco observations were filtered to only include points between 0 - 600 m above sea level which is considered the suitable elevation range for growing cacao (Sitohang & Siahaan, 2018).
- Observation points were restricted to Central and South America.

Pineapple

Pineapple presence points were also obtained from the Global Biodiversity Information Facility (GBIF) dataset and filtered following the same process as the Ovalle-Rivera et al. study.

- Pineapple points were filtered to 0 - 900 m above sea level based, which is considered the suitable elevation range in our study area (Dorey et al., 2018 & Rodrigo de Sousa, personal communication, January 27, 2021).
- Observation points were restricted to Central and South America.

Supplemental Observation Points

- Coffee, cacao, and pineapple presence points were also obtained from Osa Conservation, an environmental non-profit local to the study area. A farm location dataset was obtained from them via email.

Processing

- Crop presence data were obtained from all sources (CIAT, GBIF, and Osa Conservation) in tabular form with location data in the form of longitude and latitude columns.
- Datasets were appended together and plotted in ArcGIS to check for accuracy and then the file was converted to .csv format for use in MaxEnt.

Validation of Crop Presence Data

In order to check the validity of our pineapple and crop presence points, we followed the methodology of Ovalle-Rivera et al. and produced a table of averaged current environmental conditions for all crop observation points obtained from GBIF.

- Data from all 19 bioclimatic factor layers, and elevation, were extracted for each of the filtered points for each crop using the Extract Multi Values to Points (Spatial Analyst) tool in ArcGIS.
- Values of each factor were averaged across all points for each crop and put into a table where they were checked against the known growing condition thresholds obtained during literature review for each crop.

Appendix F. Processing Setup in MaxEnt

Spatial analysis to predict current and future crop suitability was conducted using MaxEnt software using the following steps and settings:

- Uploaded crop presence .csv file to the "Samples" input section
- Uploaded ASCII files that were created from the current environmental factors downloaded from WorldClim in the "Environmental layers" input section
- Unchecked "Auto Features"
- Checked
    - ○ Create response curves
    - ○ Make pictures of prediction
    - ○ Do jackknife to measure variable importance
- Output directories were set with each GCM model and RCP projection
- Uploaded ASCII files that were created from the future projection environmental factors downloaded from WorldClim in the "Projection layers directory file" input section

Figure F1. *Example MaxEnt parameters (coffee).*

- Only the "Basic" settings were changed in the Maximum Entropy Parameters:
  - Random Seed was checked
  - Random test percentage was changed to 20
  - Replicates was changed to 10
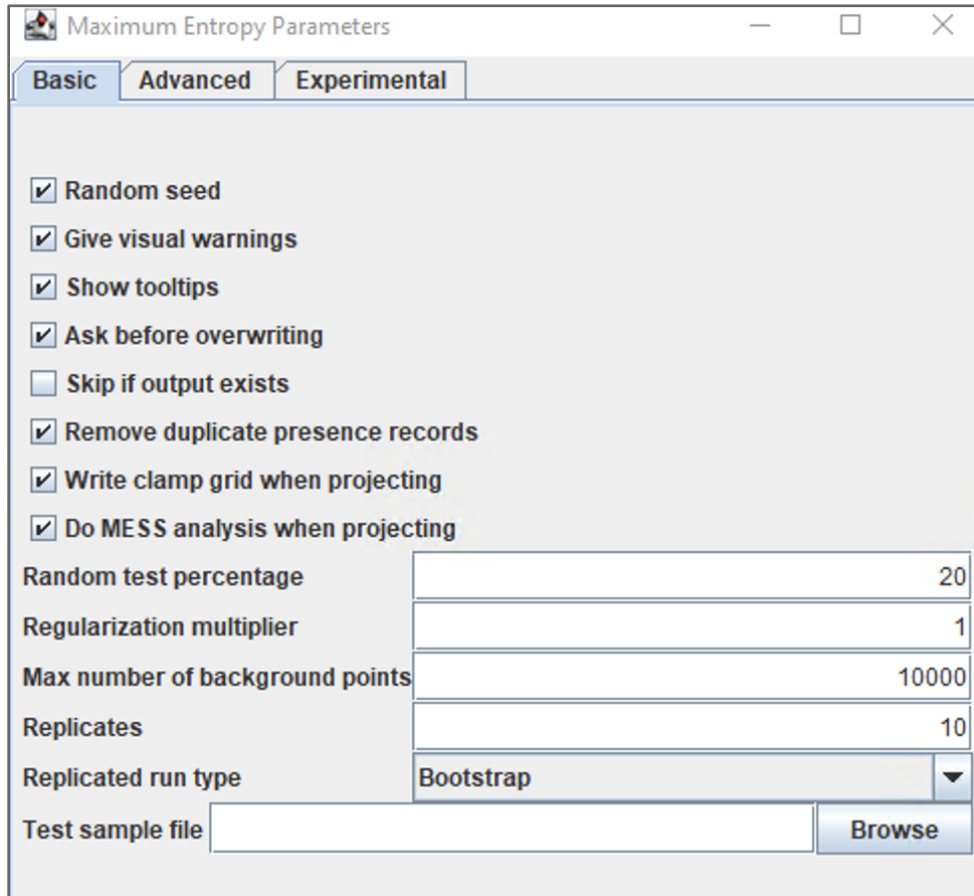 - Replicate run type was changed to Bootstrap

Figure F2. *Example MaxEnt parameter settings.*

Appendix G. Processing MaxEnt Results

Outputs from running MaxEnt for each of the four GCMs (CNRM-CM5, MIROC-ESM-CHEM, MIROC5, MPI-ESM-LR) for each time period (Current, 2050, and 2070) for the two different climate scenarios (RCP 4.5 and RCP 8.5) were processed in ArcGIS using the following steps:

- MaxEnt created an output ASCII file of the average of the 10 replicates of each run. These output files were converted to raster files using the ASCII to Raster (Conversion) tool.
- Each output raster was then given a coordinate system using the Define Projection (Data Management) the four rasters from each GCMs were averaged together using Raster Calculator (Spatial Analyst) for each time period and for each RCP in order to create suitability rasters for the present, 2050, and 2070 for each climate scenario.
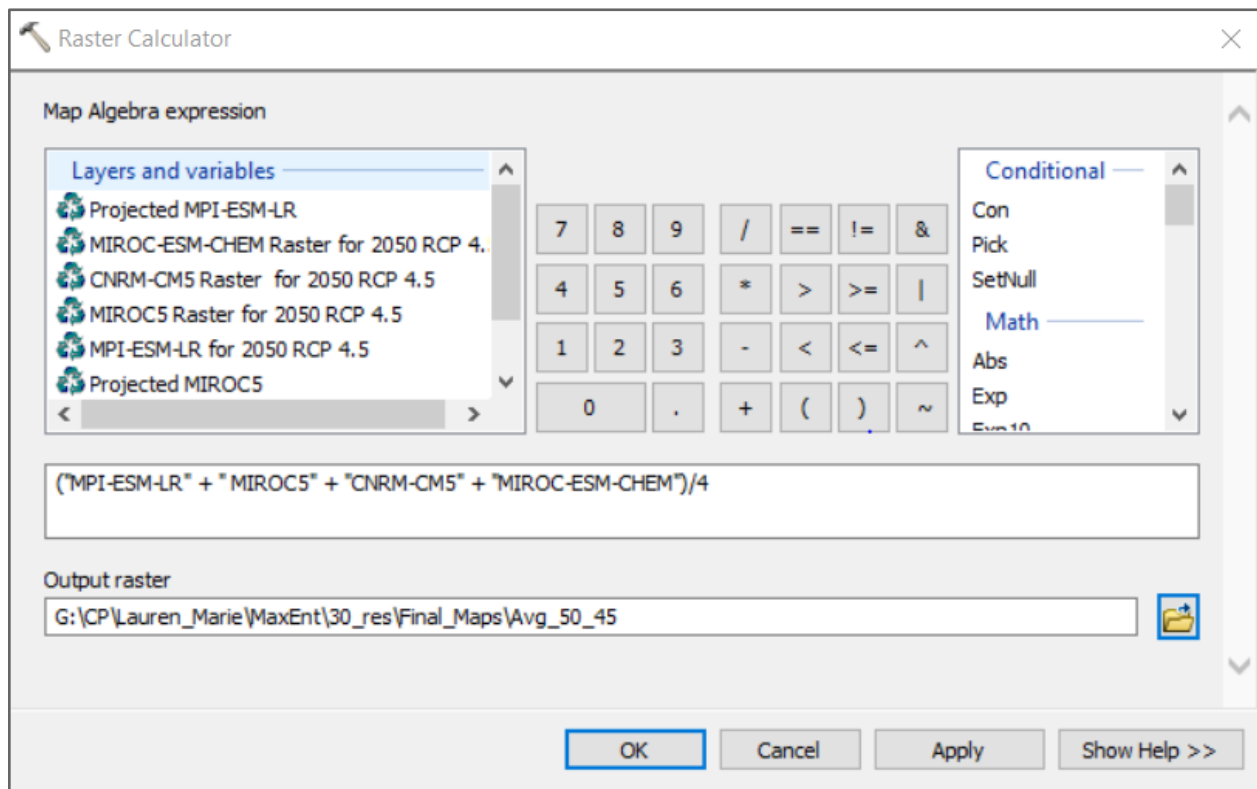
Figure G1. *Example Raster Calculator expression for averaging GCM outputs for coffee (2050 RCP 4.5).*

Each of these averaged suitability rasters were then clipped to our study area shapefile (the Talamanca-Osa region) using the Clip (Data Management) tool.
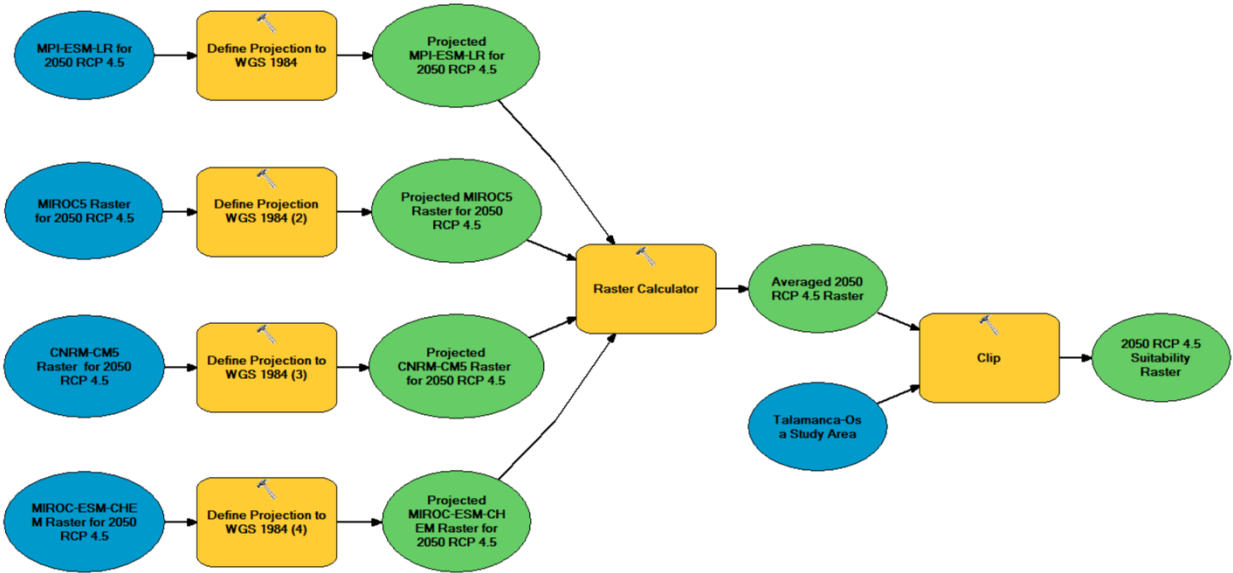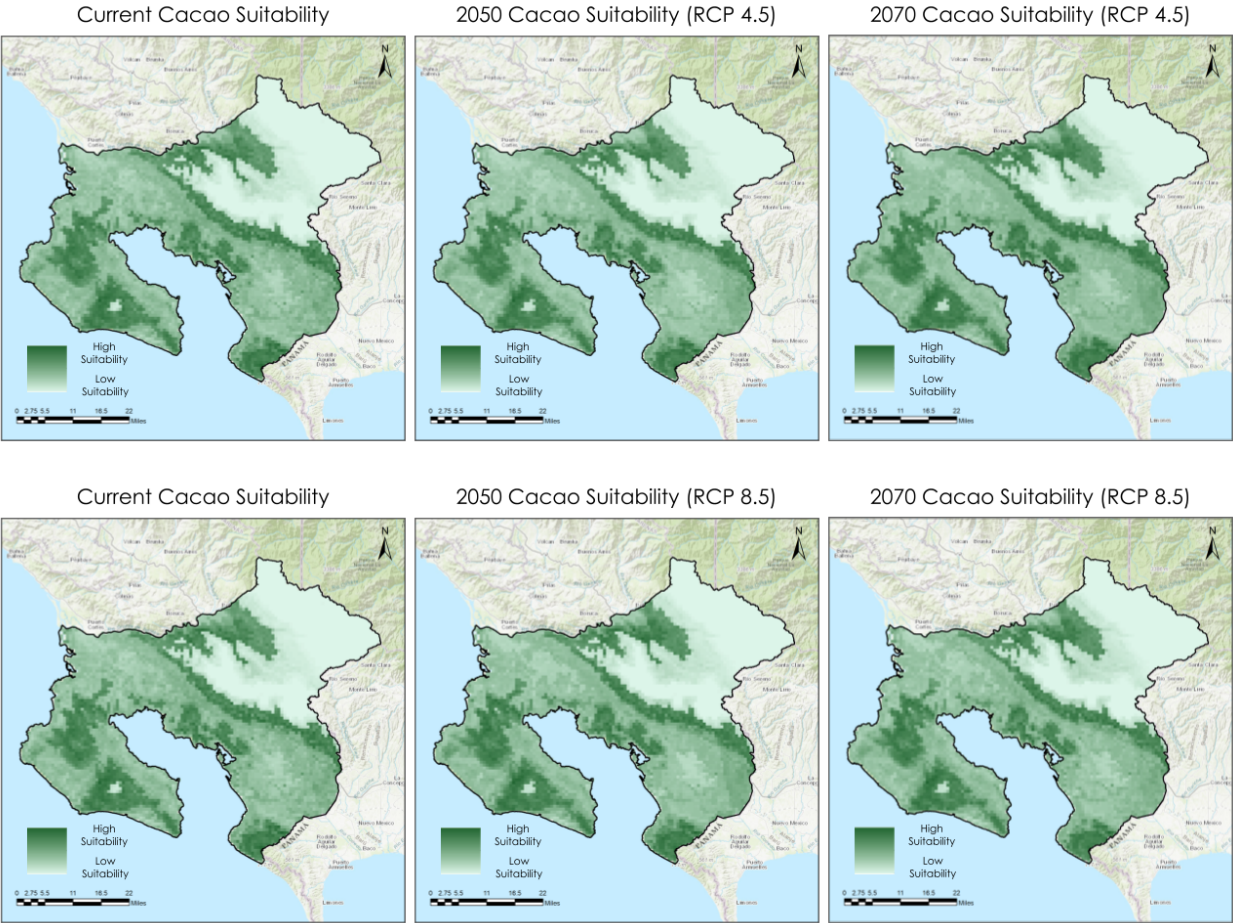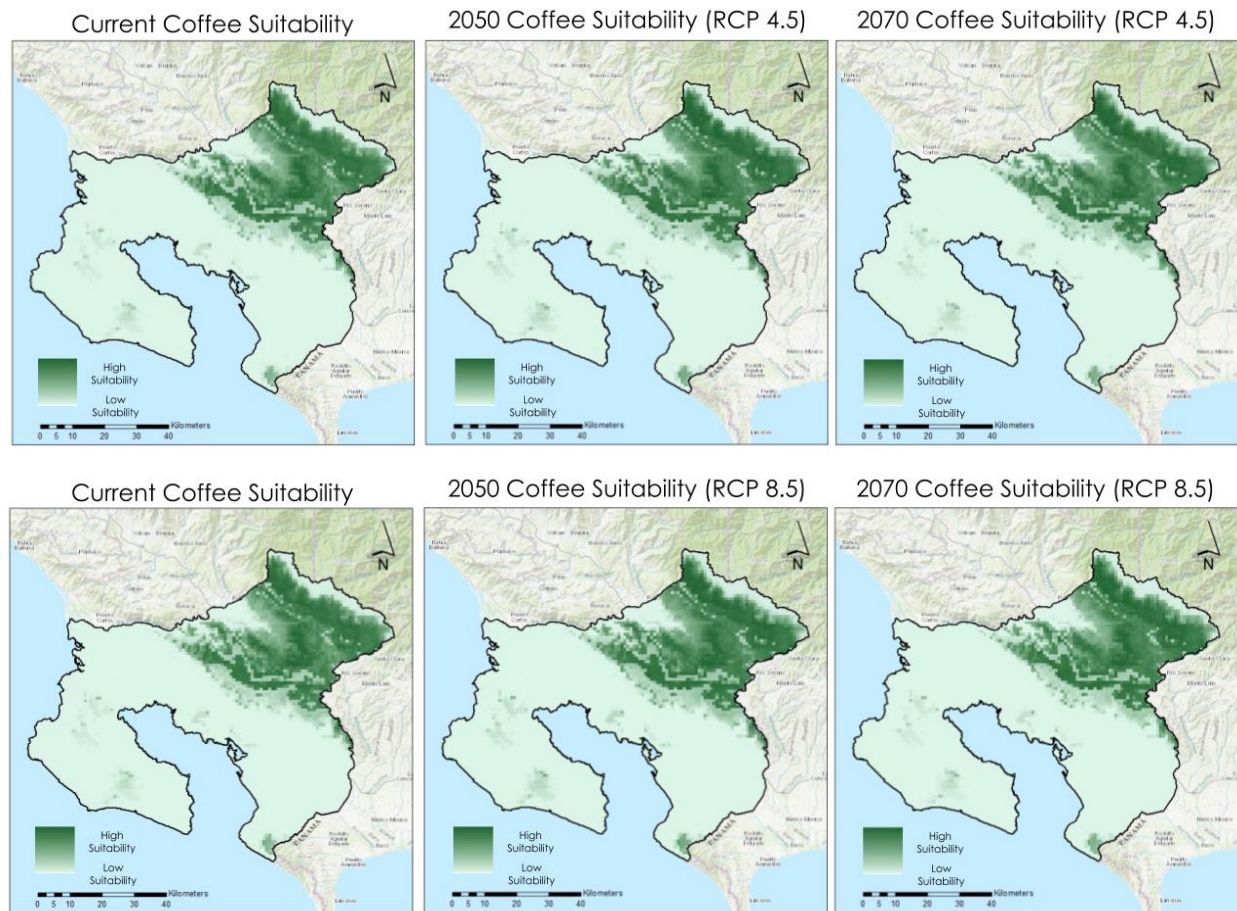
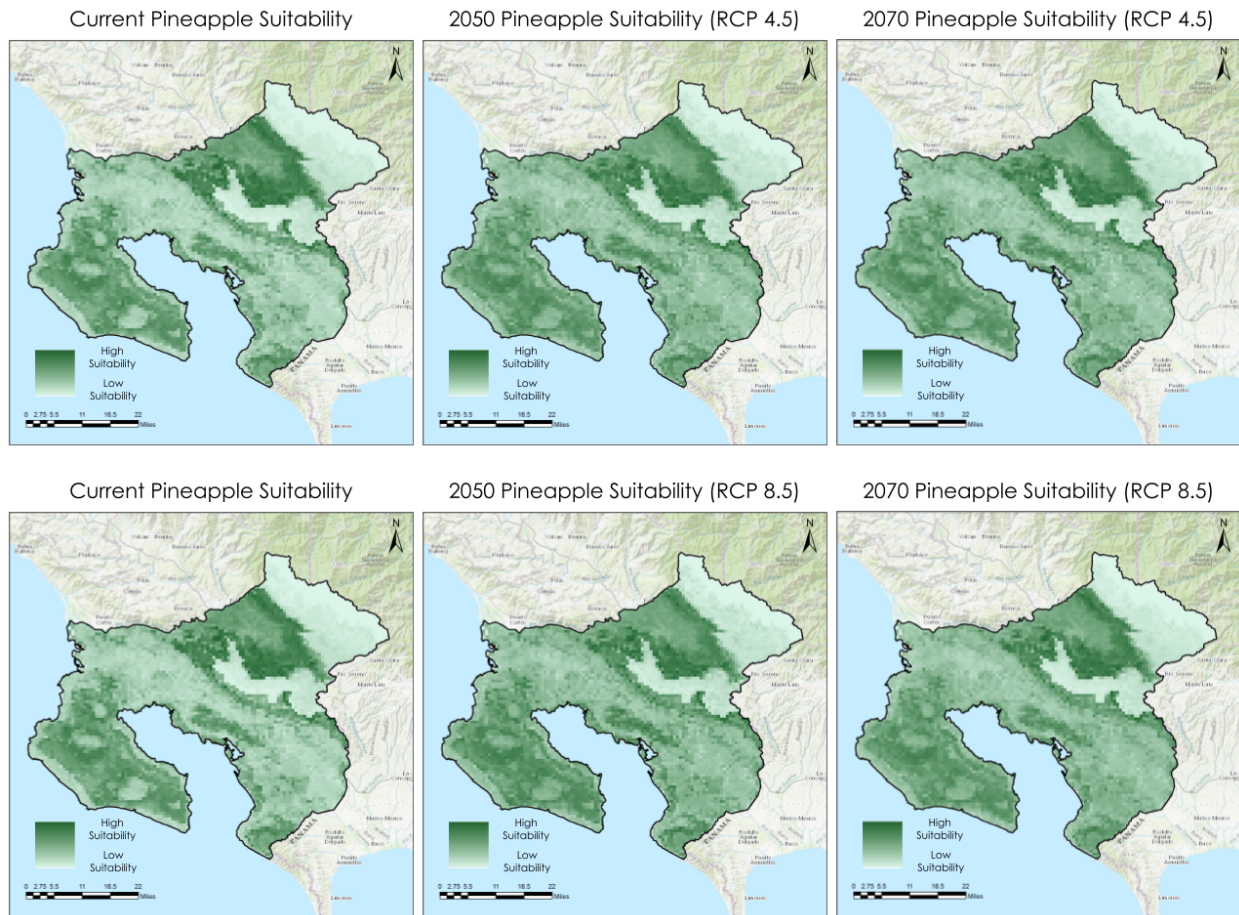**Figure G2:** *Suitability raster processing model.*

Cacao

Figure G3. *Cacao Crop Suitability Maps. Cacao Suitability maps were created to display how suitability for cacao growing is projected to spatially shift in future decades under two different climate scenarios. Dark green areas represent the highest probability of being suitable locations for growing cacao while the light green areas show areas that are predicted to be the least suitable.*

Coffee

Figure G4. *Coffee Crop Suitability Maps. Coffee Suitability maps were created to display how suitability for coffee growing is projected to spatially shift in future decades under two different climate scenarios. Dark green areas represent the highest probability of being suitable locations for growing coffee while the light green areas show areas that are predicted to be the least suitable.*

Pineapple

Current Pineapple Suitability	2050 Pineapple Suitability (RCP 4.5)	2070 Pineapple Suitability (RCP 4.5)

| Current Pineapple Suitability	2050 Pineapple Suitability (RCP 8.5)	2070 Pineapple Suitability (RCP 8.5)

Figure G5. Pineapple Crop Suitability Maps. Pineapple Suitability maps were created to display how suitability for pineapple growing is projected to spatially shift in future decades under two different climate scenarios. Dark green areas represent the highest probability of being suitable locations for growing pineapple while the light green areas show areas that are predicted to be the least suitable.

Appendix H. Binary Suitability Maps

Outputs from the suitability rasters averaged from the four GCMs (CNRM-CM5, MIROC-ESM-CHEM, MIROC5, MPI-ESM-LR) for each time period (Current, 2050, and 2070) for the two different climate scenarios (RCP 4.5 and RCP 8.5) were further processed in ArcGIS to create binary maps showing suitable and unsuitable areas for each crop using the following steps:

- The four averaged rasters as well as the current suitability raster were reclassified to show unsuitable pixels (0) and suitable pixels (1) using the Reclassify (Spatial Analyst) and using the 10th percentile training threshold maxent output as the suitability threshold.
- The 10th percentile training threshold averaged across replicates for each crop was obtained from each MaxEnt model run's output .csv file. The threshold numbers used were averaged across GCMs for each time period and RCP scenario.
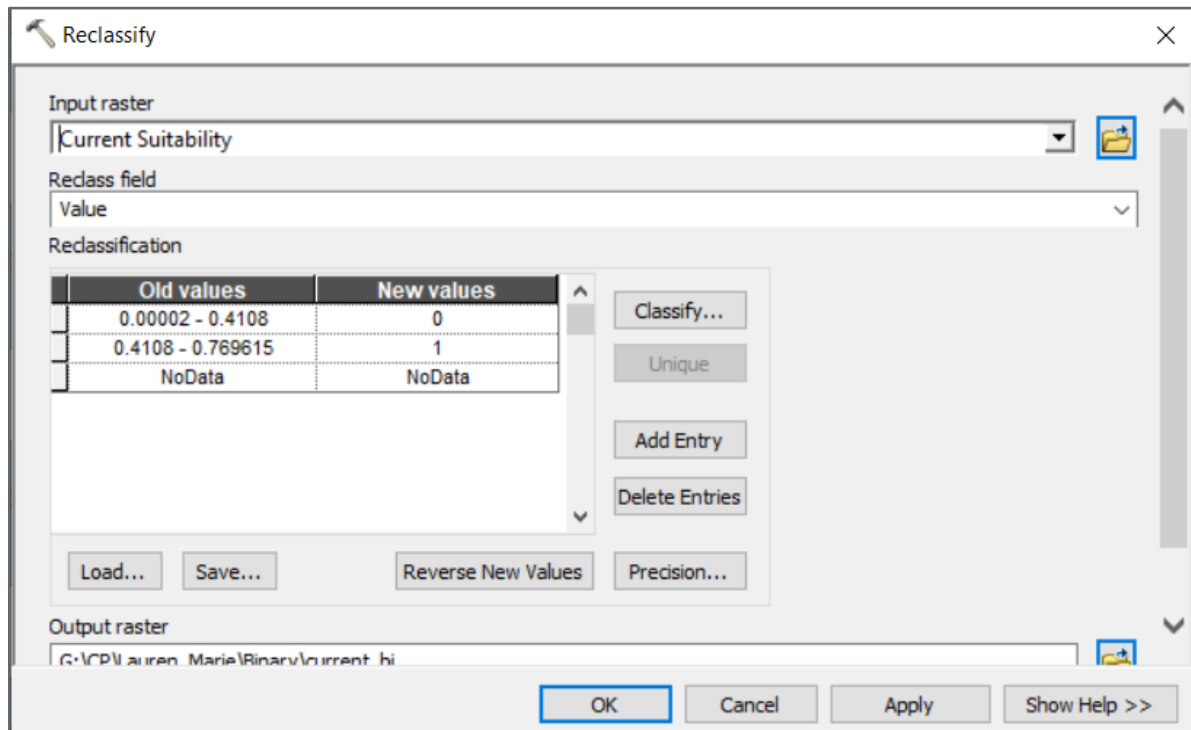
Figure H1. *Example Reclassify Raster settings (Coffee Current Suitability).*

Table H1. *Cacao Threshold Table of the average 10th Percentile Training Presence Logistic values that were used as suitability thresholds for the RCP 4.5 Scenario.*

Time Period	Average 10th Percentile Training Presence Logistic Threshold
Current	0.347409
2050 (average of 2041-2060)	0.3269705
2070 (average of 2061-2080)	0.3317386138

Table H2. *Cacao Threshold Table of the average 10th Percentile Training Presence Logistic values that were used as suitability thresholds for the RCP 8.5 Scenario.*

Time Period	Average 10th Percentile Training Presence Logistic Threshold
Current	0.347409
2050 (average of 2041-2060)	0.329747909
2070 (average of 2061-2080)	0.3328908863

Table H3. *Coffee Threshold Table of the average 10th Percentile Training Presence Logistic values that were used as suitability thresholds for the RCP 4.5 Scenario.*

Time Period	Average 10th Percentile Training Presence Logistic Threshold
Current	0.4108
2050 (average of 2041-2060)	0.41115
2070 (average of 2061-2080)	0.4081

Table H4. *Coffee Threshold Table of the average 10th Percentile Training Presence Logistic values that were used as suitability thresholds for the RCP 8.5 Scenario.*

Time Period	Average 10th Percentile Training Presence Logistic Threshold
Current	0.4108
2050 (average of 2041-2060)	0.410525
2070 (average of 2061-2080)	0.407575

Table H5. *Pineapple Threshold Table of the average 10th Percentile Training Presence Logistic values that were used as suitability thresholds for the RCP 4.5 Scenario.*

Time Period	Average 10th Percentile Training Presence Logistic Threshold
Current	0.336245455
2050 (average of 2041-2060)	0.3361865
2070 (average of 2061-2080)	0.3346113635

Table H6. *Pineapple Threshold Table of the average 10th Percentile Training Presence Logistic values that were used as suitability thresholds for the RCP 8.5 Scenario.*

| Time Period	Average 10th Percentile Training Presence Logistic Threshold
Current	0.336245455
2050 (average of 2041-2060)	0.3327773638
2070 (average of 2061-2080)	0.3305477955

Cacao
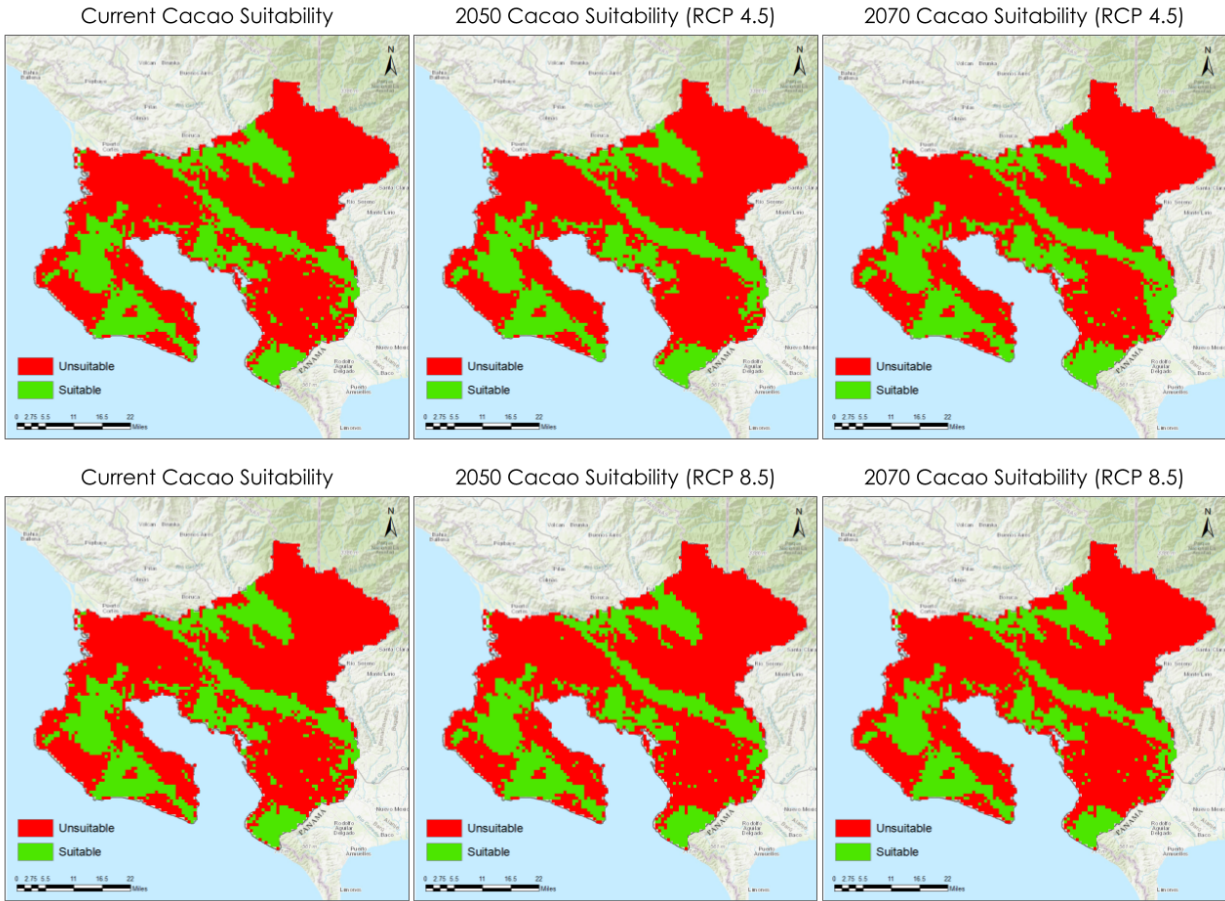
Figure H2. Binary Cacao Crop Suitability Maps. *Cacao Suitability maps were converted to binary maps showing suitable and unsuitable locations for cacao crops in order to clearly communicate functional changes in suitability. The results show that suitability will expand under the RCP 4.5 and decline under the RCP 8.5 scenario.*

Coffee
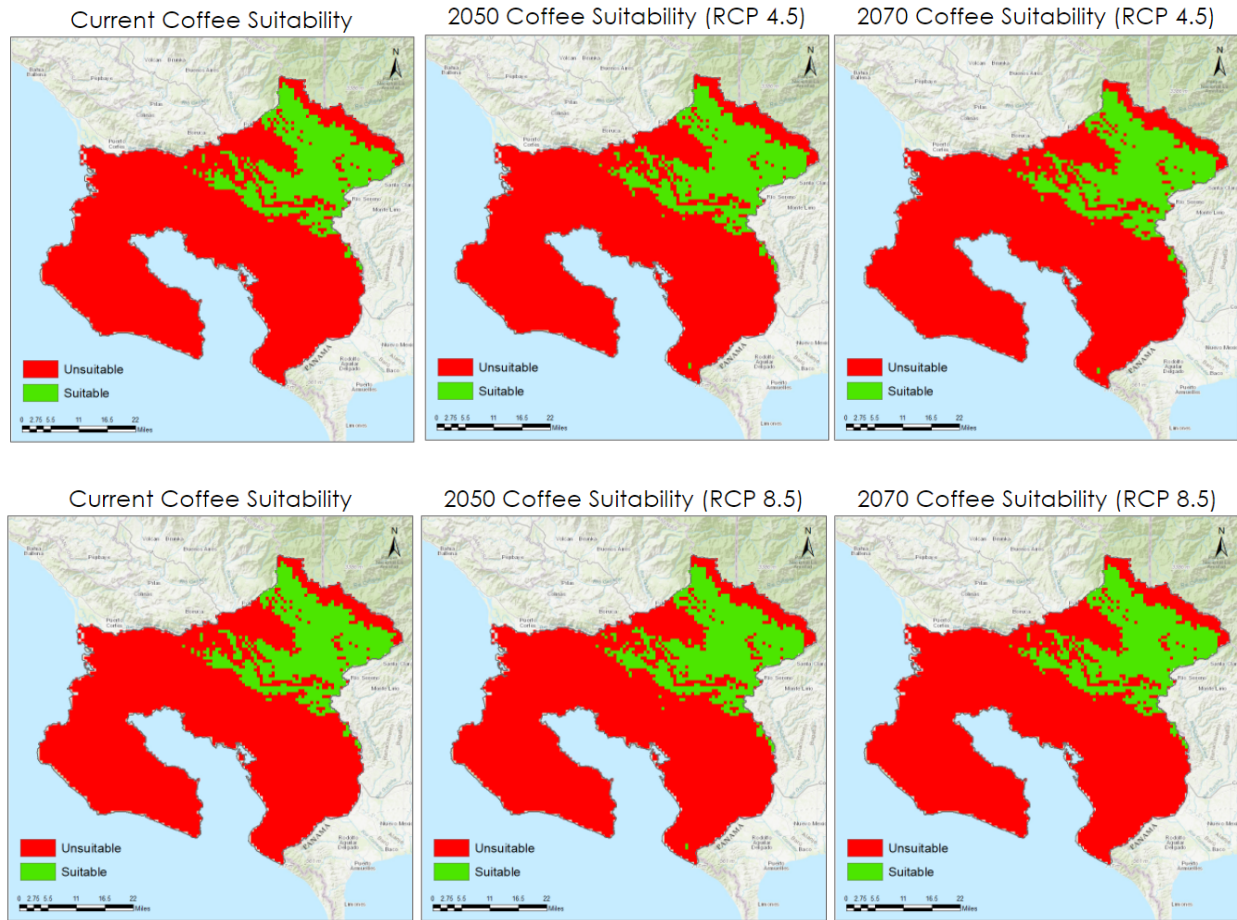
Figure H3. Binary Coffee Crop Suitability Maps. *Coffee Suitability maps were converted to binary maps showing suitable and unsuitable locations for coffee crops in order to clearly communicate functional changes in suitability. The results show that large portions of the higher elevations in the Talamanca Mountains are suitable for growing coffee and will remain so through the 2070 time period in these climate scenarios. Under both RCP 4.5 and RCP 8.5, the total area suitable for growing coffee increased overall during the time periods.*

Pineapple
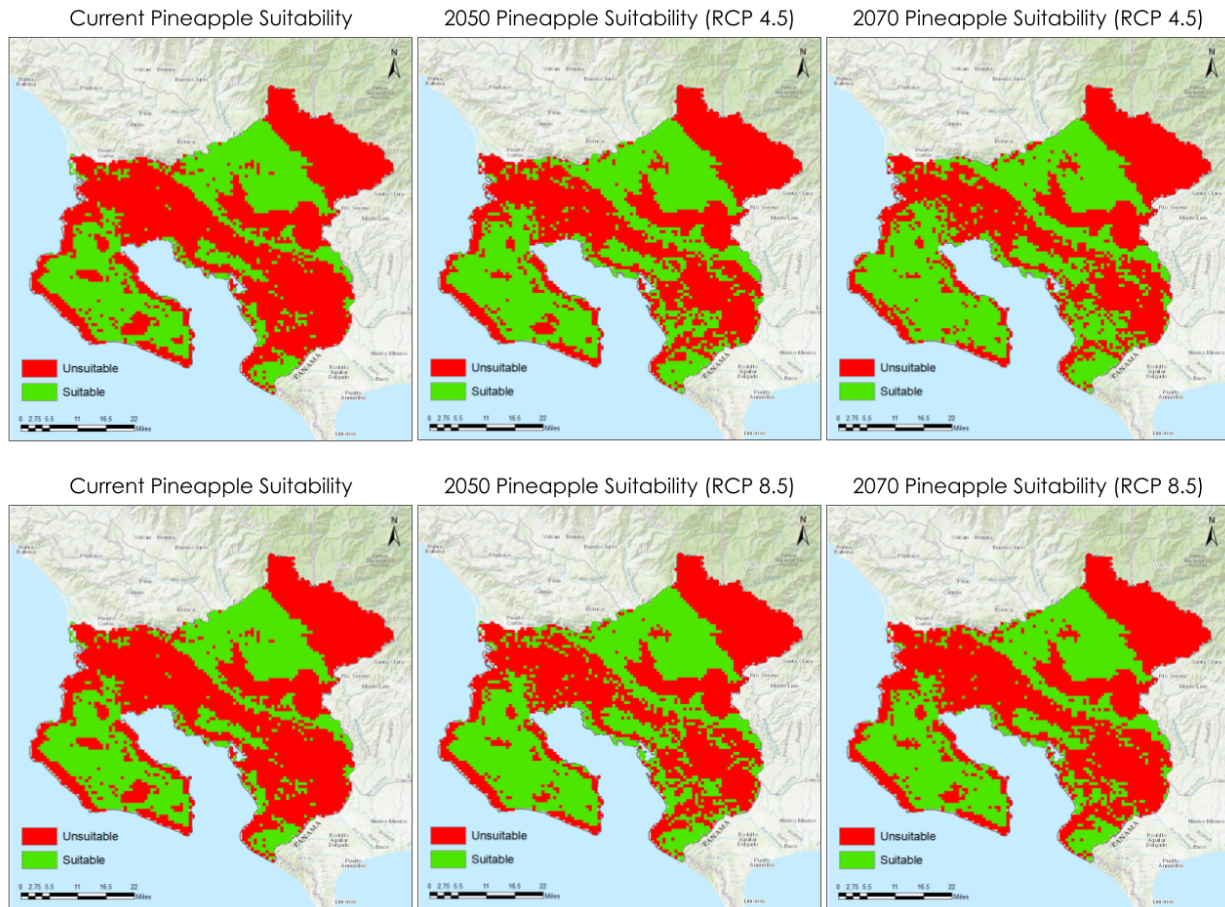
Figure H4. Pineapple Crop Suitability Maps. *Pineapple Suitability maps were converted to binary maps showing suitable and unsuitable locations for pineapple crops in order to clearly communicate functional changes in suitability. The results show an overall increase in suitable areas, particularly in the lowlands and around the Pan-American Highway.*

Calculating Suitability Change

Total area change (in hectares) in binary suitability between current and future scenarios was calculated in ArcGIS using the following process:

- Binary suitability rasters were projected from the WGS 1984 geographic coordinate system to the NAD 1983 UTM Zone 17N projected coordinate system in order to convert units of measurement from degrees to meters.
- Differences between current suitability and each future scenario were calculated using the Raster Calculator (Spatial Analyst) tool and the following equation:

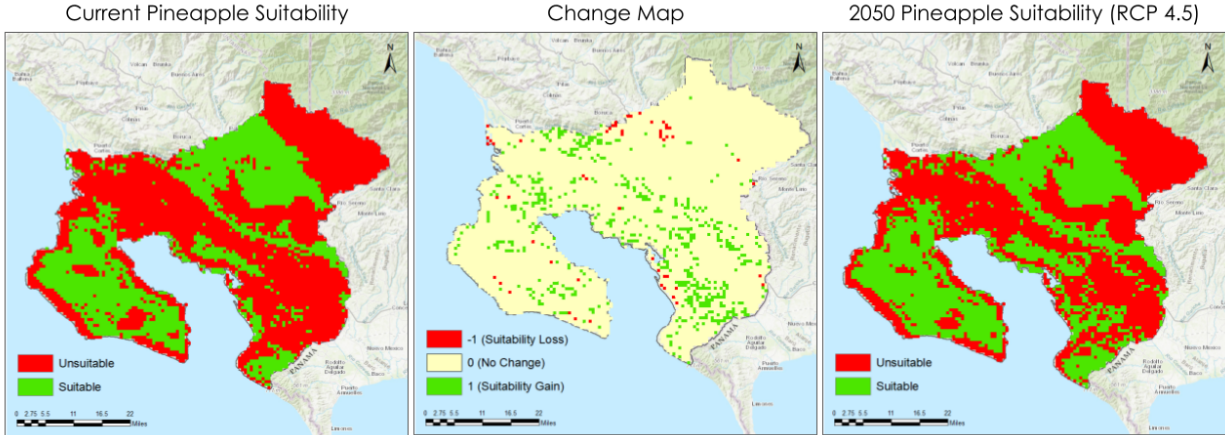$$(Future\ Scenario\ Suitability\ Raster) - (Current\ Suitability\ Raster)$$

Figure H5. *Example change map (middle) showing the differences between current suitability (left) and projected suitability in 2050 RCP 4.5 (right).*

- The outputs of this calculation were change map rasters representing change as:
  - Suitability loss (value of -1) where the pixel is considered suitable for the crop under current conditions but unsuitable under the future scenario
  - Suitability gain (value of 1) where the pixel is considered unsuitable for the crop under current conditions but suitable under the future scenario
  - And no change (value of 0) where the pixel suitability did not change between time periods.
- The total area (in meters) of each class was calculated using the Zonal Geometry as Table (Spatial Analyst) Tool and a hectare column was added to the output table to convert meters to hectares using the following equation in the Field Calculator tool:

$$[AREA]/10{,}000$$

50_45_pineapple

VALUE	AREA	HECTARES
-1	46209200	4620.919434
1	464659100	46465.914063
0	4830573000	483057.25

H6. *Example Zonal Geometry as Table output for pineapple suitability change 2050 RCP 4.5.*

- The resulting tables and calculated net change were reported in the results to indicate the overall impact on suitability for each time period and climate change scenario.
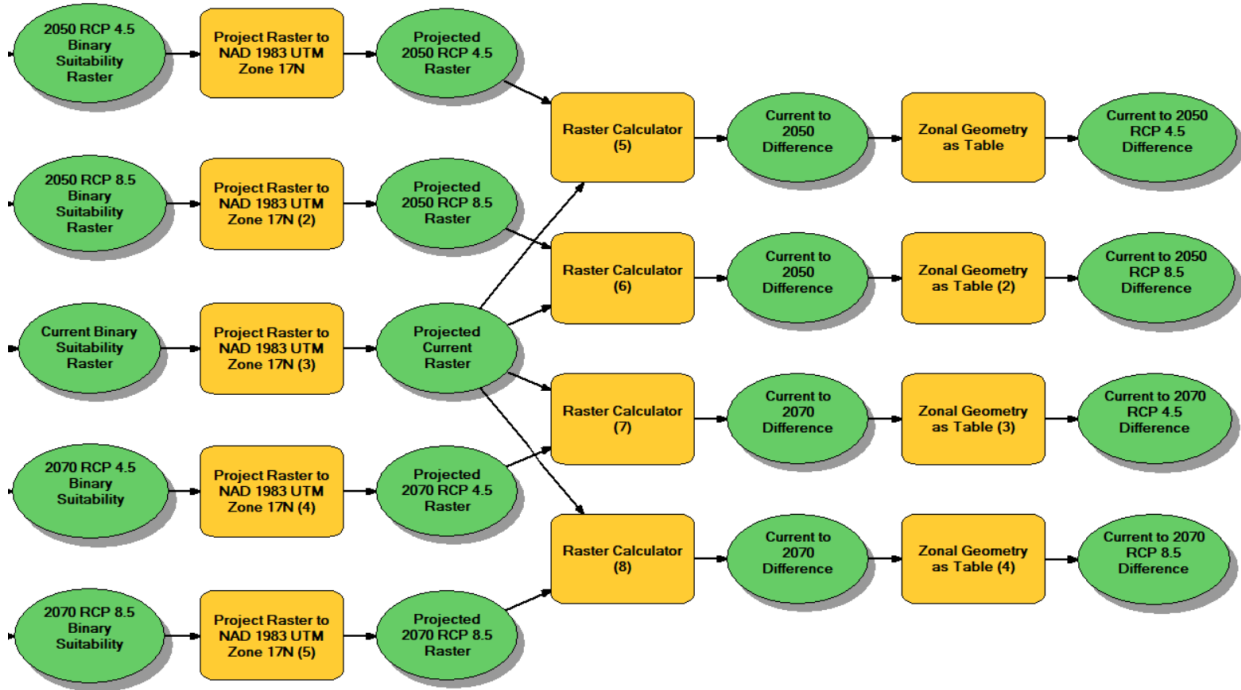

Figure H7. Binary suitability change model.

Binary Time Period Overlap Analysis

To easily compare how binary suitability for each crop changed over the three time periods, combined time period maps were created for each climate scenario (Figures 9, 10, and 11). The maps illustrate where the crop is suitable in each time period, and where suitability overlaps with other time periods. This was done by reclassifying the binary maps. The current time period rasters for each crop and RCP were left unchanged: suitable pixels had a value of 1 and unsuitable pixels had a value of 0. The 2050 binary suitability rasters were reclassified so that suitable pixels now had a value of 5 but unsuitable pixels kept a value of 0. Finally, the 2070 binary suitability rasters were reclassified so that suitable pixels had a value of 10 and unsuitable pixels kept their value of 0. This was done so that when the three time period rasters for each crop and RCP were added together using the Raster Calculator tool, each overlap combination had a unique score from which it could be determined which time periods overlapped there (Table G1). An overlapped color scheme was then applied to each of the rasters in order to clearly communicate which suitable time period each pixel represented (Figure G10).

Table H7. *Pixel values resulting from the addition of each reclassified time period raster for each crop to indicate for which time period(s) each pixel is suitable for the crop.*

Suitable Time Period(s)	Pixel Value
Never suitable	0
Only current	1
Only 2050	5
Current and 2050	6
Only 2070	10
Current and 2070	11
2050 and 2070	15
All Time Periods	16
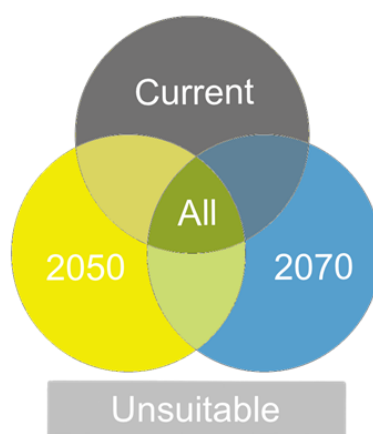
Figure H8. *Time period combination map legend color scheme where pixels that are never suitable for the crop are indicated in light gray, pixels only suitable in the current time period are dark gray, pixels only suitable in 2050 are yellow, pixels only suitable in 2070 are blue, pixels that are suitable in both the current and 2050 time periods are dark yellow, pixels that are suitable in both the current and 2050 time periods are dark blue, that are suitable in both the 2050 and 2070 time periods are light green, and pixels that are suitable in all three time periods are dark green.*

Binary Crop Overlap Analysis

To clearly illustrate where suitable ranges for each crop overlap each other and how these intersections change over the time periods and under each climate scenario, combined crop suitability maps were created (Figure 12). These maps indicate where each crop is suitable and where this suitability overlaps with the other crops in each time period and under each climate scenario. These maps were created using a similar methodology to the time period overlap maps. The coffee binary suitability maps for each time period were reclassified so that pixels that were suitable for coffee had a value of 10 and unsuitable pixels retained their value of 0. The cacao binary suitability maps for each time period were reclassified so that suitable pixels had a value of 50 and unsuitable pixels retained a value of 0. Finally, pineapple binary suitability maps were reclassified so that suitable pixels had a value of 200 and unsuitable pixels retained a value

of 0. The reclassified binary suitability rasters for each crop were added together for each time period and RCP, resulting in combined rasters with unique values for each possible combination of suitability so that it could be determined which crops were suitable for each pixel and where they overlapped with each other (Table G2). Another overlapped color scheme was applied to each of the maps in order to clearly communicate which crop or crops were suitable for each pixel (Figure G12).

Table H8. *Pixel values resulting from the addition of each reclassified crop raster for which crop(s) each pixel is suitable for the crop.*

Suitable Time Crop(s)	Pixel Value
No Suitable Crops	0
Only Coffee	10
Only Cacao	50
Coffee and Cacao	60
Only Pineapple	200
Coffee and Pineapple	210
Cacao and Pineapple	250
All Crops	260
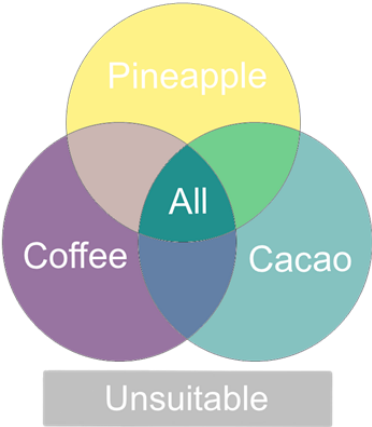
Figure H9. *Crop suitability combination map legend color scheme where pixels that are not suitable for any crop are indicated in light gray, pixels only suitable for coffee are purple, pixels only suitable for cacao are blue, pixels only suitable for pineapple are yellow, pixels that are suitable for coffee and cacao are blue-purple, pixels that are suitable for coffee and pineapple are yellow-purple, pixels that are suitable for cacao and pineapple are light green, and pixels that are suitable for all three crops are dark teal.*

Crop Overlap Values

Table H9. Crop overlap areas for the current time period in the Talamanca-Osa region.

Suitable crop(s)	Suitable Hectares	Percent of Total Area
None	203149.33	38.13%
Only Coffee	59301.80	11.13%
Only Cacao	61184.40	11.48%
Only Pineapple	0	0%
Coffee and Cacao	72052.13	13.52%
Coffee and Pineapple	37994.23	7.13%
Cacao and Pineapple	97895.04	18.37%
All Crops	1198.02	0.22%

Table H10. Crop overlap areas for 2050 RCP 4.5 in the Talamanca-Osa region.

Suitable crop(s)	Suitable Hectares	Hectare Change	Percent of Total Area	Percent Change
None	179188.98	-23960.34	33.60%	-4.53%
Only Coffee	57847.07	-1454.73	10.85%	-0.28%
Only Cacao	45096.75	-16087.65	8.46%	-3.03%
Only Pineapple	95841.30	23789.17	17.97%	4.45%
Coffee and Cacao	0	0	0%	0%
Coffee and Pineapple	39705.68	1711.45	7.45%	0.31%
Cacao and Pineapple	112699.09	14804.05	21.13%	2.76%
All Crops	2909.47	1711.45	0.55%	0.32%

Table H11. Crop overlap areas for 2070 RCP 4.5 in the Talamanca-Osa region.

| Suitable crop(s)	Suitable Hectares	Hectare Change	Percent of Total Area	Percent Change
None	155656.53	-47492.80	29.19%	-8.94%
Only Coffee	59472.95	171.14	11.15%	0.02%
Only Cacao	49888.82	-11295.58	9.35%	-2.13%
Only Pineapple	106366.73	34314.60	19.95%	6.42%
Coffee and Cacao	256.72	256.72	0.05%	0.05%
Coffee and Pineapple	38336.52	342.29	7.19%	0.06%
Cacao and Pineapple	119630.48	21735.44	22.43%	4.06%
All Crops	3679.62	2481.60	0.69%	0.47%

**Table H12.** *Crop overlap areas for 2050 RCP 8.5 in the Talamanca-Osa region.*

Suitable crop(s)	Suitable Hectares	Hectare Change from Current	Percent of Total Area	Percent Change from Current
None	181927.33	-21222.00	34.15%	-3.98%
Only Coffee	58274.93	-1026.88	10.94%	-0.19%
Only Cacao	39106.67	-22077.73	7.34%	-4.14%
Only Pineapple	96440.30	24388.18	18.10%	4.58%
Coffee and Cacao	85.57	85.57	0.02%	0.02%
Coffee and Pineapple	39192.25	1198.02	7.36%	0.22%
Cacao and Pineapple	113298.11	15403.07	21.27%	2.89%
All Crops	4449.77	3251.76	0.84%	0.61%

**Table H13.** *Crop overlap areas for 2070 RCP 8.5 in the Talamanca-Osa region.*

| Suitable crop(s)	Suitable Hectares	Hectare Change from Current	Percent of Total Area	Percent Change from Current
None	197415.97	-5733.36	37.05%	-1.08%
Only Coffee	58446.08	-855.73	10.97%	-0.16%
Only Cacao	46808.20	-14376.20	8.79%	-2.70%
Only Pineapple	85829.30	13777.18	16.11%	2.59%
Coffee and Cacao	0	0	0%	0%
Coffee and Pineapple	39277.82	1283.59	7.37%	0.24%
Cacao and Pineapple	103542.83	5647.79	19.43%	1.06%
All Crops	1454.73	256.72	0.27%	0.05%
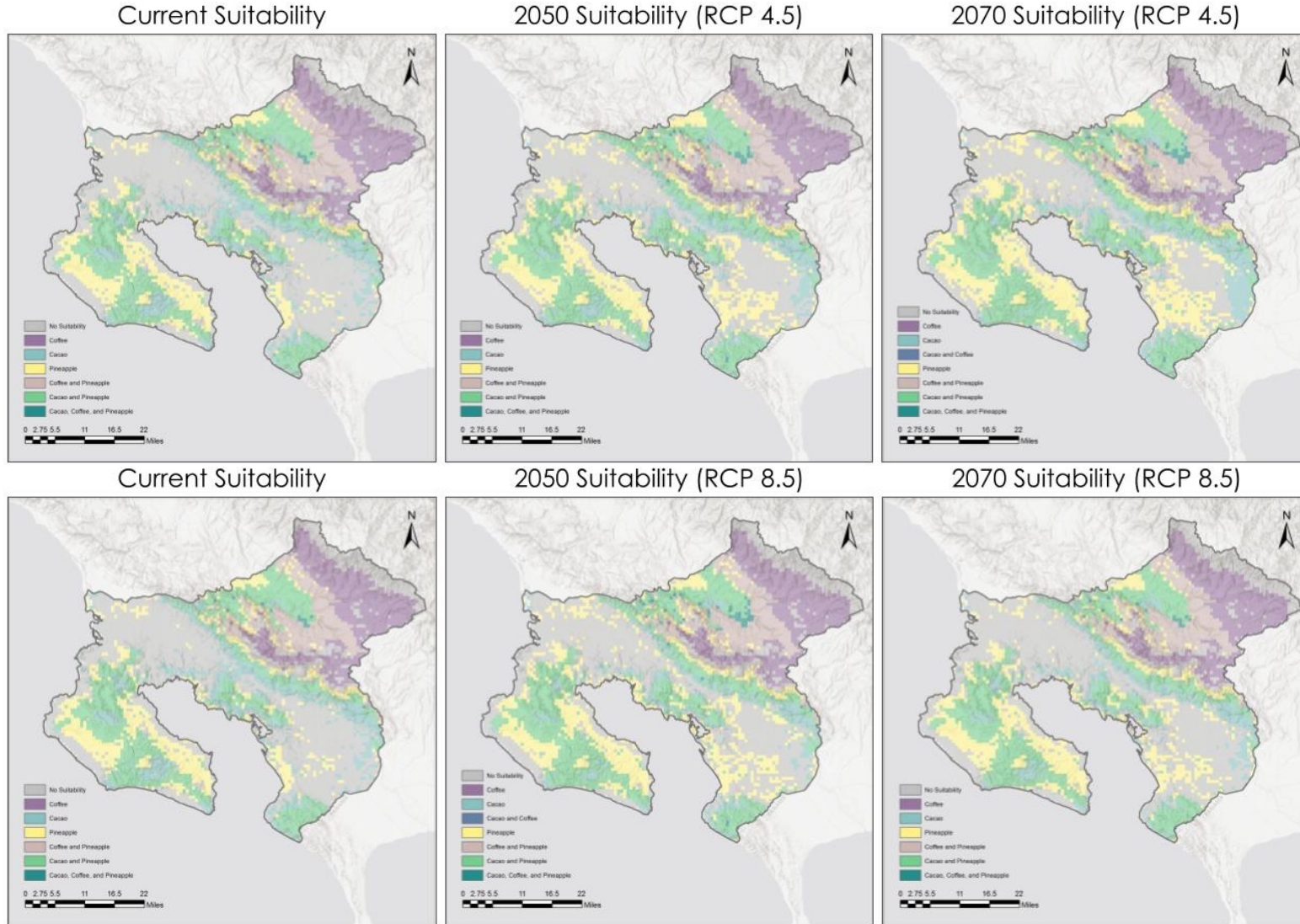
Figure H13. *Crop suitability ranges in the Talamanca-Osa region for cacao, coffee, and pineapple were combined to highlight where suitability would overlap between crops and time periods for RCP scenarios 4.5 and 8.5. Basemap indicates elevation change and high-slope areas.*
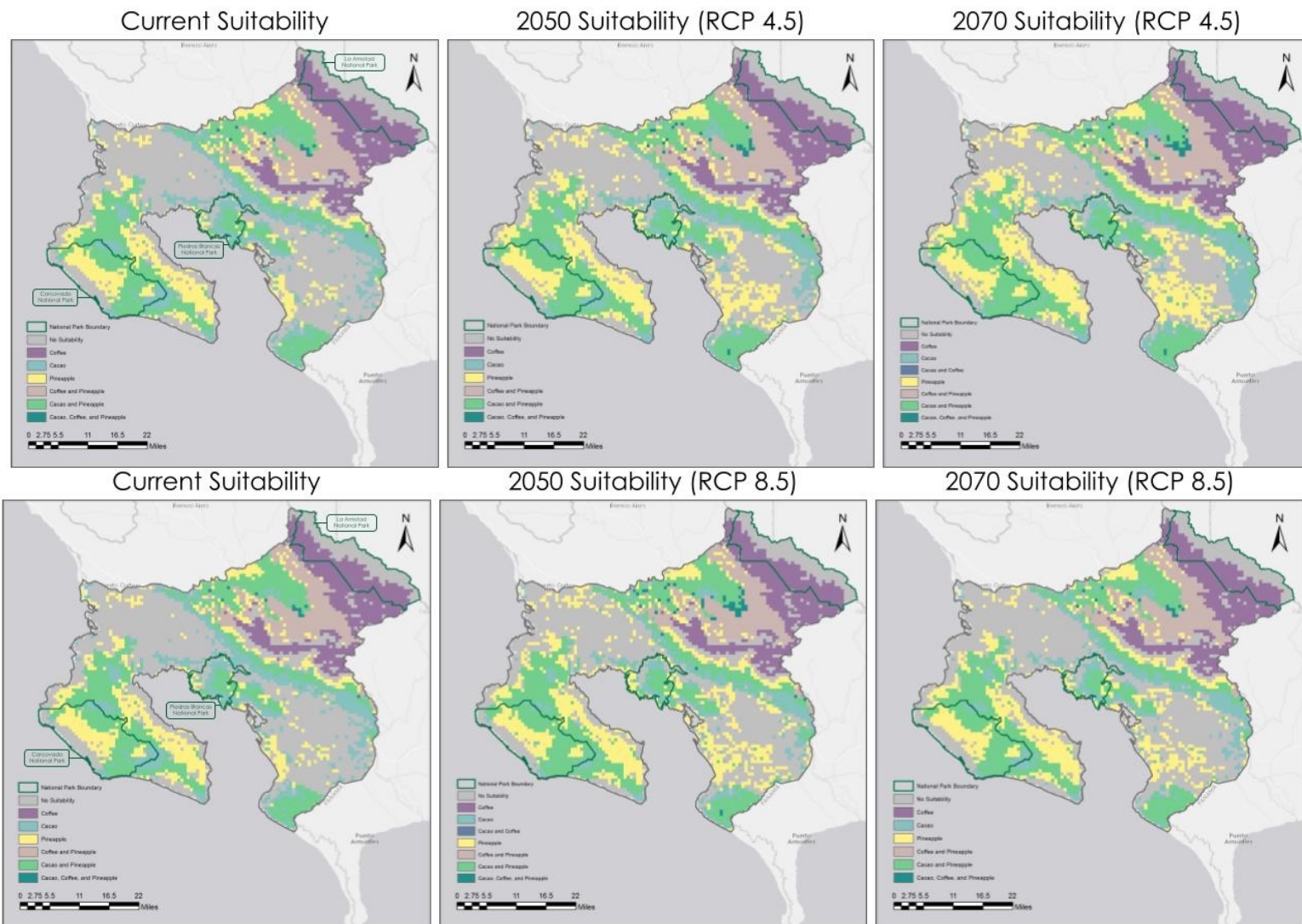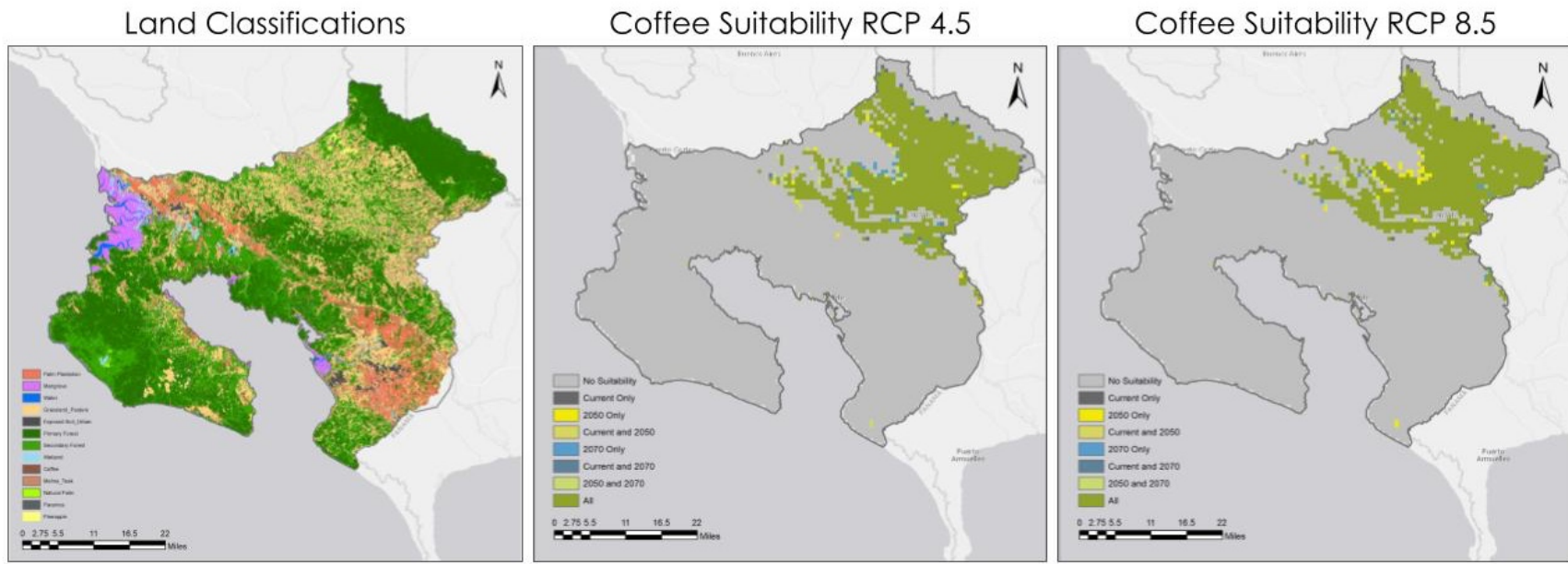
Figure H14. *Crop suitability ranges in the Talamanca-Osa region for cacao, coffee, and pineapple were combined to highlight where suitability would overlap between crops and time periods for RCP scenarios 4.5 and 8.5. A national park boundary layer was added as an overlay outlining La Amistad International Peace Park (northeast), Corcovado National Park (southwest), and Piedras Blancas National Park (central) to show where farming would not be allowed where suitability is present.*
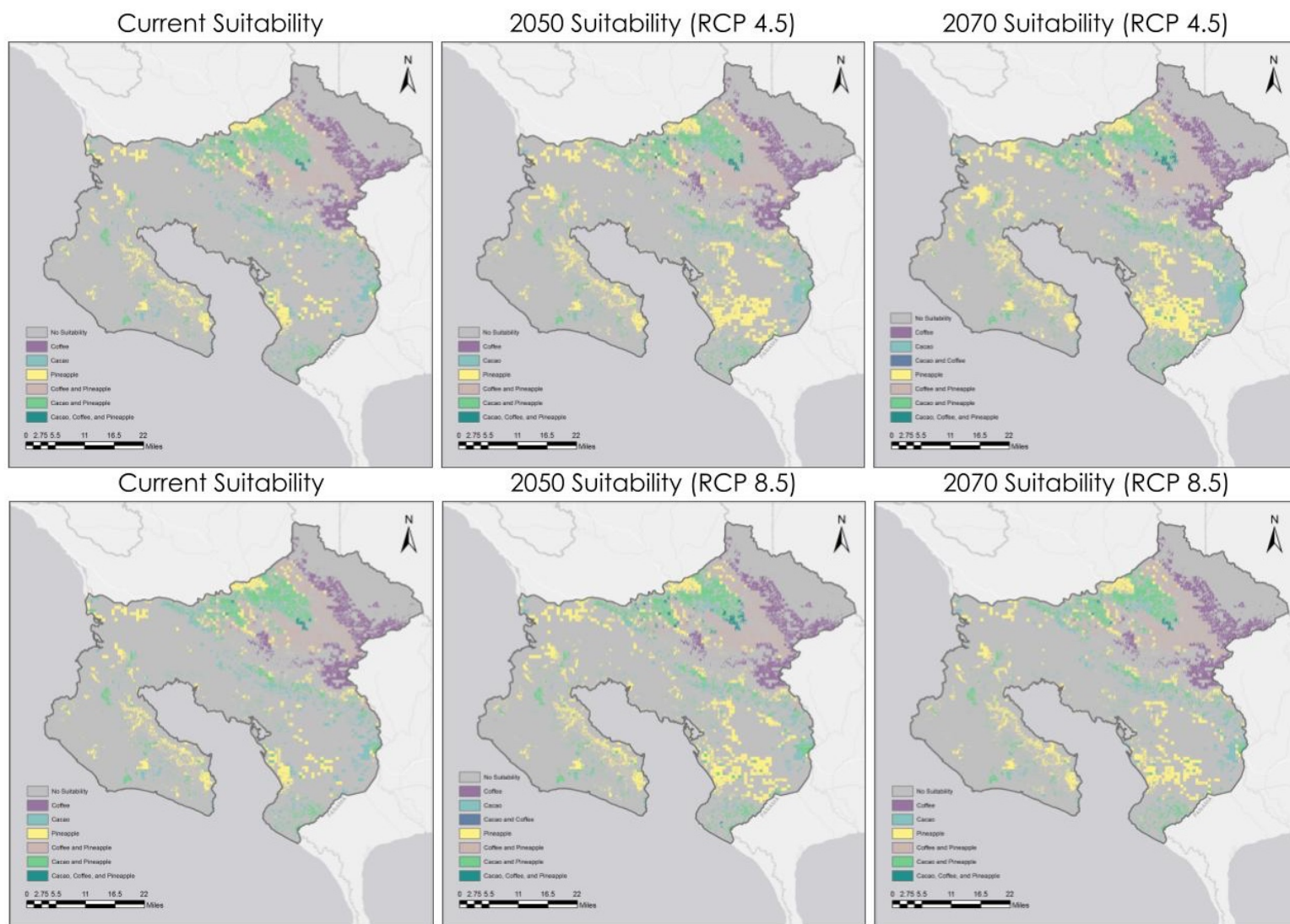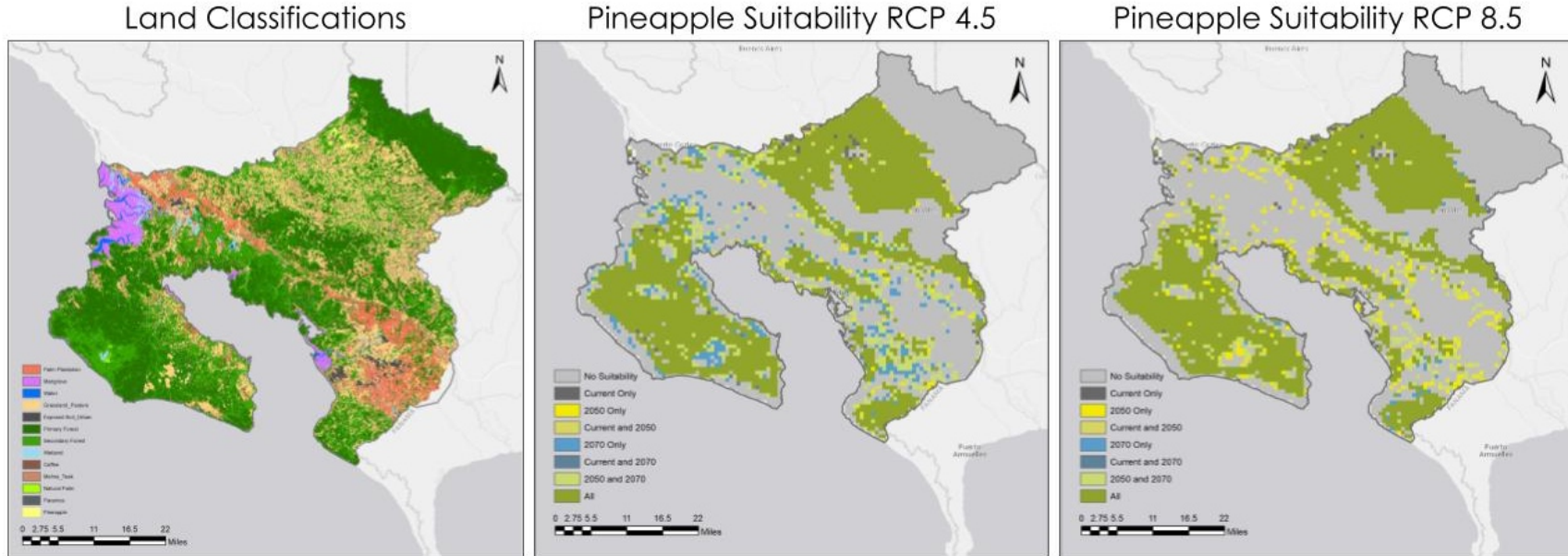
Figure H15. *Crop suitability ranges in the Talamanca-Osa region for cacao, coffee, and pineapple were combined to highlight where suitability would overlap between crops and time periods for RCP scenarios 4.5 and 8.5. Additionally, crop suitability was removed where there were primary and secondary forests to show that farming could not shift there despite being suitable.*
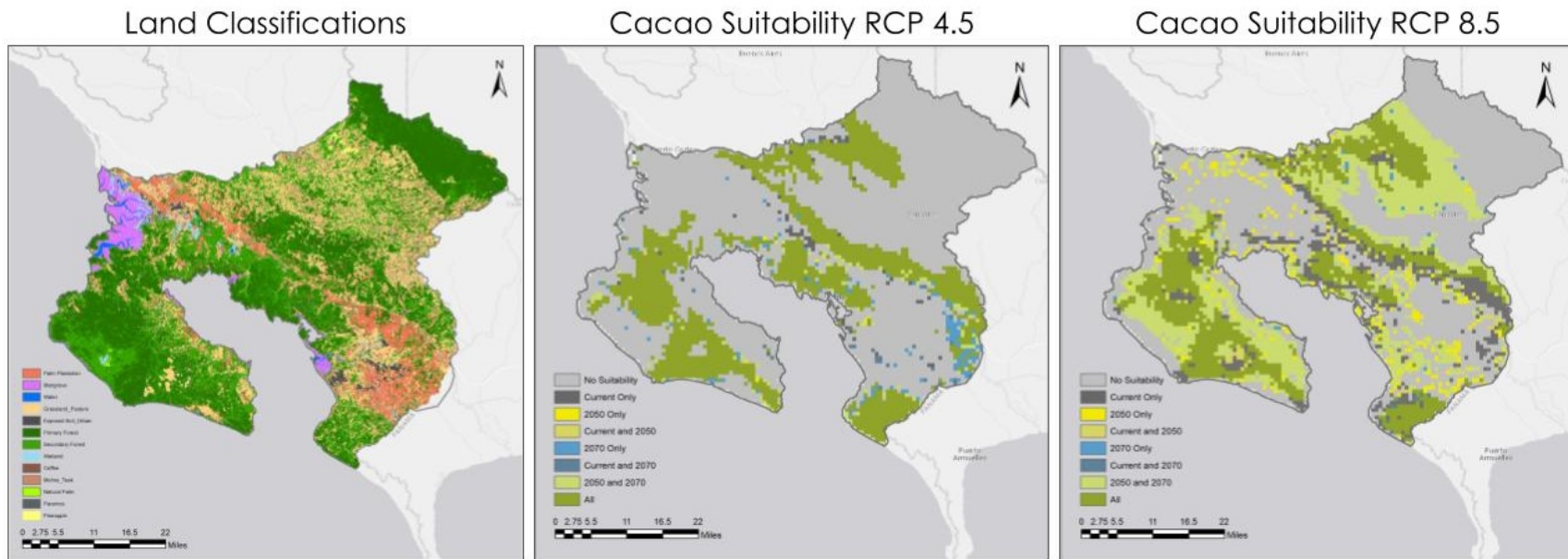
Figure H16. Cacao Crop Suitability Maps in Comparison to Land Classifications. *A map of land classification in the Talamanca-Osa region was used to compare where there are cacao suitability ranges. The cacao suitability maps display spatial shifts and expansion in the Talamanca-Osa region for future decades under two different climate scenarios. Different colors represent overlaps in suitability for different time periods.*

Figure H17: Coffee Crop Suitability Maps in Comparison to Land Classifications. *A map of land classification in the Talamanca-Osa region was used to compare where there are coffee suitability ranges. The coffee suitability maps display spatial shifts and expansion in the Talamanca-Osa region for future decades under two different climate scenarios. Different colors represent overlaps in suitability for different time periods.*

Figure H18: Pineapple Crop Suitability Maps in Comparison to Land Classifications. *A map of land classification in the Talamanca-Osa region was used to compare where there are pineapple suitability ranges. The pineapple suitability maps display spatial shifts and expansion in the Talamanca-Osa region for future decades under two different climate scenarios. Different colors represent overlaps in suitability for different time periods*